Fall Chinook Salmon Life Cycle Production Model
Report to Expert Panel

January 10, 2011

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EXECUTIVE SUMMARY

The Expert Panel was convened to provide a review of the Chinook salmon of the Klamath River Basin for the Secretarial Determination under two alternatives: conditions with dams (No Action Alternative) and conditions with dams out and the Klamath Basin Restoration Agreement (Dam Removal Alternative). The second alternative includes the removal of the lower four Klamath River dams in the year 2020 (Iron Gate, Copco I, Copco II, and J.C. Boyle) and the implementation of the full range of actions and programs described in the Klamath Basin Restoration Agreement (KBRA). The same goals were defined for the Fish Production Modeling team with some additional objectives: 1) construct a quantitative model capable of forecasting abundances two alternatives; 2) incorporate uncertainty in the forecasts of abundance; 3) incorporate future climate change; and 4) focus only on Type I fall Chinook (juvenile migration in the spring shortly following emergence). This report to the expert panel describes the approaches and progress of the Fish Production Model (FPM) for meeting these objectives.

We first give an introduction to the FPM including a general overview of Type I fall Chinook life history (Chapter 1). Next, we discuss the approaches for understanding the productivity, capacity, and growth of fall Chinook in the Upper Klamath Basin (Chapter 2). The FPM uses SALMOD to calculate the downstream movement and mortality and several chapters are devoted to describing the methodology (Chapters 3 – 5). We then discuss analyses on stock recruitment relationships in the Klamath River tributaries below Iron Gate Dam (Chapter 6). Finally, we end with a chapter on the ocean and harvest (Chapter 7).

The FPM is broken into components to address the full life-cycle of Type I fall Chinook in the Klamath Basin (Chapter 1): 1) spawner to juvenile production 2) outmigration, 3) ocean survival and harvest, and 4) adult upstream migration. The source populations for natural juvenile production are: 1) Upper Basin (Sprague, Williamson, and Wood rivers), 2) Keno to Iron Gate Dam bounded Creeks (Spencer, Shovel, Jenny, and Fall creeks), 3) Klamath Mainstem (including above Iron Gate in Dam Removal Alternative), 4) Bogus Creek, 5) Shasta River, 6) Scott River, 7) Salmon River, and 8) Trinity River. In addition the FPM includes production by Iron Gate Hatchery and Trinity River Hatchery. Natural juvenile production is modeled using Beverton-Holt stock production functions for all source populations but the Trinity River (a Ricker stock production function is used on the Trinity River). The coefficients of the production functions in tributaries below Iron Gate Dam are based on retrospective analyses of adult to juvenile data (Chapter 6). Further, KBRA actions are expected to improvements the

stock production functions from their current state (Chapter 6). Capacity estimates for the tributaries above Iron Gate Dam are being evaluated by using the Ecosystem Diagnosis and Treatment (EDT) software, due to the unknown production potential for fall Chinook in the Upper Klamath Basin (Chapter 2).

Outmigration is modeled largely by SALMOD (Chapter 3). SALMOD was expanded from previous versions to span Keno Dam to the ocean (details on the mesohabitat characterization of SALMOD in Chapter 4). SALMOD and other components of the FPM use temperature information to reflect global climate change; temperature is being modeled by HEC5Q (Chapter 5). Once the Klamath Basin fall Chinook enter the ocean, there is an early ocean survival to age 3, when they become vulnerable to the fishery.

The early ocean survival rate is based on a retrospective analysis of patterns in Iron Gate and Trinity River hatchery fish and natural stock production variability (Chapter 7). Annual harvest, ocean mortality, and maturation rates are calculated with the Klamath Harvest Rate Model, which is a simplified version of the Klamath Ocean Harvest Rate Model (Ch. 7). Mature adults return to the Klamath River and migrate upstream with the potential for pre-spawn mortality due to predation and thermal stress (Ch. 1).

Finally, this document is an attempt to provide an interim view of the FPM construction process. The approaches defined in this report are preliminary and subject to modification during the process of model calibration. In addition, there are ongoing analyses that will inform the model development. We expect to complete the evaluation of the No Action Alternative and Dam Removal Alternative with the FPM by April 15, 2011.

1. GENERAL OVERVIEW OF THE FALL CHINOOK SALMON LIFE CYCLE PRODUCTION MODEL (HENDRIX & LINDLEY)

1.1 OBJECTIVES

The objective of the Klamath River fall Chinook Fish Production Model (FPM) is to develop a model that is capable of providing annual forecasts of fall run Chinook abundance with uncertainty. The model must be capable of reflecting the important life-history stages of type I (spring sub-yearling juvenile outmigration) fall Chinook salmon. The FPM is limited to type I fall Chinook due to limitations in the amount of available information for other life history types to parameterize the model. The model must also be capable of evaluating two alternative scenarios (Figure 1-1): a Dams Removal Alternative (DRA) in which the four mainstem dams (Iron Gate, Copco I, Copco II, and J.C. Boyle) are assumed to be removed in 2020 and flows in the Klamath River are managed to attain hydrology as described in the Klamath Basin Restoration Agreement (KBRA); and a No Action Alternative (NAA) in which the four mainstem dams remain in place and the flows in the Klamath River are managed to attain hydrology as described in the 2010 NMFS Biological Opinion (Hamilton et al. 2010). The period of record for the simulation of the two alternatives is 2012 – 2061; thus modeling of both alternatives begins with the dams in place.

As of the writing of this document, the FPM model is not fully constructed. The following chapter represents a methodological blue print of the model. It is likely that some alterations in the model structure as well as final parameterization will occur during the calibration and validation process. This chapter is organized as follows: we describe the type I fall Chinook life history; describe the FPM components used to capture the important aspects of the life history; define the two types of uncertainty to be incorporated into the model; and finally describe how the model will function for evaluating the two defined alternatives.

1.2 LIFE HISTORY

Historically, Chinook salmon (*Oncorhynchus tshawytscha*) in the Klamath River used the full extent of the watershed including tributaries to Upper Klamath Lake (Fortune et al. 1966; Lane and Lane Associates 1981; Moyle 2002; Hamilton et al. 2005). There are two distinct populations native to the Klamath Basin, namely spring and fall run. Spring run enter the river between March and July prior to maturation and hold in pools for 2 to 4 months prior to spawning, whereas fall run enter as mature adults from July through December and move directly to spawning grounds (Andersson 2003). In the tributaries of the Klamath Basin that

currently have anadromy, the majority of Chinook runs are fall run (Andersson 2003); spring run Chinook populations are found in the Salmon and Trinity rivers. The fish production model is focused on fall run Chinook only, thus we focus on its life history here.

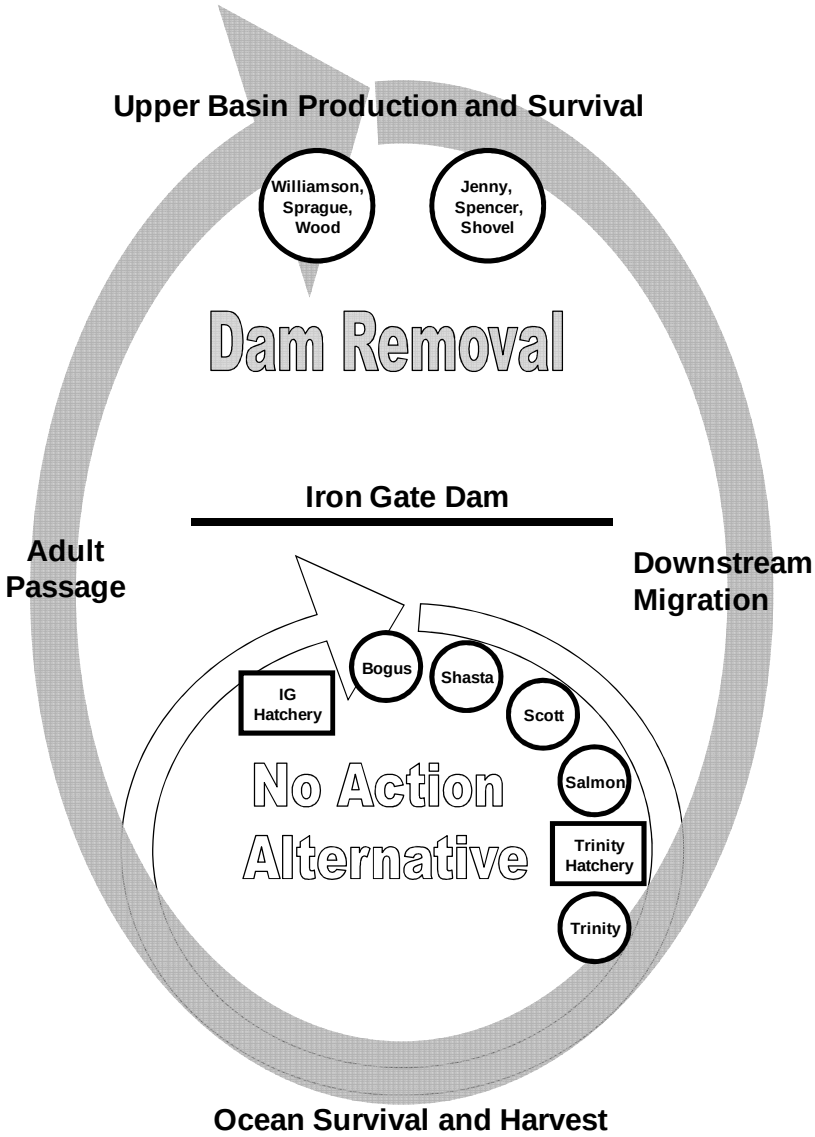

Figure 1-1. Schematic of the two alternatives being investigated in the Klamath River fall Chinook Production Model.

Within the fall run of Chinook salmon there are multiple life history strategies expressed during the juvenile stage. Some individuals emerge and almost immediately begin migrating to the ocean, which are referred to as "Type I" migrants. Other individuals will rear for a period of several months in the streams, typically over the summer after emergence, and migrate out of their natal streams and to the ocean in the fall. These are referred to as "Type II" migrants. Finally, some individuals will remain in their natal stream over the winter and migrate the following spring. This life history strategy is referred to as "Type III" migrants (Sullivan 1989). Although most populations of fall Chinook express one of these life history strategies with some dominance, ocean type fall run Chinook tend to express the Type I strategy. In the FPM, we confine the model to only the Type I life history strategy.

1.2.1 Klamath Basin Fall Chinook Type I Life History

The first goal of the FPM is to reproduce the salient features of Klamath River fall run Chinook with a type I life history strategy. We have created a schematic to identify important life history stages and have used this schematic as a starting point for subsequently defining the life history stages that will be modeled (Figure 1-2). A brief overview of the biology of Klamath Basin fall run Chinook are provided below starting with adult immigration.

Fall run Chinook enter the Klamath River beginning in late July and with peak immigration occurring in September (USFWS, 1998). Arrival on the spawning grounds tends to occur around the first couple of weeks in October (Figure 1-3). Historically (1939 – 1958) Chinook arrived at the Klamathon Racks (mid way between Iron Gate Dam and Shasta River) in late August through late September, whereas more recently the timing has shifted with the peak now occurring during the first week of October (USFWS 1998). Spawning occurs relatively quickly after arrival on the spawning grounds (USFWS 1998). Historically, spawning occurred in most major tributaries of the Klamath Basin including the Wood River, Sprague River, and Williamson River (Moyle 2002; Hamilton et al. 2005). For the purposes of the fish production model, we target 7 tributaries plus the mainstem Klamath as spawning locations (Figure 1-2). The spawning grounds in order of upstream to downstream are:

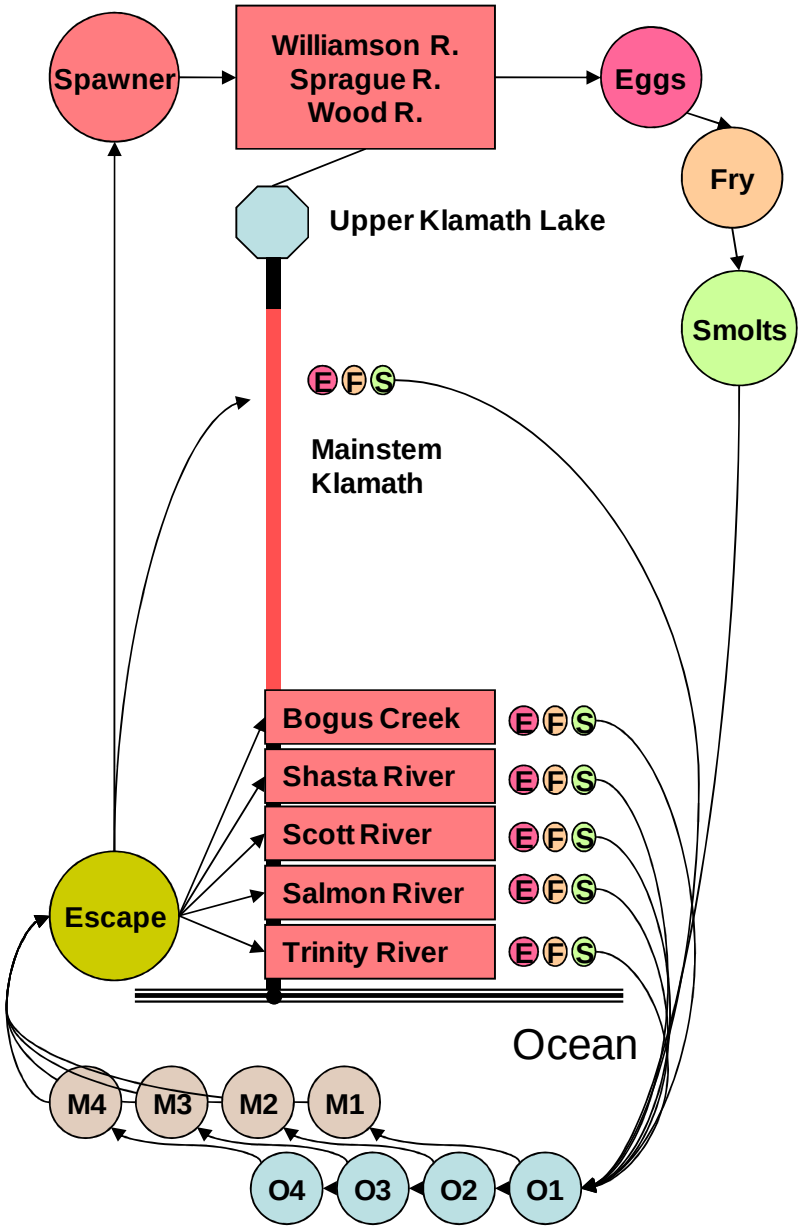

Figure 1-2. Life cycle schematic for Type I fall run Chinook salmon in the Klamath River, Oregon. Spawning occurs in multiple tributaries throughout the basin to produce eggs (E) that transition to fry (F) and smolts (S) before migrating to their first year in the ocean (O1, second year of life). In the ocean, some fall Chinook migrate after their first summer in the ocean as jacks (M1), whereas others remain in the ocean for another year (O2). There are up to 4 ages in the ocean with all O4 returning to spawn as 5 year olds.

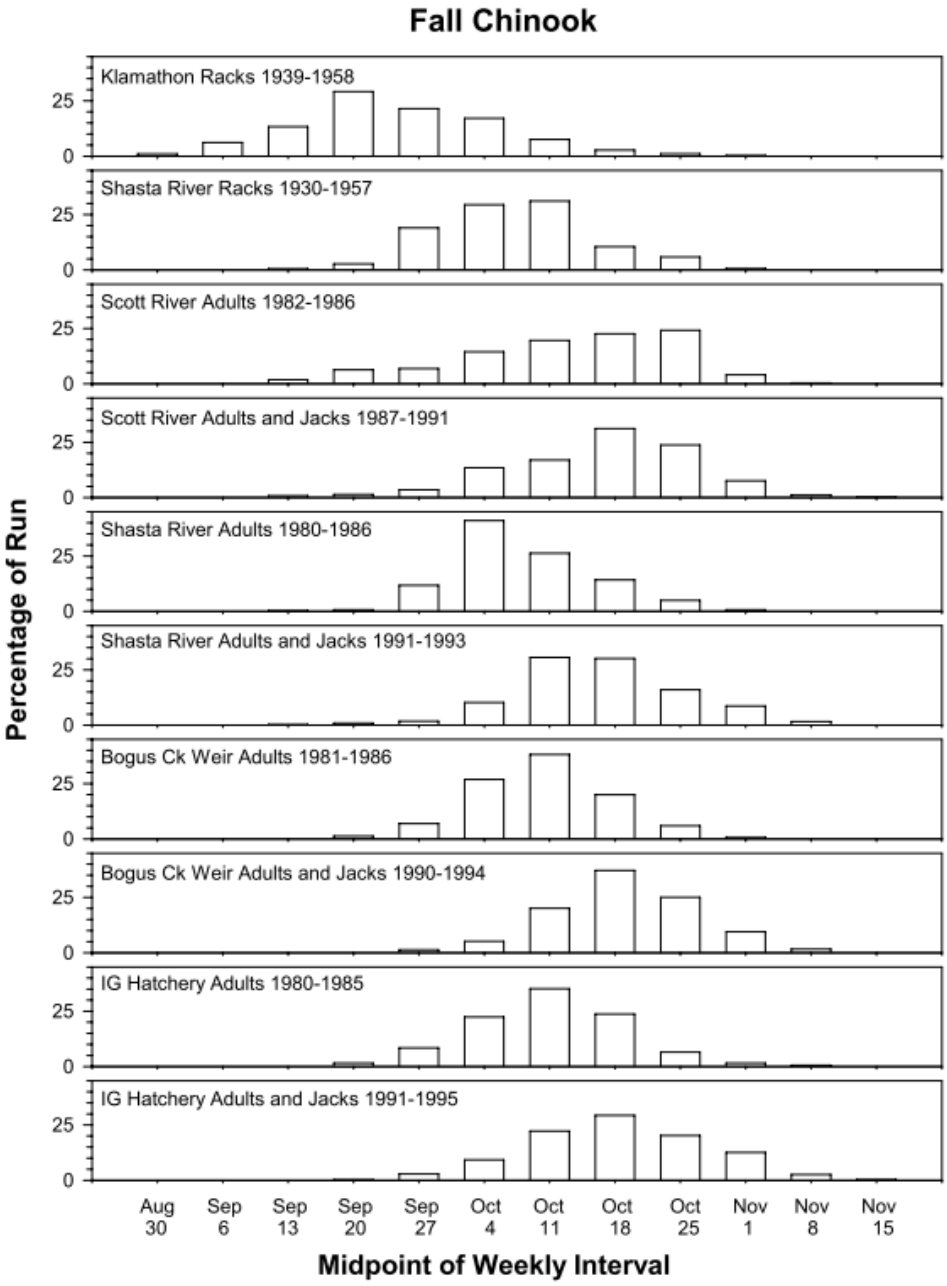

Figure 1-3. Fall Chinook run timing to Klamath River (Figure 22 from Dunsmoor and Huntington 2006).

1. Upper Basin (Sprague, Williamson, and Wood rivers),
2. Keno to Iron Gate Dam bounded Creeks (Spencer, Shovel, Jenny, and Fall creeks),
3. Klamath Mainstem (including above Iron Gate in DRA),
4. Bogus Creek,
5. Shasta River
6. Scott River,
7. Salmon River,
8. Trinity River.

Chinook eggs deposited in the gravel (redd) incubate for approximately 1 to 3 months depending upon water temperature during the fall and winter incubation period (Andersson 2003). Newly hatched Chinook that still have the yolk sac attached are called alevins. The alevins remain in the spawning gravel where the eggs were laid for an additional 2-4 weeks before emerging from the gravel as fry (Andersson 2003). Timing of emergence varies from February through April with peak emergence in March on average (Andersson 2003). Juveniles migrate throughout the year (USFWS 1998), but most Type I migrants initiate their migration shortly after emergence between February and July, peaking in May (USFWS 1998). Timing and size of entry into the mainstem Klamath River varies among tributaries. For example, mean emigration timing from Bogus Creek is April 10th, whereas the mean emigration timing in the Scott River is May 24th (Chapter 5). For more on the relationship between juvenile production estimates and the timing and size at entry into the mainstem Klamath see Chapter 6.

Outmigrating juvenile fall Chinook spend 30-34 days traveling from Iron Gate Hatchery (IGH) to the Klamath River Estuary, whereas Trinity River Hatchery (TRH) fall run Chinook took between 25 to 75 days for coded wire tag (CWT) groups released between 1998 – 2002 (Wallace 2003). Significant variability in the travel time of TRH fall run can be explained by the size of fish at release; CWT release groups composed of larger fish have shorter travel times than groups composed of smaller fish (Wallace 2003).

During their migration from natal redds to the estuary, there are several environmental and biological factors that may affect the survival of outmigrating fall Chinook including river flows, water temperature, predation, and the prevalence of parasite related disease (Bartholomew and Foott 2010). *Ceratomixta shasta* impacts outmigrating juvenile salmonids by attacking their gill epithelium, and mortality rates at high levels of infection can be on the order of 40% (Bartholomew and Foott 2010).

Fall Chinook enter the estuary from June through August where they reside while smoltifying for ocean residency (Healey 1991). Snyder (1931) indicated that juvenile Chinook were observed in the estuary ranging in length from 74 to 106 mm from late summer to early fall. Residency in the Klamath estuary ranges from 1 to 56 days with mean annual estimates ranging from 9 to 16 days based on information obtained from CWT fish in 1997-1999 (Wallace 2002).

After the fall of their first year, Klamath River fall Chinook exit the estuary and move to the coastal zone where they overwinter. The ocean distribution of Klamath River fall Chinook ranges from Monterey, CA to Newport, OR (KRTT 2010). In their second summer, some males return to the Klamath River to spawn as jacks (Figure 1-4). Estimates of the jacking rate for hatchery fish have been from 1% to 10% for IGH and TRH releases (Hankin and Logan 2010). During their third year, Klamath Basin fall Chinook become vulnerable to ocean and river fisheries. The ocean and river fisheries are managed by the Pacific Fisheries Management Council (PFMC) with support from the Klamath River Technical Team (KRTT).

Those adult Chinook that survive the ocean fishery either remain in the ocean for another year, or return to the Klamath River for their spawning migration. Most adults begin their return to the Klamath River in their third or fourth years (Andersson 2003). Those adults that return to spawn, hold below the Trinity River until Klamath River temperatures are conducive to upstream migration (<22°C, Strange 2008). In some years, there may pre-spawn mortality (e.g., 2002) due to high water temperatures, high densities of adults, and low river flows (Vogel 2002; Guillen 2003, CDFG 2003).

1.3 INCORPORATING UNCERTAINTY

Given the variability in global climate change predictions, uncertainty in response of Type I fall Chinook populations to conditions above Iron Gate dam and the unknown response of the existing populations below Iron Gate Dam to restoration actions in the KBRA, it is important to incorporate uncertainty in the Fish Production Model. The two types of uncertainty being incorporated into the FPM are environmental and demographic uncertainty. Monte Carlo simulation is being used to integrate across the two sources of uncertainty, and we are expecting to conduct 1000 Monte Carlo simulations for each alternative.

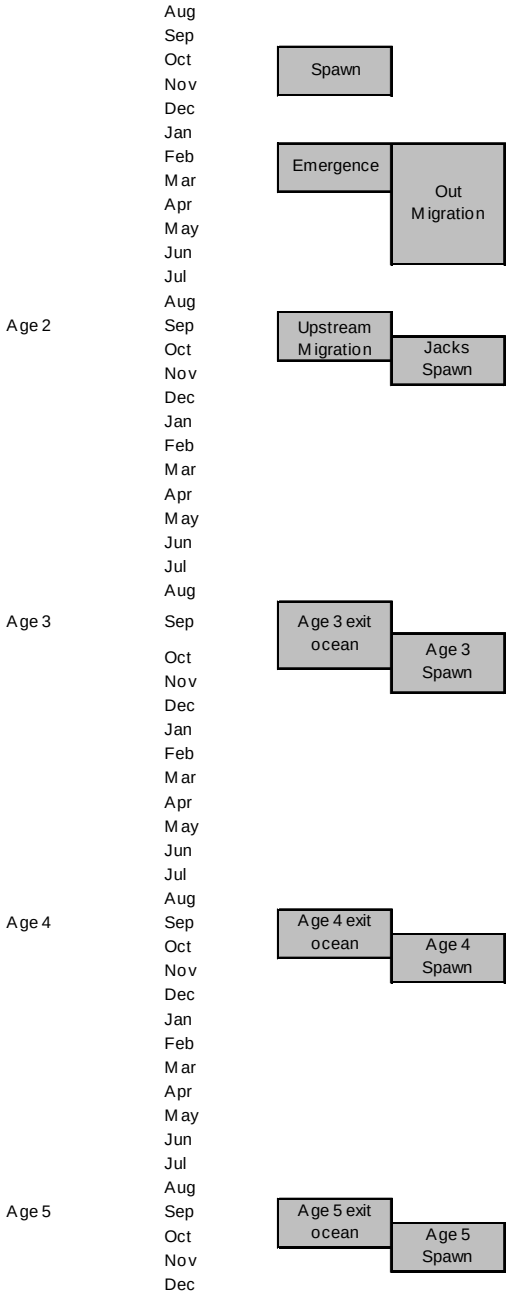

Figure 1-4. Ageing diagram for Klamath River type I fall run Chinook used in the Fish Production Model.

1.3.1 Environmental Uncertainty

Environmental uncertainty arises when the physical conditions that will be present in the Klamath River in the future projections is not known exactly. The environmental conditions being used in the Fish Production Model are stream flow and water temperature, and the model needs to be able to calculate fish abundances given uncertainty in the future levels of these environmental drivers. Uncertainty in these simulated inputs under future conditions for all scenarios in the estimation of Chinook abundance are being incorporated into the FPM framework.

Variability in future stream flow and temperature will arise from different assumptions regarding the climate conditions in the future. To address the uncertainty in future climate, a series of Global Climate Change Models (GCMs) have been used to create monthly estimated flows for specific locations in the Klamath River (Grieman 2010). Temperatures associated with these flows are being developed through HEC5Q modeling (discussed in Chapter 5) to create monthly temperature data for each of the GCM model outputs. The result is a set of paired hydrology and temperature data sets. Each data set is a 50 year period of record (2012 to 2061) utilizing a different assumption about climate change. Each of the climate change scenarios will be sampled at random (each one approximately 200 times to develop the 1000 Monte Carlo simulations), to incorporate the range of future climate projections into the forecasts of fall Chinook abundance as described below.

1.3.2 Demographic Uncertainty

Demographic uncertainty refers to the uncertainty in the parameters that drive population dynamics, such as juvenile survival, adult survival, or fecundity. We will model demographic uncertainty by using probability distributions to define population rates in the model such as survival, juvenile production, capacity, etc. For example, the production of juveniles from spawners is being modeled as a Beverton-Holt with uncertainty in the productivity and capacity estimates (see section 1.4.1 Juvenile Production below). The distributions are typically derived in several ways: 1) professional judgment, 2) literature derived values, and 3) statistical analysis of historical data to estimate the vital rates (e.g., spawner recruit analyses in Chapter 6, mixed effects modeling in Chapter 7). In our experience, the latter two methods provide the most realistic characterization of uncertainty in the model parameters if adequate sources of these data types are available. When empirical data or published data are available these will be utilized. When these sources of data are not available, professional judgment will be utilized.

1.3.3 Monte Carlo Simulation

Monte Carlo simulation is a technique that involves using random numbers sampled from some form of a probability distribution as input to a deterministic equation or model to derive an outcome under conditions of uncertainty. The simplest Monte Carlo simulation begins by sampling a single random variable from a probability distribution. The random variable is then used as input to a mathematical function (or model); the function calculates an outcome using the random variable; and the outcome is saved. The simulation is repeated, i.e., another random variable is drawn, the calculations are completed, and the outcome is saved. These steps are repeated many times, thus creating a series of outcomes referred to as an ensemble. The ensemble of outcomes is evaluated for descriptive statistics, such as the mean, standard deviation, 95 percent confidence interval, etc. As the number of outcomes in the ensemble approaches infinity, the statistics (mean, standard deviation, etc.) converge to their true value (Givens and Hoeting 2005). In practice, a finite number of Monte Carlo simulations are performed with the goal of balancing computational time with the needed precision of the desired statistics. Many fields of study today use Monte Carlo simulations, including biology (Manly 1997), finance (Jackel 2002), physics (Metropolis and Ulam 1949), and statistics (Robert and Casella 1999), among others (Kalos and Whitlock 1986). In practice, a Monte Carlo simulation is used to translate uncertainties in model inputs into uncertainties in model outputs (Manly 1997).

A Monte Carlo simulation does not have to be restricted to a single sample from a probability distribution or to just one parameter. Any parameter or combination of parameter in the deterministic function (or model) can be defined by a probability distribution and thus incorporated into the Monte Carlo simulation. In the FPM, many parameters in the model are defined by both continuous probability distributions (e.g., survival rates) and by discrete probability distributions (e.g., the GCM hydrology and temperature series). The Monte Carlo simulation approach will utilize random samples from both environmental and demographic parameters. The corresponding uncertainty inherent in both the environmental and demographic factors will therefore be represented in the resulting statistics (mean, 95% confidence interval, etc.) for important model outcomes (e.g., abundance, escapement, catch, etc.).

1.4 FALL CHINOOK FISH PRODUCTION MODEL COMPONENTS

The Klamath River fall Chinook Fish Production Model is composed of several components in order to address the objectives described above and to capture the important life history elements of Chinook biology (Figure 1-5). The components of the model are described below with some

explanation of the objective of the component, required input, resulting output, and where appropriate the linkage to the next component.

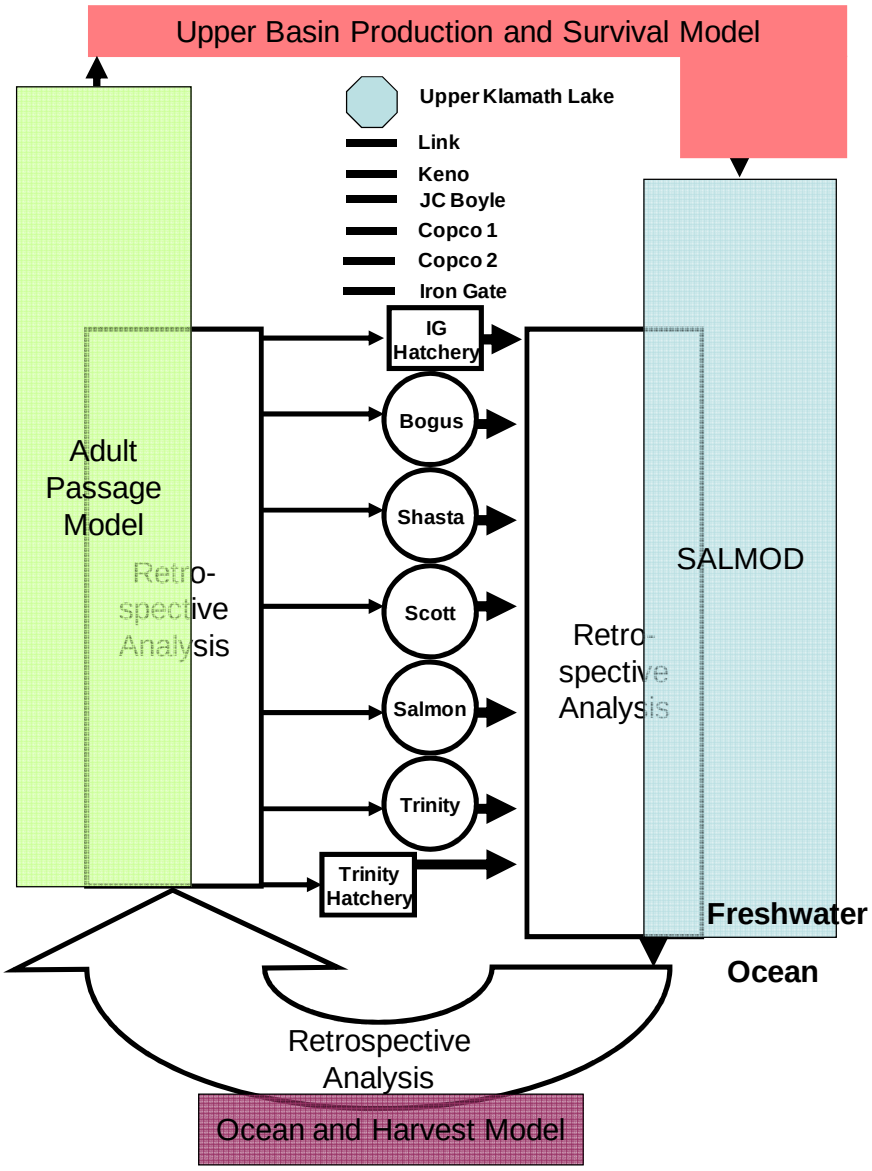

Figure 1-5. Fish Production Model components for modeling the No Action Alternative and the Dam Removal Alternative on Klamath River Type I fall Chinook life history. Open symbols indicate locations of current natural juvenile production (circles) and hatchery juvenile production (boxes).

1.4.1 Juvenile Production

The objective of the juvenile production component of the FPM is to estimate the numbers of juveniles as a function of spawning adults that incorporates environmental variables that may impact annual variability in the number of juveniles produced per adult spawner. There are several sources of spawning adults (i.e., natural locations versus hatcheries) that requires differential tracking of juvenile production by the FPM. The major tributaries that currently contribute fall run Chinook to the Klamath River include the Trinity, Salmon, Scott, and Shasta Rivers as well as Bogus Creek. There is spawning in the mainstem Klamath and production from Iron Gate Hatchery and Trinity River Hatchery that contributes to production below Iron Gate Dam. Other potential sources of natural production are the tributaries to Upper Klamath Lake including the Wood, Williamson, and Sprague Rivers. In addition there is the potential for juvenile production in the streams located in the reaches bounded by J.C. Boyle and Iron Gate dams (Fall, Shovel, and Jenny Creeks) (Figure 1-5).

Production in all tributaries will be modeled using Beverton-Holt (BH) stock recruitment functions with the exception of the Trinity River, in which a Ricker stock recruitment function will be used. The Beverton Holt stock production function is described by the following equation:

$$R_y = \frac{S_y}{\frac{1}{p} + \frac{S_y}{K}} \qquad (1)$$

where R_y is the sub-yearling juveniles in year y, S_y is the spawning abundance in year y, p is the productivity (number of sub-yearling juveniles per spawner at low spawner abundance), and K is the carrying capacity. The BH stock recruitment function has an asymptote that approaches the carrying capacity as spawner abundance gets larger (Figure 1-6). Uncertainty is incorporated into the BH function by specifying probability distributions for the productivity parameter p (Normal distribution for productivity based on the retrospective analysis in Chapter 6), and the capacity parameter K (logNormal for capacity to keep it positive). The result is that a range of juveniles can be produced for a given spawner abundance (Figure 1-6).

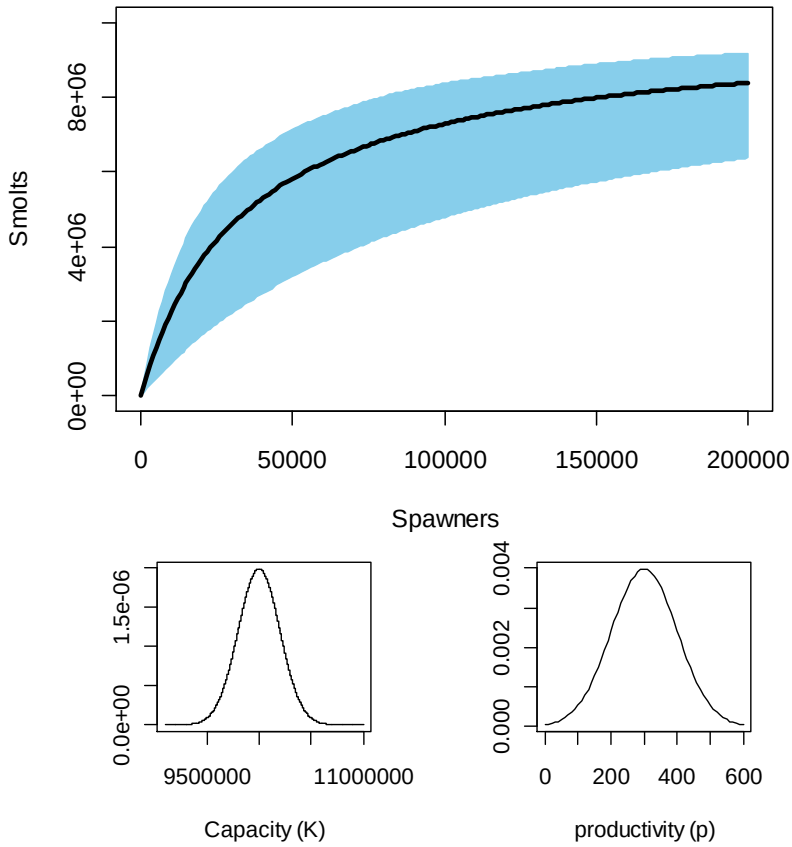

Figure 1-6. Beverton-Holt stock recruitment function from adults to outmigrant juveniles incorporating uncertainty in the productivity and capacity parameters of the function.

In a retrospective analysis of several lower basin tributaries (Bogus Creek, Shasta River, Scott River), Dr. Russell Perry (USGS) utilized a Ricker production function which is defined as:

$$R_y = \alpha S_y e^{-\beta S_y} \qquad (2)$$

where R_y, is the number of sub-yearling Chinook salmon emigrating in year y, S_y is the number of spawners α is the sub-yearling juvenile Chinook per spawner at low spawner abundance and β describes the rate at which the production of juveniles drops as the spawner abundance increases. Calibration of the function was achieved by selecting the parameters α and β through statistical fitting to available juvenile and spawner data (details are presented in Chapter 6).

There are important differences between the Ricker and BH production functions. The Ricker curve peaks at an intermediate spawner abundance (S_{max}, the spawner abundance that maximizes

recruitment). Spawner abundances above S_{max} decrease productivity, thus the Ricker function has a unimodal shape. In contrast, the BH function is monotonic and recruitment continues to increase as spawner abundance increases (Figure 1-6). For all tributaries of the Klamath River except the Trinity River, there is no support for the unimodal Ricker shape over the monotonic BH shape (please see the stock recruitment analysis in Chapter 6). Yet, applying a Ricker curve in the simulations would assume that productivity decreases beyond S_{max}. Using the Ricker curve would have the unexpected consequence that higher spawning abundance would lead to lower productivity in the system, which to date has only been documented in the Trinity River.

For tributaries where there were spawner and juvenile data (Bogus Creek, Shasta River, and Scott River), the parameters α and β were estimated through statistical fitting (more detail can be found in Chapter 6). Furthermore, the values of α can be used to approximate the values of p in the BH production function, since they both represent the sub-yearling production at low spawner abundances.

For tributaries where there were no data (Upper Klamath Lake tributaries, project reach tributaries) or insufficient data to estimate a stock production function (Salmon River), the results of the statistical fitting can be used to estimate the productivity by evaluation of run timing (Chapter 6). Further, probability distributions, which are needed for the Monte Carlo simulations, can be derived from the estimates of the Ricker productivity value (α) from the statistical fits by using the maximum likelihood estimates and standard errors to fit parametric statistical distributions (e.g., Normal for the BH productivity p).

Estimates of juvenile capacity in tributaries of the Klamath River are based on the method applied in Parken et al. (2006), in which watershed size was used to develop capacity estimates assuming a Ricker production function (see Chapter 5 for details). The Parken (2006) approach provides the spawner abundance at which productivity is maximized in the Ricker curve (S_{max}), and the amount of productivity at this spawner abundance is R_{max}. Because salmon are semelparous (reproduce once and die) species, we can use the estimate of maximum recruitment under the Ricker R_{max} to approximate K in the BH production function. The equations in Parken (2006) provide an estimate of S_{max} which occurs at $1/\beta$ for semelparous species such as salmon (Hilborn and Walters 1992). The maximum amount of production, R_{max}, is equal to $\alpha/\beta * e^{-1}$ (Hilborn and Walters 1992). In the BH equations for semelparous species, productivity is maximized when the abundance is infinity (i.e., $S_{max}= \infty$) due to the asymptotic nature of the function. Further, the maximum level of production (R_{max}) is K. In the analysis conducted by Dr. Russell Perry (Chapter 6) the spawner abundances were typically below S_{max}, thus the fitted Ricker curves were similar in shape to BH curves (recruitment increasing over the range of

spawner abundances). We therefore approximate K with the maximum level of production (i.e., $K = \alpha/\beta * e^{-1}$) for all lower basin tributaries but the Trinity, where a Ricker curve is used.

Capacity estimates from the tributaries to Upper Klamath Lake are being developed from two sources of information. First, estimates of watershed area are being used to estimate capacity using the Parken et al. (2006) approach. Further, the Ecosystem Diagnosis and Testing (EDT) model is being utilized to generate estimates of juvenile capacity for type I fall Chinook in these tributaries (please see Chapter 2 for details).

Production from Iron Gate Hatchery and Trinity River Hatchery will also be incorporated into the FPM. Historical releases from Iron Gate Hatchery have been on the order of 6 million juveniles, whereas Trinity River releases were on the order of 2.8 million juveniles (Myers et al. 1998). We assume that these levels of production from the hatcheries will persist for as long as the hatchery is operational. In the dam removal alternative (DRA), the removal of Iron Gate dam may impair operations at Iron Gate Hatchery, thus the ability to produce fish at this facility is uncertain after 2020. The fate of IGH under DRA is being evaluated currently by PacifiCorp. Without further information from PacifiCorp, we assume that production at IGH will be transferred to Fall Creek Hatchery and will continue through 2028.

1.4.2 Downstream Migration

The objective of the downstream migration component is to move juveniles from the confluence of their natal tributary or spawning locations within the mainstem Klamath River to the ocean and apply an appropriate mortality rate through this life-stage. This includes juveniles from sources upstream of Upper Klamath Lake. Factors known to affect survival include: flow, temperature, predation, and disease (which are also affected by flow and temperature through the intermediate invertebrate host). For the majority of the outmigration, the effects of flow, temperature, and disease mortality are being modeled in SALMOD (details are presented in Chapter 4). For the spawning reaches above Keno (Upper Klamath Lake (UKL) tributaries of Wood, Sprague, and Williamson Rivers), the survival rate and outmigrant timing are being developed for the tributaries of UKL to Keno, where the juveniles are supplied to SALMOD as input for that modeling component (see Chapter 3).

There is the potential for the strain of *Ceratomyxa shasta* that is virulent to Chinook to become established in the Williamson River once the series of dams are removed (Bartholomew and Foott 2010). The FPM model will incorporate the probability of a disease “hot spot” in the Williamson River. This process can be implemented in a two ways: 1) by incorporating an explicit disease function with a format similar to that being employed in SALMOD, or 2) by

modifying the productivity *p* in the BH production function from the tributaries to UKL for disease when temperatures during outmigration become high enough to infect outmigrating juveniles. In the FPM, we have used a modification of the productivity *p* as a function of temperature given the lack of data available to parameterize a disease function in the Williamson River.

Survival through Upper Klamath Lake is based on a literature review of Chinook migrating through reservoirs on the Columbia and Snake rivers and studies of survival of Chinook in UKL. Estimates of survival through reservoirs on the Snake River range from 0.73 to 0.99 with a median of 0.84 (Chandler and Chapman 2003) and estimates of survival through the lower Snake and Columbia reservoirs range from 0.77 to 0.98 with a median of 0.84 in 1998 (Smith et al. 2000). Estimates of survival from a study exposing sub-yearling Chinook to spring conditions in Upper Klamath Lake in 2006 indicated survival was 1.0 (Maule et al. 2009).

1.4.2.1 SALMOD

The objective of SALMOD is to move juvenile sub-yearling Chinook from the confluence of a tributary with the Klamath River to the ocean. In addition, SALMOD calculates the location of spawning and the production of juveniles in the mainstem Klamath for mainstem spawners. SALMOD will be used to estimate downstream survival of Chinook emigrating from sources above UKL. The sources of mortality incorporated into SALMOD include flow, temperature, and disease. SALMOD has been developed to operate from Keno dam on the upstream end to the ocean on the downstream end (please see Chapters 3 and 4 for details on SALMOD construction for the FPM).

SALMOD requires specific types of biological data to initiate the model. For the application of SALMOD in the Klamath River, abundance and size of individuals entering the model are specified in weekly increments. To provide these biological input data, an emergence timing and growth model is being developed for the populations in tributaries to Upper Klamath Lake using EDT (please see Chapter 2 for details). Abundances of juveniles in other tributaries to the Klamath River will be provided in weekly intervals by utilizing the historical pattern in outmigration timing and disaggregating the total production by week (see Chapter 5 for estimates of peak outmigration timing among tributaries of the Klamath River). Hatchery production of sub-yearling Chinook will be modeled with historical release timing and size information.

Depending upon the alternative being evaluated, SALMOD will track different source populations. In the NAA scenario, SALMOD will account for juveniles from 7 source populations including the mainstem production: 1) Iron Gate Hatchery, 2) Bogus Creek, 3)

Mainstem Klamath River, 4) Shasta River, 5) Scott River, 6) Salmon River, and 7) Trinity River. In the DRA scenario, SALMOD will account for the previously mentioned 7 populations from 2012 to 2019, but from 2020-2061 it will account for juveniles from 7 source populations plus the mainstem spawners: 1) Upper Klamath Lake Tributaries, 2) Project Bounded Creeks, 3) Bogus Creek, 4) Mainstem Klamath River, 5) Shasta River, 6) Scott River, 7) Salmon River, and 8) Trinity River (Figure 1-5).

SALMOD incorporates a disease function due to *C. shasta* that is based on the environmental conditions prevalent during the window of outmigration (please see Chapter 5 for a description of the disease function in SALMOD). Research into the relationships between environmental conditions and subsequent mortality of outmigrating juvenile Chinook in reaches below Iron Gate dam are ongoing; however, information to date has been incorporated into the disease function in SALMOD. For more information on the dynamics of *C. shasta* and the environmental conditions that promote infection of juvenile salmonids, please see Bartholomew and Foott 2010).

SALMOD outputs the abundance and size distribution of juveniles in weekly intervals by source population at the Klamath estuary. The abundances of juveniles from each source population are subsequently summed into an annual production by source population and tracked in the ocean.

1.4.3 Ocean

The objective of the ocean component of the model is to track the individual source populations through their first two summers in the ocean prior to harvest, calculate the harvest that occurs in the ocean and estuary for age 3 to 5 fish, track the natural mortality of fish that remain in the ocean, and calculate the proportion of the population returning to spawn at ages 2 (jacks) to 5.

There are no existing estimates of survival from the estuary to subsequent ages in the ocean; however, there are two sources of information that can be used to help understand survival of fall Chinook from the juvenile stage in the Klamath and Trinity Rivers to early ages in the ocean. We used estimates of survival of hatchery fish to age 2 (e.g., Hankin and Logan 2010) and a stock recruitment regression analysis (STT 2005) to understand how much variability in survival of the hatchery fish could be attributed to a common source of variation (assumed to represent estuary and early ocean conditions).

The production function from spawners to age 3 in the ocean has been evaluated by the STT (2005), and they found that the hatchery survival to age 2 was an important predictor of variability in natural adult production. We are in the process of evaluating the sources of

variability inherent in this regression analysis. Our goal is to estimate the amount of variability in age 3 natural production attributable to factors in common to the Trinity River and Klamath Rivers as an indicator of lower estuary and early ocean survival. This survival would be applied to all 8 natural source populations in the DRA scenario and the natural populations in the NAA alternative. Please see Chapter 7 for more information on the analyses of these data for developing the survival in the early ocean stage.

1.4.3.1 Harvest Model

From ages 3 to 5, the ocean survival, harvest, and migration rates are computed by a simplified version of the Klamath Ocean Harvest Model (KOHM) entitled the Klamath Harvest Rate Model (KHRM). The objective of the harvest model is to calculate the optimum harvest of age 3, 4, and 5 year old Chinook from the Klamath and Trinity Rivers that meet conservation constraints on the proportion of spawners being harvested and the harvest rate on 4 year olds (Prager and Mohr 2001). The KHRM is spatially and temporally implicit; thus, providing an approximation to the behavior of the KOHM. The model incorporates natural and fishery related mortality and provides harvest estimates on an annual basis.

The KHRM uses the following series of steps to calculate harvest. The pre-harvest abundances of age 3, 4, and 5 are supplied to the KHRM in the fall (September 1). The fishery is assumed to have natural mortality from fall to spring with fishing occurring in the summer following the overwinter period. Harvest is calculated in the ocean commercial and recreational fisheries. A proportion of each age that survive the ocean fishery mature into adults and they return to spawn (all age 5 fish return as adults). Those 3 and 4 year olds that do not mature remain in the ocean for another year. There is some straying out of basin that is applied to adult fish. Adult fish returning to the Klamath River are subjected to the river tribal and recreational fisheries. Those fish that survive the river fisheries escape to spawn in either the natural basin or in one of the two hatcheries. For more information on the KHRM, please see Chapter 6.

After surviving the ocean and river harvest sectors, adult Chinook return to the Klamath River where they begin their upstream migration. These two stages overlap somewhat in that Chinook are captured in the river and tribal harvest in the estuary.

1.4.4 Adult Migration Component

The objective of the adult migration portion of the model is to move the adults from the estuary back to their spawning grounds and apply mortality through this portion of their migration. The adult migration component is split into two phases with different sources of mortality in each phase. In the first phase, individuals are susceptible to mortality from pre-spawn mortality due

to thermal, flow, and density dependent factors. In the second phase fish migrate upriver to their natal spawning grounds with reach specific survival rates applied to upstream migrants. A trap and haul program at Keno has been proposed, which would move adults into UKL where they continue their migration to the Wood, Sprague, and Williamson Rivers (Figure 1-7).

Klamath River fall Chinook return to the Klamath River between June and September. Klamath River fish typically arrive earlier than Trinity stocks (CDFG 2003). Chinook acclimate by using the cold salt wedge that can extend up to 4km upriver from the mouth of the estuary (Strange in review). Time in the lower estuary is minimized due in part to predation. Pinniped predation from California sea lions (*Zalophus californianus*) was estimated at 33% and 14% in 2005 and 2006, respectively. Predation occurred mostly in the estuary (up to rkm 3) and infrequently in the lower river (up to rkm 7) (Strange in review). Chinook move through the estuary and lower river using temperature cues to time upstream migration. The thermal blockage to movement upstream depends upon whether the trend in temperatures was increasing or decreasing; however, the thermal threshold of 22°C weekly average temperature was a consistent indicator of Chinook movement (Strange 2008).

After moving rapidly through the estuary, adult Chinook hold in pools above Blue Creek that provide thermal refugia (and potentially predator refugia due to the murky water) for approximately 10 days to 2 weeks (Strange 2010). During this period of holding above Blue Creek, Chinook may be susceptible to pre-spawn mortality events, which have been documented in the lower Klamath River as far back as 1987 (CDFG 1994). In 2002, a pre-spawn event occurred in mid to late September, in which approximately 32,500 adult Chinook perished downstream of river mile 36 (Guillen 2003); this die off event represented approximately 19% of the total Klamath – Trinity escapement in 2002. The acute cause of death was Ich and columnaris; (Gullen 2003; CDFG 2003); however, these parasites and pathogens, respectively, tend to be present in low levels and become problematic when water quality is conducive for growth (i.e., temperatures above 18°C) and fish are crowded (CDFG 2003).

Evaluation of flow levels, temperatures, and abundance of the 2002 run size indicated that while none of the three factors were extreme, they acted in concert to cause a die off event (CDFG 2003). Flow releases at Iron Gate Dam were less than 1000 cfs due to drought conditions in the Klamath basin and discharge during August and September was the fourth lowest in the period from 1978 to 2002; the run size was the eighth largest in the same period; and water temperatures were high relative to Chinook salmon tolerances (i.e., 17.2 - 20°C, Marine 1992), but typical for this period of the year.

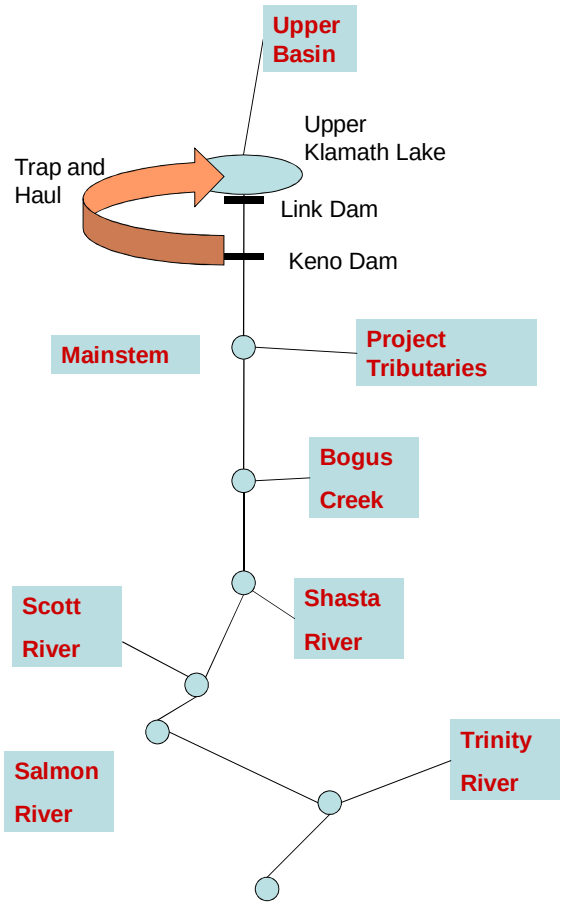

Figure 1-7. Schematic depicting the adult upstream migration reaches and trap and haul program at Keno dam for the Dams Removal Alternative.

Due to the nature of the fish kills being binary, the event will be modeled as a Bernoulli random variable with an annual probability p_t of a fish kill event occurring in year t. Although there is some uncertainty as to the cause of the 2002 fish kill event, there may be some combination of factors that lead to a higher probability of a fish kill event. We are in the process of investigating if there are factors that could be used to predict annual variability in the probability of a fish kill event. Some potential factors include: annual escapement, flow in the lower Klamath River, and water temperature. The modeling framework for incorporating such factors is logistic regression:

$$p_t = \text{logit}^{-1} (\beta_0 + \beta_1 X_t)$$

where logit^{-1} is a transformation that ensures that p_t remains in the interval (0,1), β_0 is the average probability of an event, β1 is the coefficient associated with the covariate value X_t in year *t*. Such pre-spawn mortality events can impart significant mortality on the escaping spawners (19% for the 2002 event [CDFG 2003] and > 30% for a 1987 event [CDFG 1994]); thus when there is a pre-spawn event the amount of mortality imparted will be on the order of 20-30%.

After the 10 day to 14 day migration through the lower Klamath River to Weitchpec, fall Chinook begin their migration in a directed fashion toward their spawning locations. Historical arrival on spawning grounds suggests that fall Chinook in the Klamath Basin targeted the first couple weeks of October (Figure 1-3). The timing of arrival would be timed as closely as possible to historical timing assuming that the migration rates were not being violated. Migration rates for fall Chinook have been estimated by radiotelemetry studies. For example, Dunsmoor and Huntington (2006) used an estimate of 9.5 rkm/day for fish migrating above Weitchpec. More recent data are available (e.g., Strange 2008) and are currently being analyzed to describe the distribution in migration rates for Klamath and Trinity River fall Chinook.

Annual straying rates (5%, ranging from 2.5% to 7.5%) are applied to the spawning locations to incorporate the likelihood of mixing among spawning stocks. Estimates of lower Columbia hatchery straying rates ranged from 10% to 28.5% for hatchery stocks (Quinn et al. 1991), whereas estimates of straying among natural origin Columbia fall Chinook were approximately 4.2% (Keefer et al. 2005). Because the stock structure of the Klamath River is assumed to be dominated by natural stocks after the removal of Iron Gate Dam, the 5% straying rate is for the DRA scenario.

The remainder of the migration is associated with reach specific estimates of mortality with each reach being defined as a tributary in the FPM (Figure 1-7). The mortality in any specific reach is currently being modeled as a function of temperature experienced through those reaches, e.g., $S_i = exp\{-\delta * T_i\}$, where δ is the mortality rate per unit thermal load of reach *i*. Thus, fish that are exposed to higher thermal loading have a higher mortality rate associated with upstream migration than those with lower thermal loading. There is evidence that Klamath Chinook time migration to avoid additional thermal loading during migration past the confluence with the Trinity River at Weitchpec (Strange 2010; Dunsmoor and Huntington 2006). For example, Dunsmoor and Huntington (2006) evaluated the thermal conditions during upstream migration and compared the thermal conditions to observed locations of radio-tagged adult Chinook (Figure 1-8). The majority of radio tag locations were in either suboptimal or optimal thermal conditions with few observations in stressful or severely stressful thermal conditions.

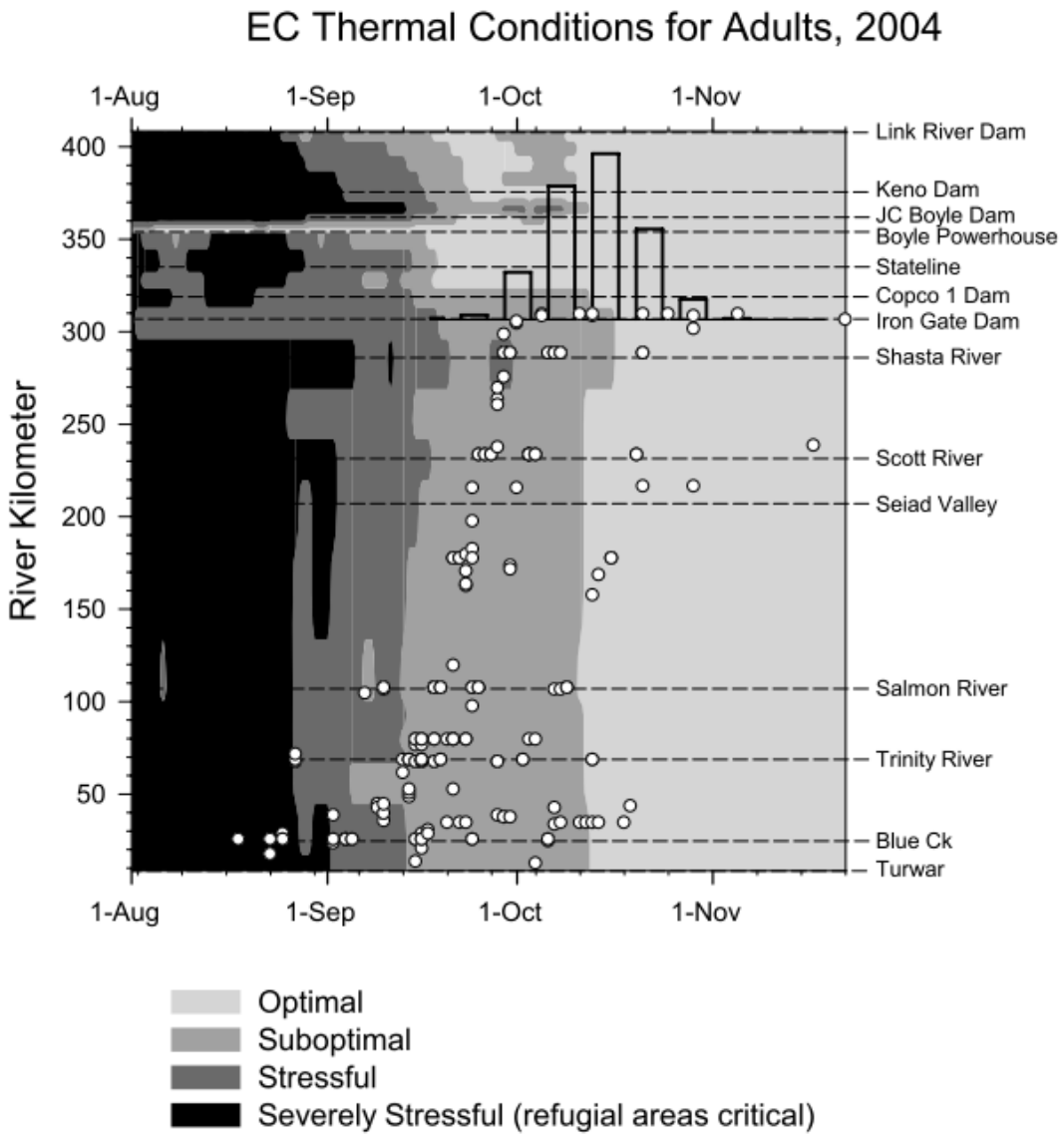

Figure 1-8. Figure 25 from Dunsmoor and Huntington (2006) showing the existing thermal conditions in 2004 and locations of radio-tagged adult Chinook.

The final element to the upstream migration model is the trap and haul that is planned for the group of spawners in the tributaries to UKL. The proposed trap and haul protocol will be to collect adult Chinook salmon at Keno Dam and truck them to release sites in UKL. Mortality associated with trap and haul is expected to be on the order of 4 to 6% (Oosterhout 2005; Zimmerman and Duke 2003). Release after trap and haul may cause delayed mortality, however.

Estimates of delayed mortality range from 2 to 25%, with the majority of estimates in the 10% - 20% range (Stuart 2005).

1.5 MODELING THE TWO ALTERNATIVES

The two alternatives differ in several important aspects besides the removal of the four mainstem dams in the DRA. There are differences in the flow management, habitat restoration actions, and hatchery programs (Table 1-1). Restoration of the lower Klamath (Bogus, Shasta, Scott, Salmon, and Trinity Rivers) will occur as part of the KBRA package (Stillwater 2010, Chapter 5) and in the Upper Basin (KBRA 2010). Because the period of record of the model is from 2012 to 2061, there is a period in the DRA scenario where the four mainstem dams are in place. The DRA scenario must also account for the process of dam removal and the resultant population level effects on Type I Chinook. Finally, there is interest in understanding how climate change may affect the abundances of Chinook salmon under the two alternatives. Thus there are two hydrologic time series that are being developed, one that reflects historic conditions from 1961 – 2010, and one that incorporates the output of several Global Climate Change (GCM) models. Here we briefly describe how the Fish Production Model will reflect the differences in the NAA and DRA.

Table 1-1. Differences in the No Action Alternative and Dam Removal Alternative incorporated into the Fish Production Model.

Topic	No Action Alternative	Dam Removal Alternative
Four mainstem dams	Remain	Removed in 2020
Klamath River Flow Management	2010 Biological Opinion	Klamath Basin Restoration Agreement Flows
Habitat Enhancement	No Improvement	Klamath Basin Restoration Agreement Restoration Actions for Upper and Lower Klamath Basin
Hatcheries	Iron Gate and Trinity River Hatcheries	Upper Klamath Basin Conservation Hatchery and Trinity River Hatchery

1.5.1 No Action - Dams in Scenario with 2010 NMFS Biological Opinion Flows

The No Action alternative uses the existing physical structure of the Klamath River, which the four mainstem dams (Iron Gate, Copco I, Copco II, and J.C. Boyle). The upstream terminus for anadromy is Iron Gate Dam (Figure 1-9). Further, the flow management uses the flows as set forth in NMFS 2010 Biological Opinion (NMFS 2010). Hatchery operations at Iron Gate

Hatchery continue under existing operations for mitigation for the mainstem dams with releases of approximately 6 million fall Chinook (Myers et al. 1998). Finally, there will be no enhancement to the existing habitat in Bogus Creek, Shasta River, Scott River, or Salmon River (Hamilton et al. 2010, Chapter 5).

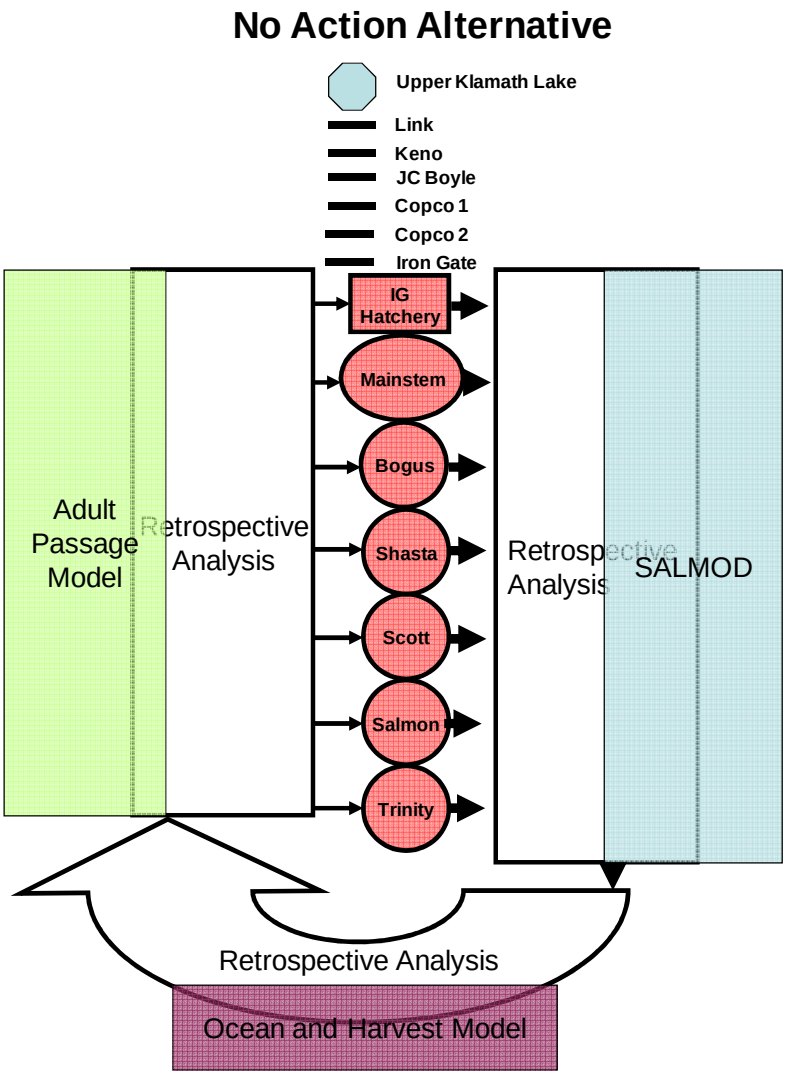

Figure 1-9. Fish Production Model components to reflect the No Action Alternative.

1.5.2 Dam Removal Scenario with KBRA Flows and Habitat Enhancement

The second scenario includes the removal of the four mainstem dams (J.C. Boyle, Copco I, Copco II, and Iron Gate) (Figure 1-10). The dams will be removed in a single year (2020) with some impact to adults spawning below the dams. There is expected to be some sediment that will be released and flushed down stream as part of the dam removal process; however the effects are expected to be contained to a single year (Stillwater 2009). Flows will be managed according to the Klamath Basin Restoration Agreement Grieman (2010). In addition, there will be habitat improvement as part of the KBRA actions that are expected to improve the conditions in spawning and rearing reaches. Finally, fish will be stocked in the upper basin tributaries prior to dam removal so that the year of the dam removal, juveniles will be able to migrate downstream from the Upper Klamath Basin (Wood River, Sprague River, and Williamson River) to return in 2 to 5 years as adults (Hooton and Smith 2008).

The specific actions being proposed for habitat enhancement of the lower and upper Basin tributaries to the Klamath River are numerous (KBRA Agreement). Many of them are focused on improving the quality of existing habitat, where as a few may be aimed at increasing access to otherwise blocked habitat. To reflect these actions on the population dynamics of fall Chinook in the Fish Production Model, we will modify the Beverton-Holt stock production functions over time to reflect the improving quality and quantity of habitat as a result of the KBRA actions (e.g., Figure 1-11). The rates of change in Figure 1-11 are for illustration purposes only, and estimates of improvements in productivity need to be made in light of the biological limitations of Chinook populations. For example, in the ODFW Willamette River Recovery Plan, a target productivity of 500 sub yearling juveniles was used for the parameter p in a BH stock production function, which represented the maximum productivity of spring Chinook populations in the McKenzie basin attainable from habitat restoration (ODFW 2010). Changes in capacity are expected where additional habitat is being made available to the population s of Chinook in the Klamath Basin. Actions that remove barriers or improve access are thus expected to affect the capacity in the BH production function relative to the current conditions. In most cases, such actions are identifiable in the KBRA actions and estimates of increased can be made explicitly (e.g., Chapter 6).

ODFW (Hooton and Smith 2008) describes the conditions prior to dam removal as having stocked juveniles in the upper basin. The goal will be to imprint juveniles with the upper basin, and time the stocking such that they will be ready to migrate out of the system when the dams are removed in 2020. Stocking is expected to begin in 2018 to fully seed the habitat above Iron Gate Dam.

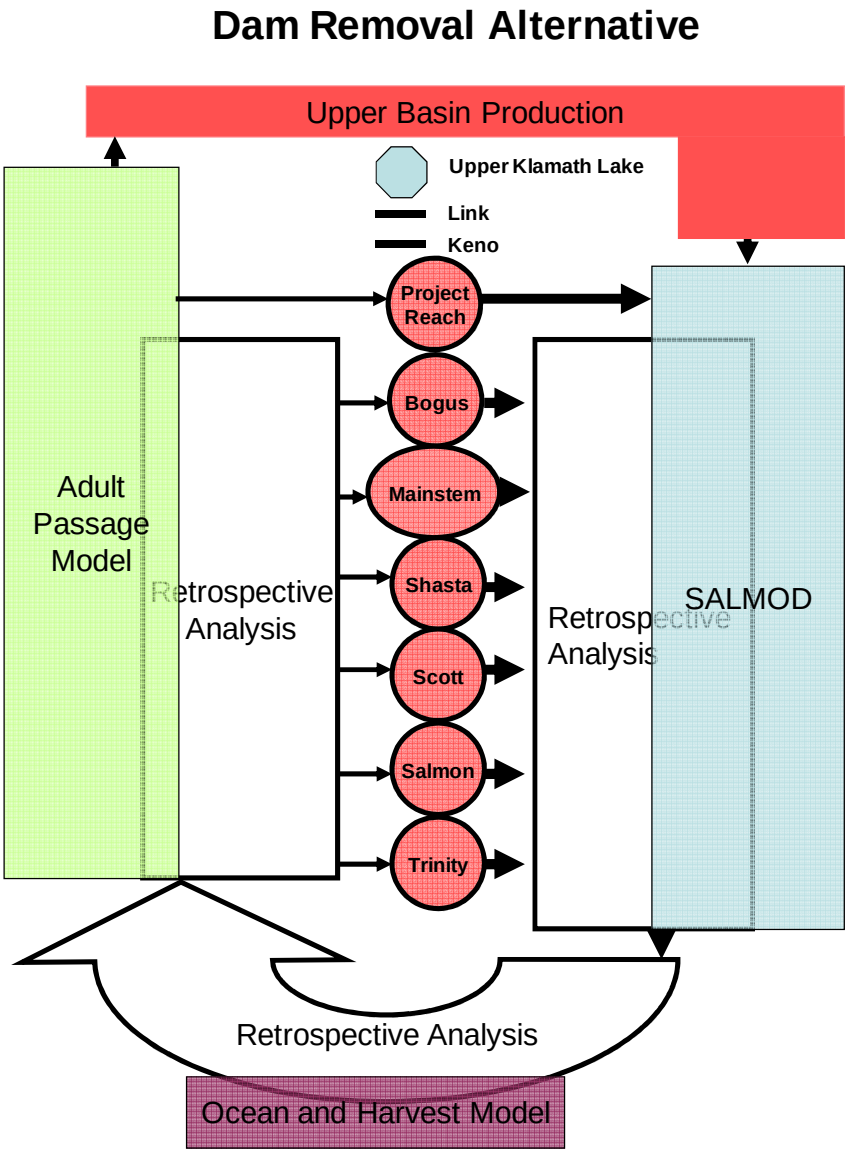

Figure 1-10. Fish Production Model components to reflect the Dam Removal Alternative.

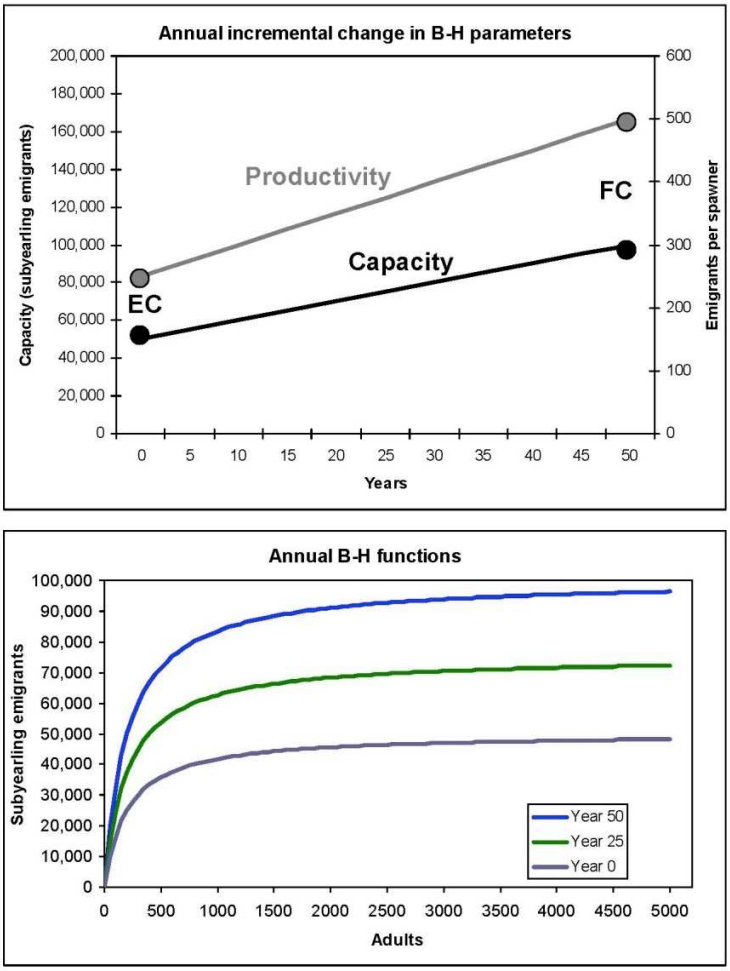

Figure 1-11. Schematic of potential modifications to Beverton-Holt production functions due to Klamath Basin Restoration Agreement Actions. Existing conditions (EC) and future conditions (FC) after KBRA habitat enhancements could potentially increase the productivity and capacity of the production function.

The dam removals are expected to occur during the winter of 2020. The expected effects of dam removal to the Klamath River are described by Stillwater (2009). In the FPM, dam removal is being modeled in two ways: 1) the loss of production by mainstem spawners in 2021 due to sedimentation of the redds and 2) lack of growth in juveniles outmigrating in the spring of 2021 due to high turbidity affecting feeding in the mainstem Klamath River.

1.6 MODEL OUTPUTS

Because the model uses Monte Carlo simulations, the estimates of annual abundance under each alternative will be calculated as probability distributions. The distribution of annual abundances incorporates the uncertainty in environmental conditions (e.g., flows and temperatures from different global climate change models), and uncertainty in population vital rates (e.g., juvenile production, juvenile outmigration survival rates, maturation rates, etc.). For each year of the 2012-2061 period, there will be a distribution of abundance for the NAA and for the DRA. In addition, there will be a distribution of harvest for each year under each alternative broken down by harvest component. The distributions will be summarized by mean, median, and central 95% confidence intervals so that the central tendency (mean and median) and the uncertainty (confidence intervals) in predictions in absolute abundance can be compared between the two alternatives.

We can also design the Monte Carlo simulations to facilitate the decision to perform the NAA or the DRA. The structure of the Monte Carlo simulations can be developed so that the same set of environmental conditions (i.e., hydrology and temperature from the same climate model) and the same population vital rates (i.e., same juvenile productivity values, same juvenile survival rates and same maturation rates) are used to make estimates of abundance and harvest for a NAA run of the model and a DRA run of the model. These simulations are paired and the relative outcomes (abundances and harvests) can be compared. The metric of interest is the number of Monte Carlo iterations where one alternative provides higher abundances or harvest relative to the other alternative. This approach provides a mechanism to improve the decision making in light of uncertain outcomes; namely, one can understand the relative performance of each alternative despite large uncertainty in the absolute outcomes.

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2. DESCRIPTION OF UPPER BASIN PRODUCTION ASSUMPTIONS AND METHODS (HUNTINGTON)

Salmon runs have been blocked from the Klamath Basin above Copco Dam for more than 90 years and from the area between Iron Gate and Copco dams since 1961. Historical information on the distribution or abundance of salmon above Copco is sparse but suggests that the historical distribution of both spring and fall Chinook once extended into the tributary network above Upper Klamath Lake (Nehlsen et al. 1991; Huntington 2006). Details on habitat partitioning between the two races are lacking. However, thermal moderation in groundwater influenced streams and seasonal opportunities for growth in highly productive Upper Klamath Lake may have provided conditions that allowed for expression of the early (Type 1) juvenile emigration, as is being modeled in the Fall Chinook Fish Production Model.

2.1 BRIEF DESCRIPTION OF MODEL

The Production Model requires adult-to-emigrant production functions for Type 1 fall Chinook that may be produced under the KBRA-Dam Removal Alternative in two upper basin areas: (1) tributary streams between Iron Gate and Keno and (2) areas above Keno (Figure 2-1). Estimates of future emigration patterns of young Type 1 fall Chinook into the Klamath River from each of these two above-dam areas are also needed as input for SALMOD II. The specific information required on emigration patterns includes seasonal timing (by week) of emigrants entering the Klamath River from each of the two identified areas, weekly proportions of Chinook fry versus larger juveniles (55 mm+) entering from each area, and the mean weights of fry and juveniles entering each week from each area.

Without empirical data on salmon from the upper basin upon which to base estimates of the parameters identified above, a model of salmon production that accounted for the seasonal timing of life-history events and for the influences of environmental conditions on fish performance in tributaries above Iron Gate was important to the overall modeling effort. A pre-existing Ecosystem-Diagnosis-and-Treatment (EDT) model for upper Klamath Basin Type I fall Chinook (PacifiCorp 2005) was selected to fill this need for two reasons: 1) EDT had been previously used in the upper basin to address questions similar to those associated with the Secretarial Determination, and 2) EDT had the potential, with modifications, to generate outputs that could inform tributary production parameters needed by SALMOD II and the Fish Production Model. Uncertainties inherent in EDT, a complex ecosystem model, made it important that confidence bounds around the results of this effort be taken into account.

The EDT model of salmon habitat and performance for the upper Klamath Basin includes a reach-structured database of information on how fish habitat varies among locations and seasons (months) within tributaries streams of the upper basin where Chinook salmon are anticipated to distribute once fish passage is provided. The EDT model generates multiple pathways for each life stage through space and time which are referred to as *trajectories* within the model (Mobrand Biometrics 2005). Each trajectory may vary in duration, rate of travel, and timing of life stages present (Figure 2-2). Mathematical algorithms are used to describe environmental conditions within each modeled reach as defined by values or ratings for 46 ecological attributes (Table 2-1) related to stream corridor structure, hydrologic characteristics, water quality (including temperature), and the biological community (Mobrand Biometrics 2005). Information on these attributes contained within the initial model was developed by a Habitat Modeling Group to help assess the potential biological consequences of alternative fish passage measures at the Klamath River Hydroelectric Project (PacifiCorp 2005).

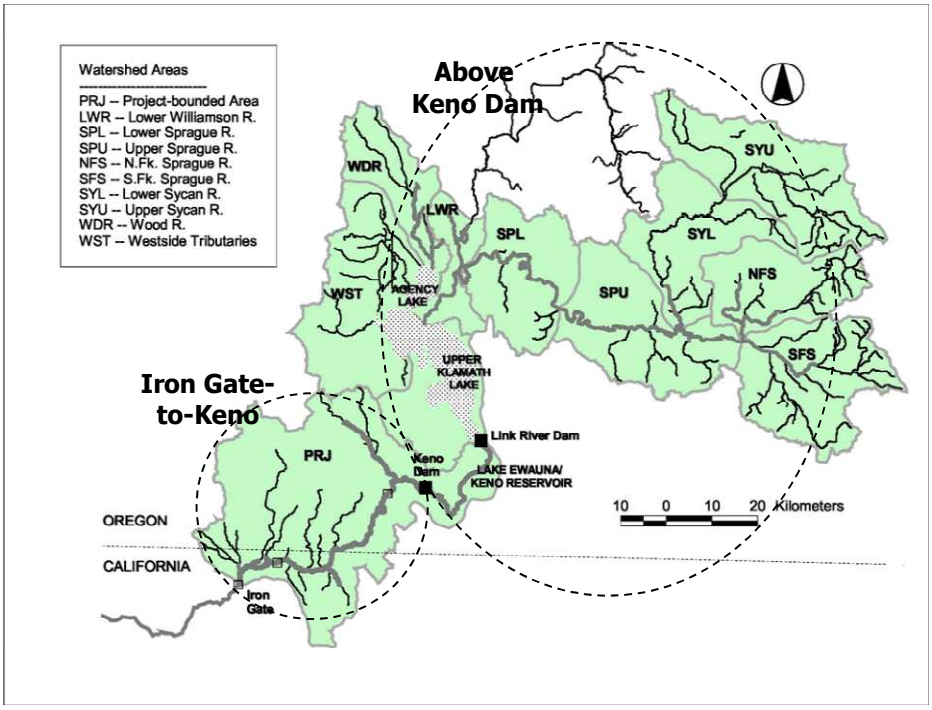

Figure 2-1. Potential distribution of Type 1 fall Chinook salmon in two locations in the Klamath basin, 1) Iron Gate to Keno, and 2) areas upstream of Keno, that are included in the production model for the upper basin.

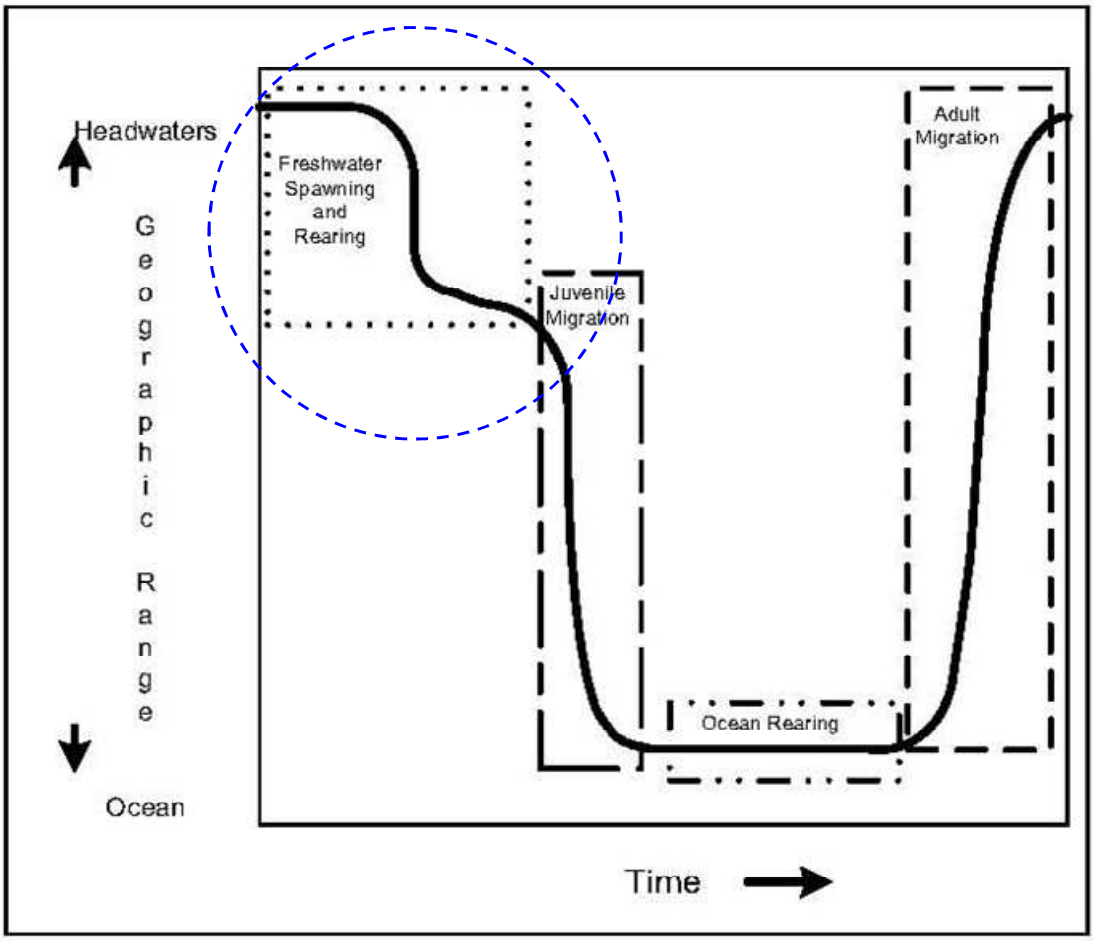

Figure 2-2. Conceptual diagram of a life history trajectory through space and time (Mobrand Biometrics 2005). The Blue dashed circle indicates portion of life history trajectories that represented by EDT for the upper basin.

Two sets of conditions were defined by the initial Klamath EDT model, (1) 2004-2005 conditions on tributaries to Upper Klamath Lake and (2) what was viewed as achievable and reasonably expected restoration conditions for tributaries above Upper Klamath Lake (PacifiCorp 2005). The restoration conditions anticipated in that model did not include some of the actions proposed under the KBRA. Therefore, for the current analysis the Klamath EDT model has been updated to incorporate new water temperature data, climate change effects, and consideration of habitat restoration actions provided in the KBRA.

Table 2-1. Ecological attributes (i.e., Level 2 attributes) used as the 46 Aquatic Key Environmental Correlates in the EDT model structure.

Ecological Feature		Ecological Attribute
Hydrology and Hydraulics	Flow Variation	Change in interannual variability in high flows
		Change in interannual variability in low flows
		Intra daily (diel) variation
		Intra-annual flow pattern
		Water withdrawals
	Hydrologic regime	Natural
		Regulated
Stream Corridor Structure	Channel morphometry	Channel length
		Channel width – month maximum width (ft)
		Channel width – month minimum width (ft)
		Gradient
	Confinement	Hydromodifications
		Natural
	Habitat type	Backwater pools
		Beaver ponds
		Glides
		Large cobble/boulder riffles
		Off-channel habitat factor
		Pool tailouts
		Primary pools
		Small cobble/gravel riffles
	Riparian/Channel integrity	Obstructions to fish migration
		Bed scour
		Icing
		Riparian function
		Wood
	Sediment type	Embeddedness
		Fine sediment (intragravel)
		Turbidity
Water Quality	Chemistry	Alkalinity
		Dissolved oxygen
		Metals – in water column
		Metals/Pollutants – in sediments/soils
		Miscellaneous toxic pollutants – water column
		Nutrient enrichment
	Temperature variation	Daily maximum (by month)
		Daily minimum (by month)
		Spatial variation
Biological Community	Community effects	Fish community richness
		Fish pathogens
		Fish species introductions
		Harassment
		Hatchery fish outplants
		Predation risk
		Salmon carcasses
	Macroinvertebrates	Benthos diversity and production

The result of these changes combined with the needs of the Secretarial Determination analysis required development of two different time periods to estimating the consequences of the KBRA-dam removal scenario upon Type 1 fall Chinook salmon. The new periods for the analysis include the time of dam removal (Dams Out; ~2020) and the end of the Secretarial Determination analysis period (Future Conditions; ~2052-2061). There have also been refinements to the treatment of the fall Chinook life histories and trajectories being modeled. These refinements have included an effort to match fry emergence timing to the thermal regimes of individual spawning reaches and closer consideration of young Chinook movements into and through the upper basin lakes. Detailed documentation of the full and final set of specific changes to the model will be included in the final Fish Production Model report.

Biological rules within EDT define mathematically how differing levels of the environmental attributes in the model decrement fish performance at specific life stages relative to species-specific benchmarks associated with optimal conditions (Lestelle 2005). The performance benchmarks, including those for fall Chinook, are derived from the literature. Cumulative productivity and capacity for a given trajectory within EDT are estimated by the model using multistage Beverton-Holt functions (Mousalli and Hilborn 1986) to calculate the incremental effects of environmental conditions encountered by each lifestage over time and space. Mathematical algorithms followed in calculating these values for a trajectory are given in Mobrand Biometrics (2005).

In a full EDT model run, the aggregate capacity and productivity of the salmon population being considered are estimated from the lifecycle performance parameters for each of a very large number of life-history trajectories simulated for the population (Mobrand Biometrics 2005). Population productivities are capacity-weighted averages of trajectory productivities. Population capacities for ocean-type fish are generally based on simple arithmetic averages for all trajectories that have been initiated in a given spawning reach, which are then scaled to the full area of that reach and summed with similarly calculated capacities for other spawning reaches.

Although EDT provides measures of capacity and productivity for adult-to-adult recruitment, the Fish Production Model requires estimates of adult-to- emigrant capacity and productivity, as well as seasonal and life-stage (fry and juvenile) distributions for emigrants produced above Keno and those entering the Klamath from Iron Gate-to-Keno tributaries. To develop these relationships, we took advantage of the detailed life-history trajectory information stored by EDT model runs. We have begun to explore using this type of information and an automated calculator (Klamath Smolt Calculator) to produce estimates of the Beverton-Holt production parameters (adult-to-

emigrant production capacity and productivity), emigrant timing and growth of sub-yearling Chinook passing downstream at the specific points of interest in the modeled drainage network.

The Klamath Smolt Calculator computes total juvenile abundance and juvenile abundance by fish size-week categories at a user specified focal reach. Juvenile abundance is based on the productivity and capacity parameters of the Beverton-Holt (B-H) spawner-recruit function. Spawner abundance is a user input value.

B-H productivity is computed across all trajectories at the juvenile focal reach using the following:

$$P_{focal\ reach} = \frac{\sum_{t=1}^{T} (P_t\ w_t)}{\sum_{t=1}^{T} w_t}\ Eggs\ /\ spawner \tag{1}$$

Where P_t is the cumulative trajectory productivity to the juvenile focal reach:

$$P_t = \prod_{s \in t} p_s \tag{2}$$

and *Eggs/spawner* is the average number of eggs per spawner (a user input parameter).

A placeholder trajectory weighting factor w_t is currently used in Equation 1 as follows:

$$w_t = \frac{P_t}{1 + \frac{P_t}{C_t}} \tag{3}$$

and cumulative trajectory capacity C_t to the juvenile focal reach in Equation 3 is computed as follows:

$$\begin{aligned} C_t &= \frac{p_s}{\frac{1}{C_{s-1}} + \frac{p_s}{c_s}} \\ p_s &= \text{Density-independent survival of trajectory segment } s \\ c_s &= \text{Capacity of trajectory segment } s \text{ (maxium number fish survive in segment)} \end{aligned} \tag{4}$$

The trajectory weight factor computed using Equation 3 does not consider survival in trajectory segments after the juvenile focal reach. In other words, differences in trajectory survival in the Klamath River downstream of the focal reach are not considered when computing the B-H

productivity at the focal reach. The factor might be improved if there were a clearer way to weight performance in a way that accounted for survival downstream than there is at present.

We compute the B-H capacity parameter at the juvenile focal reach across all trajectories originating from each spawning reach *r* using the following:

$$C_{focal\ reach} = \sum_{r=1}^{R} \left(\frac{\sum_{t=1}^{T_R} C_{t,r}}{T_r} l_r \right) \tag{5}$$

l_r = length in meters trajectory originating reach (spawn reach)

We compute juvenile abundance *N* at the focal reach using the following:

$$N_{Total\ Juveniles} = \frac{P_{focal\ reach}\ N_{spawners}}{1 + \frac{P_{focal\ reach}\ N_{spawners}}{C_{focal\ reach}}} \tag{6}$$

Where $N_{spawners}$ is the number of adult spawners for the population component and is a user input.

Fish size (grams) at the focal reach is computed for each trajectory beginning at fry emergence. At present, the following polynomial equation is used to compute temperature-dependent daily growth for each trajectory segment (*s*):

$$Daily\,Growth(g/day)_s = a + bT_w + cT_w^{\ 2} + d\,T_w^{\ 3} \tag{7}$$

Where T_w is the average daily temperature in week *w* for the trajectory segment. Parameters of the polynomial equation (*a, b, c, and d*) are constants that best describe temperature dependent growth potential within the tributaries and Upper Klamath Lake.

Fish size at the end of each trajectory segment is computed using the following equation:

$$FishSize(g)_s = DailyGrowth^{SegmentDur}\ FishSize_{s-1} \tag{8}$$

The final step in the process is to partition the total abundance at the focal reach from Equation 6 into size and week categories (Figure 2-3). Week is based on trajectory timing at the focal reach and fish size (weight in grams) from Equation 8. Size and week categories are input by the user.

Size Categories-->	A	B	C	D	E	F	G	H
Week #	**0.5**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
12	-	-	-	-	-	-	-	-
13	337	306	-	-	-	-	-	-
14	-	2,544	-	-	-	-	-	-
15	-	20,338	-	-	-	-	-	-
16	-	49,196	6,735	-	-	-	-	-
17	-	16,144	24,568	-	-	-	-	-
18	-	1,746	31,571	203	-	-	-	-
19	-	-	27,353	9,490	-	-	-	-
20	-	-	2,505	5,756	-	-	-	-
21	-	-	-	238	-	-	-	-
22	-	-	-	-	-	-	-	-
23	-	-	-	-	-	-	-	-
24	-	-	-	-	-	-	-	-
25	-	-	-	-	-	-	-	-
						Total juvenile abundance at focal reach		**199,029**
Number of trajectories	765					Average size (g):		**1.24**

Figure 2-3. Estimated juvenile abundance by size (columns) and week (rows) categories.

We compute abundance for each size-week cell in Figure 2-3 using the following:

$$N_{size,week} = \sum_{size,week} \left(N_{Total} \frac{w_{t,size,week}}{\sum_{t=1}^{T} w_t} \right) \tag{9}$$

As indicated earlier, the placeholder weighting factor w_t is worthy of further evaluation. It may be appropriate to develop a weighting factor more strongly influenced by the pattern of survival of fish downstream of the focal reach, which could be developed outside of EDT (for example, though sensitivity testing with SALMOD).

Temperature-driven growth functions used in the calculator are under refinement, and will be consistent with those used by SALMOD II (Chapter 3). Growth functions will be applied to EDT trajectory output files for Klamath tributaries above Keno and for Iron Gate-to-Keno tributaries.

2.2 MODEL INPUTS AND OUTPUTS

2.2.1 Inputs

As described above, the Klamath EDT model utilized 35 of 46 ecological attributes known as Level 2 correlates as inputs. EDT utilizes a hierarchical information structure with Level 2 correlates providing the foundation. Level 2 are used to derive up to 17 Level 3 survival factors for each life history stage (Table 2-2) (Mobrand Biometrics 2001). Level 3 survival factors are

Table 2-2. EDT Level 3 survival factor definitions.

Level 3 Attribute	Definition
Channel stability	The effect of stream channel stability (within reach) on the relative survival or performance of the focus species; the extent of channel stability is with respect to its streambed, banks, and its channel shape and location.
Chemicals	The effect of toxic substances or toxic conditions on the relative survival or performance of the focus species. Substances include chemicals and heavy metals. Toxic conditions include low pH.
Competition	The effect of competition with hatchery produced animals on the relative survival or (with hatchery performance of the focus species; competition might be for food or space within the fish) stream reach.
Competition	The effect of competition with other species on the relative survival or performance of (with other the focus species; competition might be for food or space species)
Flow	The effect of the amount of stream flow, or the pattern and extent of flow fluctuations, within the stream reach on the relative survival or performance of the focus species. Effects of flow reductions or dewatering due to water withdrawals are to be included as art of this correlate.
Food	The effect of the amount, diversity, and availability of food that can support the focus species on its relative survival or performance.
Habitat diversity	The effect of the extent of habitat complexity within a stream reach on the relative survival or performance of the focus species.
Harassment	The effect of harassment, poaching, or non-directed harvest (i.e., as can occur through hook and release) on the relative survival or performance of the focus species.
Key habitat	The relative quantity of the primary habitat type(s) utilized by the focus species during a life stage; quantity is expressed as percent of wetted surface area of the stream channel.
Obstructions	The effect of physical structures impeding movement of the focus species on its relative survival or performance within a stream reach; structures include dams and waterfalls.
Oxygen	The effect of the concentration of dissolved oxygen within the stream reach on the relative survival or performance of the focus species.
Pathogens	The effect of pathogens within the stream reach on the relative survival or performance of the focus species. The life stage when infection occurs is when this effect is accounted for.
Predation	The effect of the relative abundance of predator species on the relative survival or performance of the focus species, apart from the influence of the amount of cover habitat used by the focus species.
Salinity	The effect of the concentration of salts within the reach on the relative survival or performance of the focus species.
Sediment load	The effect of the amount of the amount of fine sediment present in, or passing through, the stream reach on the relative survival or performance of the focus species.
Temperature	The effect of water temperature within the stream reach on the relative survival or performance of the focus species.
Withdrawals (or entrainment)	The effect of entrainment (or injury by screens) at water withdrawal structures within the stream reach on the relative survival or performance of the focus species. This effect does not include dewatering due to water withdrawals, which is covered by the flow correlate.

essentially proportions (termed "sensitivities" in EDT parlance) that are combined and applied to benchmark survival levels for each life stage. Benchmark survival levels are considered to be the highest level of survival that could be achieved under optimal ecological conditions.

Level 2 correlates are assigned to each of the EDT reaches in the form of categorical index ratings that are based upon empirical data, if available, or a combination of surrogate data from nearby stream reaches and expert opinion when it is not. Level 3 survival factors are estimated according a set of predefined rules that combine the Level 2 correlates (Mobrand Biometrics 2001). Typically a Level 3 survival factory has a primary Level 2 correlate and up to 6 additional modifying Level 2 correlates that contribute to the overall sensitivity of the Level 3 survival factor. For example, the Habitat Diversity Level 3 survival factor for spawning utilizes gradient as a primary correlate, and confinement-natural, confinement-hydromodifications, riparian function and wood as modifying Level 2 correlates (Mobrand Biometrics 2003). The rules that translate Level 2 correlates to Level 3 survival factors are considered hypotheses based upon reviews of pertinent scientific literature.

2.3 MODEL ASSUMPTIONS

2.3.1 General Model Assumptions

EDT is a highly parameterized, complex ecosystem model focused on salmon and their habitat. A basic assumption underlying use of the model is that its structure and functions provide a good approximation of the how the system being modeled works. EDT assumes that biological performance (i.e., productivity and capacity) is determined through the habitat characteristics embodied in the Level 2 correlates (Blair et al. 2005). In many respects EDT can be considered an expert-system model in that empirical data, while useful, are not critical for populating Level 2 correlates and running the model. Frequently, empirical data is not available for each reach and Level 2 correlate. Under these circumstances expert opinion and surrogate data from nearby reaches are used to populate Level 2 correlates. EDT is also a deterministic equilibrium model, and the results of the model therefore assume that environmental conditions are static and no statistical error is associated with the point estimates of productivity and capacity, which should be viewed as long-term averages. Rules that translate EDT Level 2 environmental correlates to Level 3 survival factors are considered hypotheses based upon a review of the scientific literature and documented in Lestelle et al. (2004). Importantly, the EDT model develops productivity estimates relative to assumed benchmark survival levels which are also documented in Lestelle et al. (2004). Benchmark survival rates are not basin specific and with few exceptions the same benchmark survival rates have been used for all EDT model implementations.

2.4 MODEL DISCUSSION

Under nearly any circumstances, there will be uncertainties when developing model-based estimates of the productivity and capacity of a salmon population for which empirical data are absent. This is the case for EDT-based estimates of these parameters for spawning aggregates of fall Chinook that may become reestablished in Iron Gate-to-Keno tributaries or in areas above Keno. We have attempted to narrow uncertainties in our use of the EDT model for Klamath fall Chinook by updating environmental data, giving greater consideration to thermal influences on Chinook fry emergence timing and growth, and (to the degree possible) by taking two potentially key environmental influences out of EDT so that they can be addressed externally within the Fish Production Model. These two issues are the potential level of Chinook passage losses to migration through upper basin lakes and the potential future effects of *Ceratomyxa shasta* in the upper basin on juvenile survival.

Additional uncertainties associated with EDT's point estimates of productivity and capacity will be addressed in the Fish Production Model by carefully considering results of past sensitivity analyses of the EDT model, possible testing of specific sensitivities within the Klamath EDT model itself, and an assignment of reasonable distributions to the predicted point estimates from EDT. In the FPM, distributions accounting for uncertainty or natural variability may also be assigned to the seasonal size estimates being developed for young Chinook entering the mainstem Klamath. The uncertainty in size will be derived in part from fitting of the SALMOD growth function, which is similar to the growth function used in EDT, to screw trap size and timing information (please see details in Chapter 5). Thus, in contrast to relying on a single point estimate of a parameter, uncertainty will be explicitly incorporated into simulations by drawing parameter values from a distribution of possible values.

2.4.1 Model History

EDT was developed in the 1990s and early 2000s by Mobrand Biometrics in Washington State, and has become a widely used salmon restoration planning tool.

2.4.2 Model Applications Elsewhere

The EDT model has been applied to salmon watersheds throughout the Pacific Northwest and was a key component of recent extensive subbasin planning efforts conducted in the Columbia River Basin.

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3. SALMOD II (PERRY, SHAW, HARDY, AND WILLIAMSON)

3.1 BRIEF DESCRIPTION OF MODEL

Over the past 15 years, the USGS Fort Collins Science Center (USGS-FORT) has worked closely with Klamath Basin stakeholder groups to develop the Systems Impact Assessment Model (SIAM), a decision support system for fall Chinook salmon populations in the Klamath River. SIAM consists of three modeling components: a water quantity model (MODSIM), a water quality model (HEC5Q), and a fish production model (SALMOD). This decision support system has been applied to resource management issues such as dam removal, drought effects, multi-level withdrawal potential at Iron Gate Dam, thermal warming trends over the past 45+ years, analyses of historical salmon population variability, and creating favorable conditions for salmon by varying temporal flow releases from Iron Gate Dam (Hanna and Campbell 1999, Campbell et al. 2001, Flug and Campbell 2003, Bartholow et al. 2004, Bartholow 2005, Bartholow and Henriksen 2006, Campbell and Heasley 2009, Campbell et al. 2010).

The USGS was approached by the U.S. Fish and Wildlife Service (FWS), Yreka and Arcata, CA staff to provide modeling support for the upcoming Secretarial Determination (SD) to either remove or retain four hydropower dams on the Klamath. Early in the process, SIAM was eliminated from consideration as a major modeling tool for the SD process. However, two of the SIAM's modeling components, SALMOD – the fish production model, and HEC5Q – the stream temperature model, were considered highly relevant. Therefore, SALMOD and HEC5Q were extracted from the SIAM framework, and we began implementing them as stand-alone models for the SD process. SALMOD was chosen for the Klamath River since it was originally developed and tested on the Klamath's largest tributary, the Trinity River. USGS collectively engaged in an integrated modeling effort to establish linked sub-models that could capture the dynamics of various life stages and geographic locations for the Full Life Cycle Model (FLCM) for fall Chinook salmon.

SALMOD is a component of the Instream Flow Incremental Methodology (Stalnaker et al. 1999) that was constructed to link habitat limitations to a population through time and space at both microhabitat and macrohabitat scales. The conceptual model was developed in a workshop setting (Williamson et al. 1993; Bartholow et al. 1993) using fish experts concerned with Trinity River Chinook restoration. The model builds on the foundation laid by similar models (Cheslak and Jacobson 1990). SALMOD has since been applied to a number of large river systems in the West to understand effects of water management activities on salmon populations. More recently, SALMOD has been used on the Sacramento River (Bartholow 2004) and on the

Klamath River between Iron Gate Dam and Scott River (Bartholow and Henriksen 2006). In the Klamath River, SALMOD was used to assess factors limiting salmon production under historical river flows and temperature (Bartholow and Henriksen 2006).

SALMOD is a spatially and temporally explicit model that simulates spawning, egg incubation, and growth, movement, and survival of juvenile salmonids rearing in rivers (Bartholow et al. 1993). In the Fall Chinook Life Cycle Model, SALMOD's role is to simulate dynamics of adult spawning and egg incubation and then juvenile salmon in the mainstem Klamath River between Keno and the ocean. In this chapter, we briefly describe the foundations of SALMOD in terms of spatial, temporal, and biological resolution and extent. For a full account of the model's structure, we direct the Expert Panel to existing documents (Bartholow et al. 1993; Bartholow et al. 2002; Bartholow and Henriksen 2006). Our goal here is to describe changes to SALMOD required for its use in the life cycle model. Such changes have spurred a new version of SALMOD, hereafter referred to as SALMOD II. In addition, although SALMOD has been applied to the lower Klamath River, it has yet to be fully calibrated and validated (Bartholow and Henriksen 2006). Therefore, we outline our methods for calibrating SALMOD II prior to its implementation in the full life cycle model. Separate chapters are devoted to two important components of SALMOD. Chapter 5 details development of meso-habitat structure and the relationships between flow and available habitat (i.e., weighted usable area curves) for target life stages. Chapter 6 discusses the water temperature model that provides inputs to SALMOD.

The spatial, temporal, and biological resolution and extent of SALMOD II is critical to understanding how the model functions. The model operates at the meso-habitat scale (e.g., pool, riffle, run) and extends from Keno to the ocean. Thus, the entire mainstem Klamath River has been typed into 2,635 habitat units over the model's spatial domain (see Chapter 5). SALMOD then tracks a population that originate as eggs and grow from one life stage to another through emigration at the furthest downstream mesohabitat unit (the ocean, in this application; Figure 3-1). Individual cohorts either remain in the mesohabitat unit in which they emerged or move, in whole or in part, to nearby units (see McCormick et al. 1998). Model processes include spawning (with redd superimposition and incubation losses), growth (including egg maturation), mortality, and movement (habitat- and flow induced). SALMOD II has been structured to operate on a user-specified time step, with a minimum time step of 1 day; a weekly time step will be used for the life-cycle model. Its temporal extent covers the biological year, the time from spawning of adults through emigration of juvenile salmon at the river's mouth (typically Oct. 1 to August 30). SALMOD II explicitly models four life stages – eggs, fry, juveniles, and yearling smolts.

Water temperature and habitat area are the primary driving variables that influence fish dynamics in SALMOD II (Figure 3-1). Water temperature influences spawning, growth (transition between life stages), and mortality (via disease and thermal tolerance). Habitat area varies by life stage and meso-habitat type and is a function of river discharge. Life stage-specific habitat area is driven by weighted usable area curves (flow versus available habitat) developed with a 2-D physical habitat simulation model (see Chapter 5). Movement and mortality is influenced by fish density, which in turn, is a function of habitat-specific abundance and habitat area (Figure 3-1).

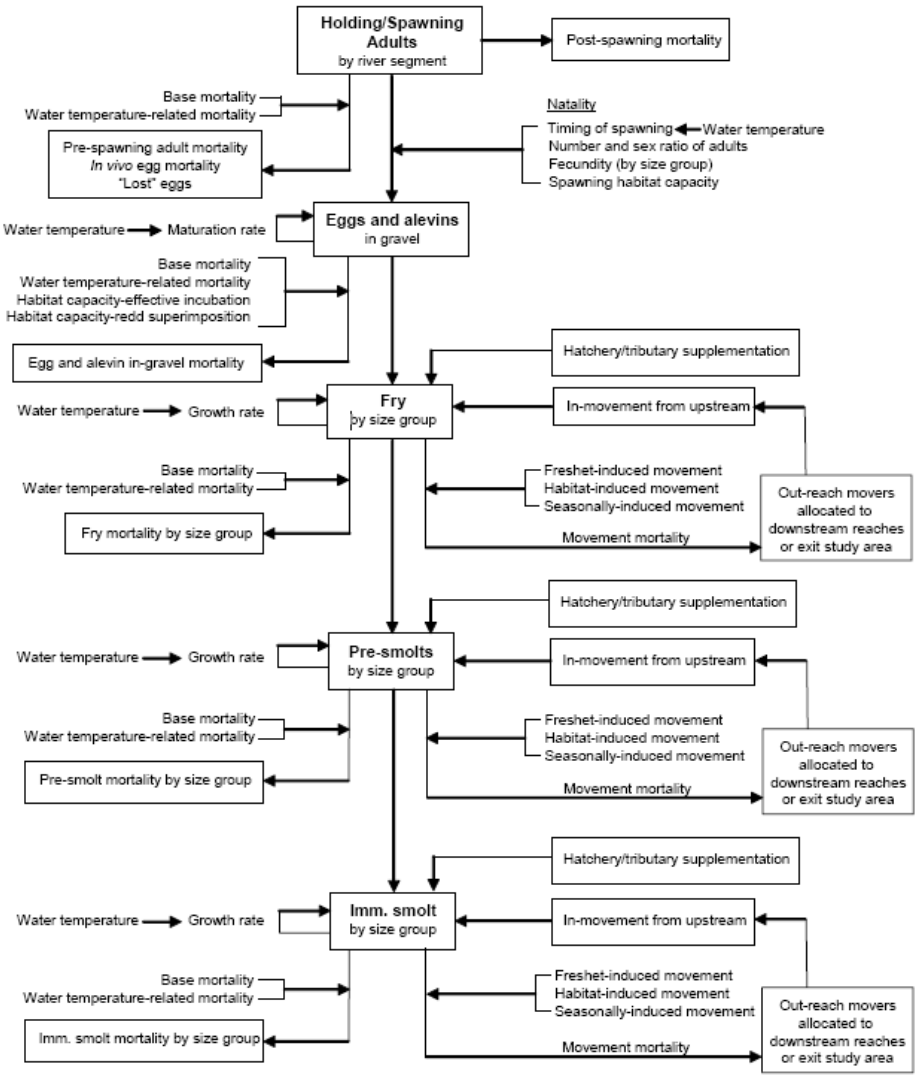

Figure 3-1. A conceptual diagram of the variety of factors controlling production through a biological year used in SALMOD (from Bartholow et al. 2001).

The primary changes to SALMOD since its last application to the Klamath River (Bartholow and Henriksen 2006) include: 1) expanding the original spatial domain upstream from Iron Gate Dam to Keno, and downstream from the Scott River to the Ocean, 2) defining new meso-habitat features for split channel and side channel habitat units, 3) updating the habitat versus flow relationships for target life stages, 4) tracking of eight source populations in the mainstem Klamath River, 5) updating the growth relationships to reflect recent research on growth of juvenile Fall Chinook Salmon, and 6) incorporating a model for disease-related mortality.

Updates to SALMOD are in various stages of development. To track multiple source populations we translated SALMOD from a FORTRAN to a Visual Basic programming environment. Expansion of the spatial domain has been completed; meso-habitat structure and associated WUA curves have been incorporated into SALMOD II. A logistic model of disease mortality as a function of temperature and yearly maximum discharge has been incorporated, but has yet to be parameterized. An analysis of disease-related information is currently underway to help inform disease modeling efforts. Both parameterization of the disease model and growth function will occur during the model calibration and validation process. The calibration process is currently being structured, but has not yet begun. Since model parameterization and outputs depend heavily on the outcome of the calibration process, we describe the approach to calibration in detail below.

3.2 MODEL INPUTS AND OUTPUTS

Physical inputs into SALMOD II are the time series of discharge and water temperature for each habitat unit. Discharge time series will be provided by Bureau of Reclamation hydrology simulations (Reclamation 2010). Water temperature time series will be simulated by HEC5Q described in Chapter 6. Biological inputs are comprised of 1) time series of spawners to given river segments, and 2) time series of fry and juveniles entering the mainstem Klamath River from tributaries and the upper Klamath Basin. Spawners will be supplied to different river segments as determined by the upstream migration sub-model described in Chapter 1. Within each river segment, adults will then be distributed among habitat units in proportion to the availability of spawning area within each river segment.

Weekly time series of fry and juvenile abundance will be input into SALMOD II for the following source populations: Trinity River, Salmon River, Scott River, Shasta River, Bogus Creek, above-Keno tributaries (Spencer, Shovel, and Jenny creeks), and the upper Basin (Sprague, Williamson, and Wood rivers). For Lower Klamath Tributaries, abundance time series will be driven by spawner-emigrant relationships based on analysis of juvenile trapping data (see

Chapter 7). For above-Keno and upper Basin tributaries, abundance time series will be based on spawner-emigrant relationships developed through the EDT model (Chapter 2).

For the purposes of the full life cycle model, SALMOD II will output the annual abundance of juvenile salmon at ocean entry from each of the eight source populations. However, abundance and other metrics (e.g., mortality) can also be examined by life stage, time step, and meso-habitat unit to understand factors driving abundance.

3.3 MODEL ASSUMPTIONS

The critical assumption in SALMOD is that habitat capacity limits production, as is formalized through the WUA curves used to drive biological processes such as density dependent mortality and movement. Many of the other functional relationships in SALMOD II are taken from the literature and from best estimates using available data from the Klamath River. The basic parameterization of SALMOD to the Klamath River, including all functional relationships and assumptions are documented and detailed in Bartholow and Henriksen (2006:21-60).

3.4 MODEL DISCUSSION

We devote model discussion to calibration of SALMOD II since calibration and validation is such an important component of parameterizing SALMOD II for the life cycle model. SALMOD II will be calibrated using data sets that provide information about size, timing, and abundance of juvenile salmon at two locations in the Lower Klamath River (just upstream of the Shasta River and just upstream of the Scott River). In the past, lack of abundance estimates for tributaries and the mainstem Klamath River have limited comparisons between predictions and observations to size and relative timing of emigration (Bartholow and Henriksen 2006). Recently, however, mark-recapture estimates of abundance for Klamath River traps between 2002 and 2009 allow for direct comparison between estimated abundance and abundance predicted by SALMOD II. Furthermore, carcass mark-recapture studies (Gough and Williamson 2009), redd counts, and mark-recapture abundance estimates of juveniles emigrating from Bogus Cr. (unpublished data, Arcata USFWS) and the Shasta River (Chesney et al. 2009) provide the input data needed to characterize initial conditions in each year.

Empirical data on abundance, timing, and size will inform movement, mortality, and growth functions in SALMOD II. Mortality processes in SALMOD II will be parameterized as logistic functions with respect to driving variables (e.g., temperature, density, and disease). The current mortality functions in SALMOD II generally follow a logistic form, and these will be used as our best estimates with which to initiate the model fitting process. Growth functions will be described using two possible models: 1) a 3-parameter Beta distribution describing the shape and

maximum growth with respect to temperature, or 2) an allometric growth model that describes specific growth rates in response to temperature and an allometric function of initial size (Forseth et al. 2001).

The calibration procedure will use a sampling-importance-resampling (SIR) algorithm implemented in a Bayesian statistical framework (Albert 2007). In general, SIR involves three steps: 1) using Monte Carlo simulation to select sets of parameter values from a prior distribution of possible values (the "sampling" part), 2) calculating weights for each parameter set such that parameter sets that fit the observed abundance data well have larger weights than those parameter sets that fit the abundance data poorly (the "importance" part), and 3) forming posterior probability distributions of parameters by sampling parameter sets proportional to the weights (the "resampling" part). Specifically, SALMOD II will be run many times (thousands), each with a randomly-drawn set of parameter values. For each simulation, we will use a joint likelihood function that measures the goodness-of-fit between observed and predicted abundance. Weights will be formed by rescaling likelihoods to a probability scale such that the weights sum to unity over all *n* simulations. The posterior probability distribution of parameters will then be formed by sampling the parameter sets with replacement according to sampling probabilities equal to the weights and proportional to the likelihood of each parameter set.

Using SIR as a means of model fitting and calibration will provide a number of important insights about parameterization of SALMOD II. First, the mode of the posterior distribution yields the best "point" estimate of a particular parameter value. Second, other statistics of the posterior distribution (e.g., the mean, median, 2.5th, and 97.5th percentiles) provide estimates of central tendency and uncertainty about a given parameter value. Third, different combinations of parameter values may yield similar predictions of abundance, indicating that the data are insufficient for disentangling, for example, different causes of mortality. Such issues can be assessed directly based on correlations between parameter values, helping to identify which parameters can be estimated from the data and which need to be based on the literature or expert judgment. Last, for implementation of the full life-cycle model, uncertainty in SALMOD II can be explicitly incorporated by sampling parameter values from their corresponding posterior distributions.

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4. SALMOD: MESO-HABITAT DEVELOPMENT KENO TO ESTUARY (HARDY & SHAW)

4.1 INTRODUCTION

SALMOD simulates the freshwater population dynamics for target salmonids and in this instance the specific application is to Chinook salmon within the Klamath River Basin. The reader is referred to Williamson et al. (1993) and Bartholow et al. (1993) (Bartholow 1996, and 2001) for a description of model development, previous applications, and key aspects related to parameter sensitivity. Revisions to the original model (SALMOD I) in support of KBRA analyses are covered elsewhere in the KBRA technical documentation materials (Perry et al. 2010). This report focuses on the technical documentation of data sources and analysis used to provide the underlying inputs required by SALMOD II for its application of existing and future conditions within the Klamath River Basin in support of the KBRA Secretarial Decision process.

4.2 SPATIAL DOMAIN

The previously developed application of SALMOD I within the Klamath River was confined from Iron Gate Dam downstream to the Scott River. Development of SALMOD II for use in evaluation of existing conditions was spatially extended to incorporate the Klamath River from Iron Gate Dam to the estuary at Requa, California. SALMOD II was further extended spatially from Iron Gate Dam upstream to below Keno Dam in order to support evaluation of KBRA conditions without dams.

4.2.1 Geomorphic, Flow, and Temperature Segments

SALMOD represents the stream environment at the broadest scale as defined by homogenous river segments (reaches). These segments are defined by the user where flow and/or temperature are relatively constant and maintain similar geomorphic characteristics of the river channel. Although hydrologic and temperature segmentation do not have to be the same, for computational efficiency and linkage to the flow and water temperature models, these segments were defined to be at the same breakpoints spatially. A total of 26 stream segments were defined as shown in Table 4-1. Under the existing conditions simulations, only the last 23 segments are utilized where the system representation basically starts at the Iron Gate Dam to Bogus Creek segment.

The segmentation also explicitly incorporated geomorphic breaks (e.g., confinement, stream width, gradient) along the longitudinal profile of the river in order to facilitate extrapolation of habitat versus flow relationships from measured mesohabitat features downstream of Iron Gate to areas above Iron Gate as described later in this document.

Table 4-1. Hydrologic and Temperature Segments utilized in SALMOD II.

Hydrologic and Temperature Segment	Length (miles)
Keno Dam to J.C. Boyle Power Plant	11.02
J.C. Boyle PP to Copco Dam	21.99
Copco Dam to Iron Gate Dam	8.21
Iron Gate Dam to Bogus Creek	0.31
Bogus Creek to Dry Creek	1.08
Dry Creek to Willow Creek	3.48
Willow Creek to Cottonwood Creek	3.61
Cottonwood Creek to Shasta R.	5.49
Shasta R. to Humbug Creek	5.51
Humbug Creek to Empire Creek	5.70
Empire Creek to Beaver Creek	4.91
Beaver Creek to McKinney Creek	6.25
McKinney Creek to Horse Creek	7.68
Horse Creek to Scott R.	5.20
Scott R. to Seiad Valley	12.40
Seiad to Indian Creek	23.29
Indian Creek to Elk Creek	1.54
Elk Creek to Clear Creek	6.84
Clear Creek to Salmon R.	33.77
Salmon R. to Orleans	7.43
Orleans to Red Cap Creek	13.60
Red Cap Creek to Bluff Creek	3.73
Bluff Creek to Trinity R.	5.74
Trinity R. to Blue Creek	28.23
Blue Creek to Klamath	12.91
Klamath to Ocean	2.89

4.2.2 Defining Mesohabitat Units

The basic spatial scale within SALMOD is the mesohabitat unit (MHU), (e.g., run, pool, and riffle). Mesoscale habitat units can be defined using a number of classification schemes, and MHU nomenclature among schemes is inconsistent. Initial efforts for development and calibration of SALMOD I within the Klamath River relied on a visual classification scheme, which was retained for use in defining CU for SALMOD II as described below. This classification scheme was also adopted for delineations of MHUs above Iron Gate Dam and required use of several techniques such as previous habitat mapping efforts and interpretation of aerial photography. The following sections of the report details our approach for quantifying mesohabitat units in various segments of the Klamath River between Keno and the estuary. These efforts resulted in 2635 MHU being defined between Keno and the estuary for use in SALMOD II.

4.2.2.1 Mesohabitat Typing – Iron Gate Dam to Regua

During 1997 and 2000, the U.S. Fish and Wildlife Service-Arcata Fish and Wildlife Office (FWS), the U.S. Geological Survey-Fort Collins Science Center (USGS) and the Yurok Tribal Fisheries Program mesohabitat typed (MHT) the main stem Klamath River between Iron Gate dam and the estuary (Figure 4-1, Table 4-2). Within this ~190 mile section over 1,600 mesohabitat units were quantified.

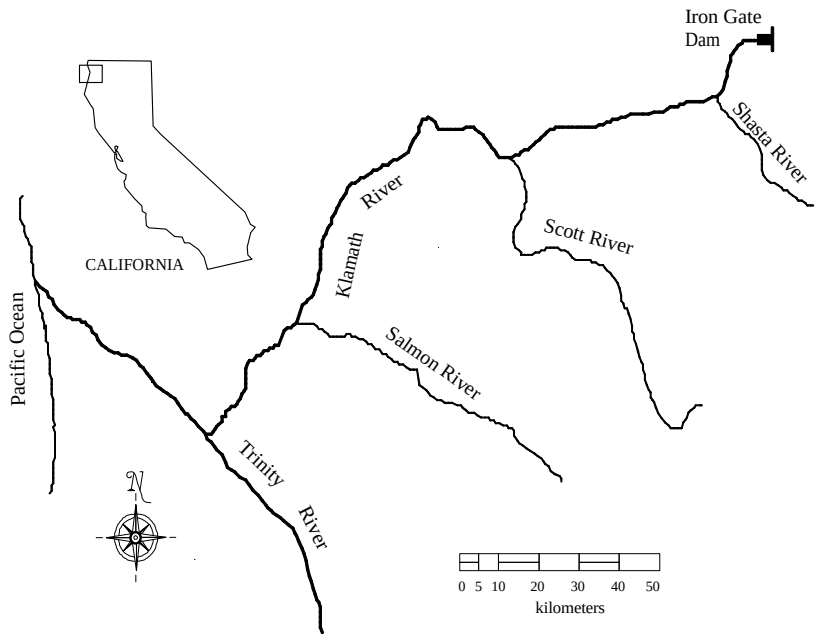


Figure 4-1. Klamath River mesohabitat mapping area.

Table 4-2. Survey dates and measured unit numbers used in mesohabitat typing in Klamath River below Iron Gate Dam.

Unit Number	Survey Date	Unit Number	Survey Date
1-97	08-Jul-97	1082-1162	21-Aug-97
98-171	09-Jul-97	1163-1191	09-Sep-97
172-269	10-Jul-97	1192-1200	08-Sep-97
270-335	22-Jul-97	1201-1217	25-Sep-97
336-419	23-Jul-97	1218-1279	26-Aug-97
419-512	24-Jul-97	1280-1314	27-Aug-97
513-603	29-Jul-97	1315-1383	28-Aug-97
604-667	30-Jul-97	1384-1434	16-Oct-00
668-795	31-Jul-97	1435-1502	17-Oct-00
796-857	06-Aug-97	1503-1603	18-Oct-00
858-939	07-Aug-97	1604-1675	19-Oct-00
940-997	19-Aug-97	1676-1741	20-Oct-00
998-1081	20-Aug-97		

Visual features of the river used to classify individual MHTs included gradient, active-channel confinement, surface disturbance, width to depth ratio, substrate compositions, and the presence or absence of backwaters associated with hydraulic controls (Table 4-3). The survey team identified three dominant gradient types for classifying the MHT slopes including: low-slope (LS), moderate-slope (MS) and steep-slope (SS). Visual calibrations and validations of slope classifications were based upon 107 total station slope measurements (Figure 4-2). A chi-square goodness of fit test was used to compare the frequency of MHT slopes observed using visual estimation with the frequency of MHTs expected based on the gradients defined for each MHT (Table 4-3). There was no significant difference between observed and expected frequencies (P>0.25) which validated the reliability and consistency of the classification scheme in the field.

Pools (P) were defined as sections of stream with a lack of slope to the water surface typically caused by an upstream scour and a downstream hydraulic control or tail-out. Other MHTs had an appreciable gradient (slope) to the water surface. Runs (R) were units having a relatively low gradient, confined channel, with limited surface disturbance. When a MHT had a mixture of mesohabitat types (e.g., a Pool with a section of LS along one bank) then both dominant and subdominant MHTs were recorded, with the dominant MHT classification being used for all data analyses.

Table 4-3. Characteristics used to define MHTs in the Klamath River from Iron Gate Dam to the confluence of the estuary.

Criteria	Pool	Run	Low Slope	Moderate Slope	Steep Slope
Gradient [a]	--	<0.3%	<0.3%	0.3%-0.8%	>0.8%
Channel Width	--	confined	relatively unconfined	moderately confined	Confined
Backwater	Yes	no	no	no	No
Substrate	fines, sand, gravel	--	gravel, small cobble	large cobble, small boulders	Small and large boulders
Standing Waves	None	<1/2'	<1/2'	1/2'-1'	>1'

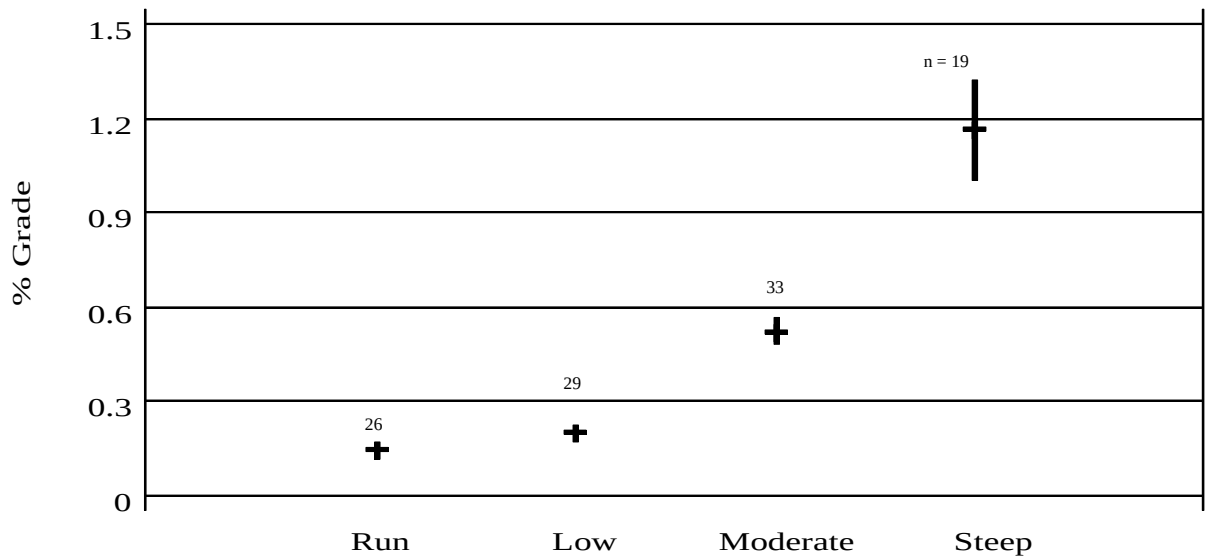


Figure 4-2. Mean gradient for mesohabitat types found between Iron Gate Dam and Seiad Creek, October and November 1996. Error bars represent +/- 1 standard error.

Habitat surveys consisted of two catarafts, each carrying a rower and observer, with units classified from an upstream to downstream direction. Data was recorded with right bank (RB) and left bank (LB) being observed from a downstream to upstream direction; that is "looking upstream." The upstream cataraft classified the MHT, logged GPS coordinates (Rockwell Encrypted Plugger), and measured the unit's length using an Advantage laser range finder shot at a prism carried by the downstream raft, (Table 4-4). When diagonal controls were encountered (e.g., a riffle that angled from left to right across the river in the downstream direction),

measurements were taken to the center of the control. The downstream raft team was responsible for establishing average width, and the maximum thalweg depth was measured with a sonar sounder (Figure 4-3). Both rafts were in constant communication with hand held radios. Dependent upon channel complexity and access, the survey team covered approximately 8 river miles (13 km) a day.

Three channel configurations were defined: main-channel (MA), split-channel (SP), and side-channels (SC). Main-channels (MA) units were defined when 100% of the river surface flow was within one channel (Figure 4-4a). Whereas, an island complex would either have a SP channel configurations, when >30% of the surface flow was divided by a permanent island (Figure 4-4b) or a SC configuration when a small secondary channel branched off from a main channel unit and returned at some point downstream (Figure 4-4c). All MHTs within each main channel and split/side channel configurations were typed, with the dominant side being denoted by a MASP or MASC, spit channel and side channel respectively (e.g., LSMASP). The sub channel units were denoted by a SP or SC (e.g., LSSC). Island sub channel MHT unit numbers were entered sequentially, as a decimal following the whole number assigned to the MC unit above (see Table 4-4 Unit 20 for example). GPS Mark numbers (i.e., waypoints), were recorded at the top of every main channel mesohabitat unit. GPS Mark numbers were recorded only at the top (start) and end (bottom) of side or split channels. Upstream GPS Mark numbers for sub-channels were designated with a 700 value while a value of 800 was used to denote the bottom of the sub-channel in order to segregate these features and lengths from the main channel (see Table 4-4).

Table 4-4. MHT data sheet and data input example.

Date: _____ **Reach:** _____ **Page** _____ **of** _____
Team: _____

Unit #	MHT	SPC/SC	GPS Mark #	GPS Error (ft)	Length (ft)	Width (ft)	Max Depth (ft)	Comments
5	P		M5	55	468	166	15	1st salmon hole, dry s/c exits LB top
6	MS		M6	54	475	127	3	
7	LS		M7	54	173	122	4	snag LB
8	SS		M8	54	230	100	3	
9	P		M9	54	929	121	13	standing waves and back eddy at top , power line over pool
10	MS		M10	80	331	151	2	
11	P		M11	63	913	118	14	standing waves and eddies at top
12	MS		M12	63	445	192	2	right hand bend
13	P		M13	57	804	126	15	"keep out" sign top LB , brown-orange house LB
14	MS		M14	55	499	108	4	
15	LS		M15	55	638	169	4	
16	P		M16	54	227	132	5	blue house - S 5 ramp, Fish Hook Bar and Grill
17	LS		M17	53	604	136	2	
18	MS		M18	66	424	208	3	
19	P		M19	62	520	110	6	
20	MS		M20	60	774	195	2	SC mid-unit RB, Turtle Rock RB bottom
20.1	LS	SC	M700		114	33	3	RB SC, spawning
20.2	P	SC			88	35	4	RB SC
20.3	MS	SC	M800		129	28	0.5	RB SC
21	P		M21	41	1268	123	11	red house LB mid-unit (diversion LB at bottom, 4" pipe)

Figure 4-3. The downstream cataraft team holds position for a distance measurement between a Pool (P) and a Low-slope (LS) on the Klamath River.

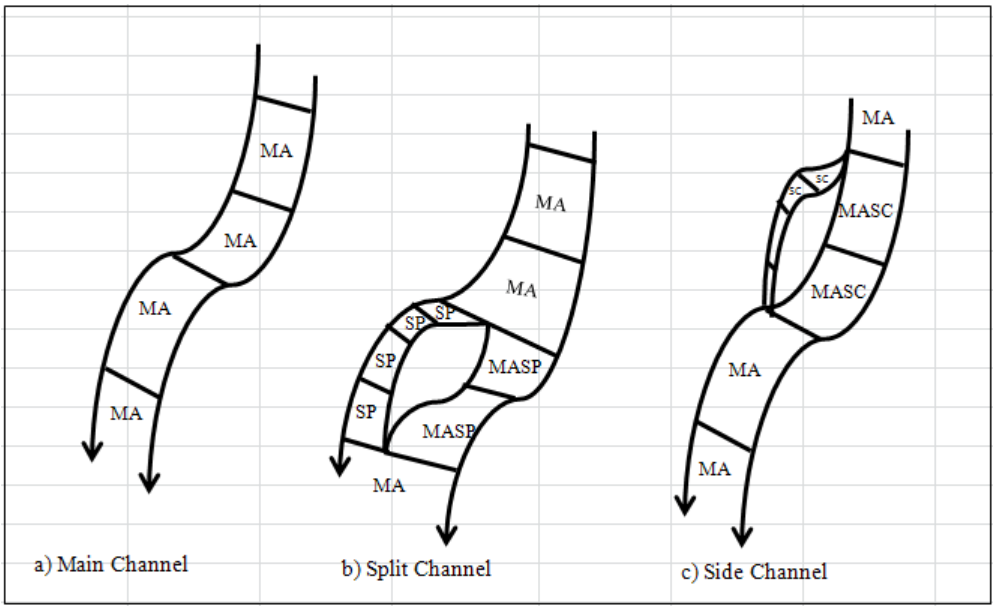


Figure 4-4. Three different classified channel configurations for use in mesohabitat mapping in the Klamath River.

4.2.2.2 Mesohabitat Typing – Bypass and Peaking Reaches Upstream of Iron Gate Dam

Mesohabitat typing data collected using ground surveys from bypass and peaking reaches below J.C. Boyle and Copco Dams were available from work conducted by PacifiCorp in their relicensing of the Klamath dams. The MHT typing utilized a similar but slightly different classification scheme than used below Iron Gate Dam (see Table 4-5). The available mapping data for these reaches were converted to the nomenclature used below Iron Gate for consistency and to simplify the extrapolation of habitat versus flow relationships for Chinook life stages as described later in this report. Google Earth imagery was utilized to locate specific habitat features from the mapping results to aide in the translation to our classification of low slope, moderate slope, steep slope, and pool. The imagery was also utilized to cross check designations of main, split, and side channel features and where necessary obtain additional length and width information in formulation of island complexes as discussed below.

Table 4-5. Example of MHT mapping data for the J.C. Boyle Peaking Reach provided by PacifiCorp.

J.C. Boyle Bypass Reach
Habitat Mapping (100 cfs Release)

(Original Mapping)										(Final Mapping - Pool Tails Combined)		
Unit Number	Habitat Type	Total Length	Unit Length	Max Depth	Mean Width	Unit Slope	Slope Category	Sub Dom/Sub	Comments	Habitat Type	Total Length	Unit Length
	START	0	0						Start - first unit upstream of PH tailwater Pool	START	0	0
1	HGR/CAS	173	173	4.3	76	6.33	ss	LB/SB		RIFFLE	173	173
2	POOL	219	46	5.3	79	0.00		LB/SB	Chute/Rapid RB	POOL	219	46
3	CAS	229	10	---	67	14.00	ss	LB/SB		CAS	229	10
4	RUN	348	119	5.0+	52	0.00	ls	LB/SB				
5	POOL	481	133	5.7	56	0.00		LB/SB		POOL	481	252
6	HGR/CAS	546	65	4.1+	67	4.74	ss	LB/SB		RIFFLE	546	65
7	POW	663	117	5.6	89	0.90	ls	LB/SB	Small riffle (~10 feet long) between Pow and Run	POW	663	117
8	RUN	764	101	3.0+	64	0.92	ls	LB/SB	Fast	RUN	764	101
9	HGR	818	54	3.0+	48	5.21	ss	LB/SB	Rapid	RIFFLE	818	54
10	RUN	872	54	4.0+	48	0.00	ls	LB/SB				
11	POOL	995	123	4.8+	69	0.00		LB/SB	Straight Scour; BW LB	POOL	995	177
12	POW	1033	38	3.7+	65	0.00	ls	LB/SB	SC starts @ 995 LB - trickle	POW	1033	38
12.1	S/C LGR		836	1.0	4	---		SB/LC		S/C RIF		
13	HGR	1050	17	---	59	8.24	ss	LB/SB		RIFFLE	1050	17
14	POW	1086	36	4.0+	66	1.70	ms	LB/SB		POW	1086	36
15	HGR	1147	61	---	64	3.00	ms	LB/SB		RIFFLE	1147	61
16	CAS	1171	24	---	52	9.58	ss	LB/SB		CAS	1171	24
17	POW	1228	57	4.2	58	1.67	ms	LB/SB	Pool-like	POW	1228	57
18	HGR	1274	46	3.7	61	3.03	ms	LB/SB		RIFFLE	1274	46
19	POOL	1292	18	4.1+	57	0.00		LB/SB		POOL	1292	18
20	HGR/CAS	1350	58	4.0+	59	3.85	ms	LB/SB		RIFFLE	1350	58
21	RUN	1464	114	3.9	68	1.43	ms	LB/SB	Some Pool mid-unit - did not break out	RUN	1464	114
22	HGR	1493	29	4.0+	68	5.17	ss	LB/SB		RIFFLE	1493	29
23	CAS	1499	6	---	71	6.50	ss	LB/SB	Step	CAS	1499	6

4.2.2.3 Mesohabitat Typing – Keno to J.C. Boyle Reservoir

Habitat typing data were not available for the Keno to J.C. Boyle Reservoir section of the Klamath River. A similar typing process was used to define habitat units in this section of

stream using available imagery in Google Earth to classify the MHT, lengths and widths as illustrated in Figure 4-5.

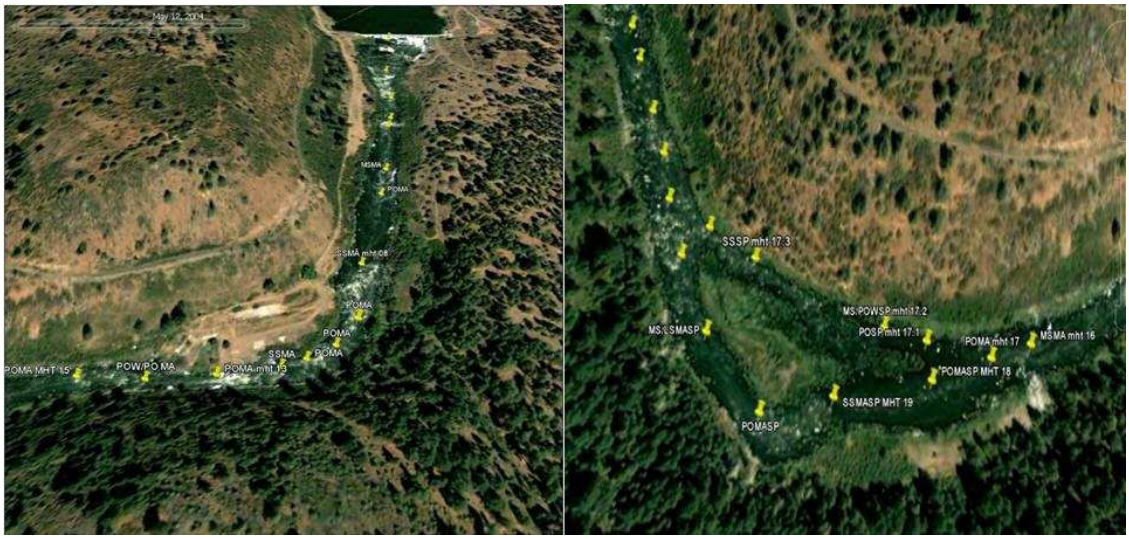


Figure 4-5. Google Earth was used to classify the MHTs, lengths and widths between Keno dam and J.C. Boyle reservoir.

The delineations were conducted visually by Mr. Tom Shaw and Dr. Thomas Hardy using a consensus based approach where agreement on MHT type, length and width was required. These data in terms of main, split, or side channel feature and the corresponding lengths and widths for each agreed upon type of MHT (i.e., low slope, moderate slope, etc) were entered into a spreadsheet for further analysis and use in SALMOD II as described below.

4.2.2.4 Mesohabitat Typing – Iron Gate Reservoir and J.C. Boyle Reservoir

The same conceptual mesohabitat classification scheme was adopted for delineation of features within Iron Gate and J.C. Boyle reservoirs. That is, main channel, split channel, and side channel features were delineated using mesohabitat units of low slope, moderate slope, steep slope, and pool classifications. These delineations were accomplished using available pre-dam construction historical photography as illustrated in Figure 4-6. In this figure, main channel, split channel, and side channel features are evident. These delineations were accomplished by consensus using a projection screen by Dr. Thomas Hardy, Dr. Sam Williamson, and Mr. Tom Shaw on a unit by unit basis. Once these features were delineated for each reservoir, the length and average channel width were then recorded to a spreadsheet for use in developing the inputs for SALMOD II as described below.

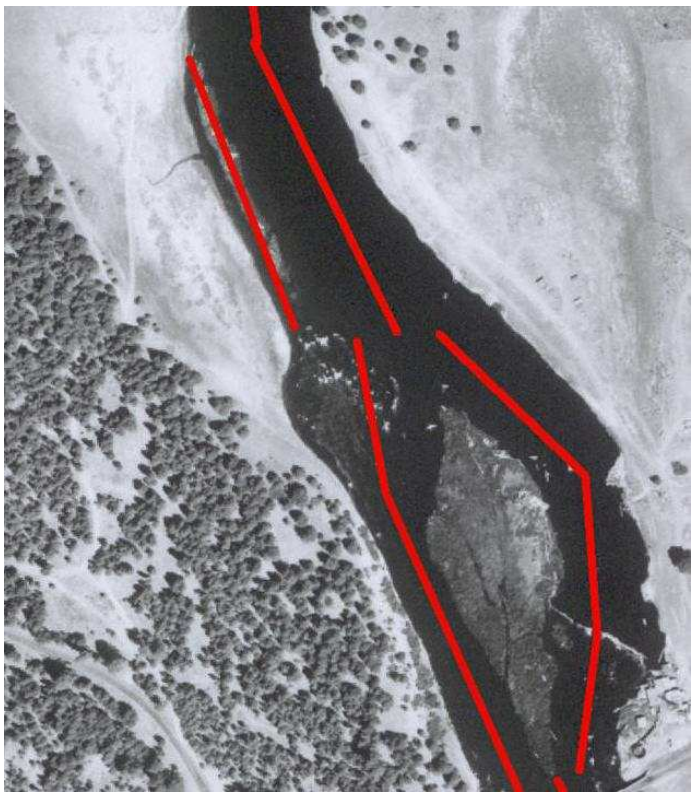
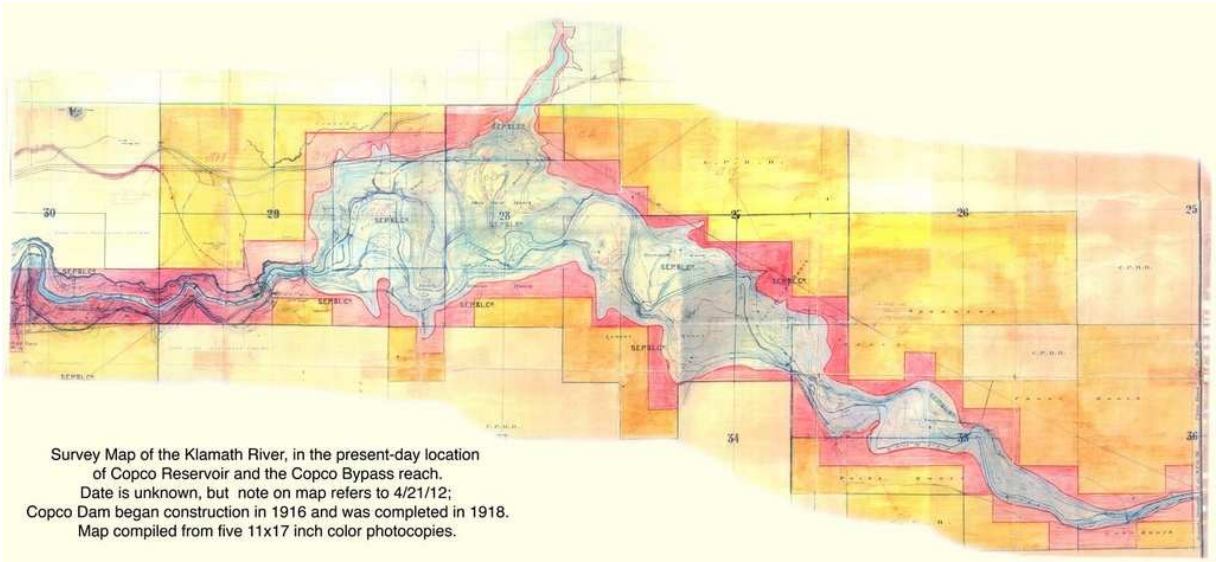


Figure 4-6. Example of mesohabitat unit delineations based on historical aerial photography for Iron Gate and J.C. Boyle reservoirs. Example shows main channel, split, and side channel features.

4.2.2.5 Mesohabitat Typing – Copco Reservoir

Pre-dam aerial imagery for the Klamath River below Copco Reservoir does not exist. The best available data was a 1912 engineering survey drawing of the reach, a portion of which is illustrated in Figure 4-7.

Mesohabitat delineations for this reach of the Klamath River were based entirely on professional judgment by Mr. Tom Shaw and Dr. Thomas Hardy. Factors considered included lengths between slope breaks (see black numbers in Figure 4-6), adjacent geomorphic and feature annotations in the map, channel width, and our 75+ years combined experience rafting similar rivers. Mr. Shaw's experience in mapping the MHTs from Iron Gate Dam to the estuary was invaluable in this regard. Length and width for each MHT were estimated from scaled measurements on the map.



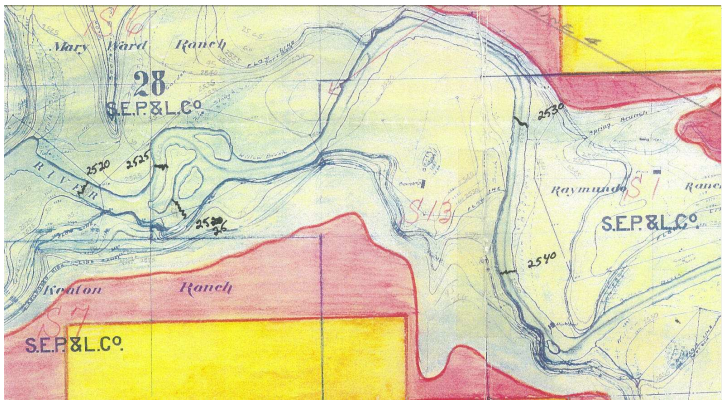


Figure 4-7. Example of the 1912 engineering drawing of the Klamath River in the vicinity of Copco Reservoir.

4.2.3 Generation of Island Complex MHT Computational Units

Earlier versions of SALMOD represented multiple channels by adding the chain of sub-channel MHT units to the bottom of the main channel chain (described in Bartholow and Henriksen 2006). This process allowed for the inclusion of the sub channels, but increased the length of the overall river and moved downstream migrant fish into much smaller habitat configurations thereby increasing the risk of habitat capacity induced movement and mortality. This is illustrated in Figure 4-8. Figure 4-8a shows a side channel complex as represented in SALMOD I while Figure 4-8b shows a single side channel island complex unit as represented in SALMOD

II. This procedure required delineating each individual island as a unique mesohabitat type over the entire length of the Klamath River as illustrated in Figure 4-9.

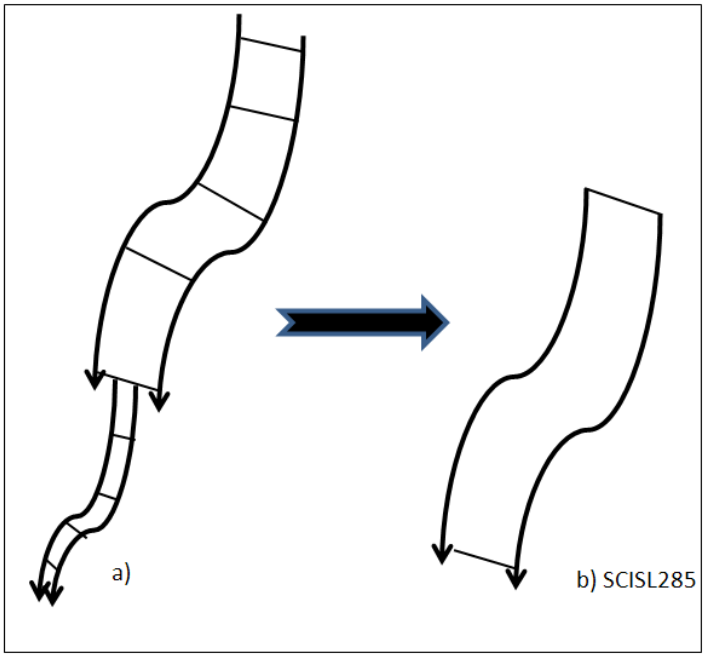


Figure 4-8. SALMOD I versus SALMOD II split/side channel island representations.

For each island complex, the main channel at the top and bottom of the complex was delineated in order to 'isolate' the island complex from main channel units. The original length of any MHT at the top or bottom that were incorporated into the island complex was adjusted accordingly for any lengths incorporated into the island unit so as to eliminate any duplicated lengths. The main channel length and corresponding side channel or split channel length were then delineated by their component MHT lengths. The widths of these component features were also determined on a MHT by MHT basis if not already available from the mapping data. These results were then used to scale the habitat versus discharge relationships for each Chinook life stage (i.e., spawning, fry, pre-smolt, and immature smolt) for each unique island complex as described below.

4.3 HABITAT VERSUS FLOW RELATIONSHIPS FOR CHINOOK LIFE STAGES

SALMOD relies upon habitat versus flow relationships for each defined mesohabitat type in the calculation of population dynamics for each life stage of Chinook. As noted previously, the 26 delineated hydrologic/water temperature segments also reflect geomorphic delineations within the Klamath River. Habitat versus flow relationships for the requisite Chinook life stages were

obtained from 2-D hydrodynamic modeling at seven sites between Iron Gate Dam and the Trinity River confluence (Hardy et al. 2006a) and at an additional 2-D site for the section of the Trinity River confluence to the estuary from an analysis conducted at the Pecwan Riffle study site (Hardy et al. 2010). Each of these eight study sites represents the source data used for the habitat versus flow relationships for the Chinook life stage by defined mesohabitat types. These data also provide the basis for development of each unique island MHT complex as described below.

4.3.1 Basic MHT Specific Habitat versus Flow Relationships

At each of the 2-dimensional study sites, the explicit mesohabitat mapping data collected from the field was overlaid onto each sites computational mesh. This allowed the specification of main, split, or side channel feature and mesohabitat type (i.e., low lope, moderate slope, steep slope, pool) to be associated for all computational elements. This is illustrated in Figures 4-10 through 13 which show the plan view of the eight 2-d based modeling sites within the Klamath River with their corresponding measured mesohabitat types that were representative of overall geomorphic sections within the Klamath River below Iron Gate Dam.

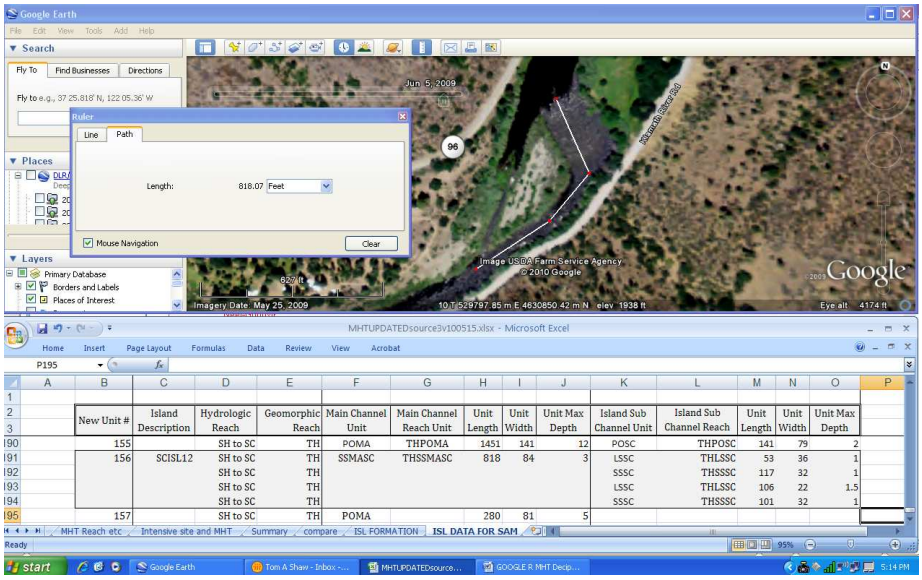


Figure 4-9. Example of defining a side channel island complex.

At each of these sites, the habitat versus flow relationships (Useable Area - UA) for spawning, fry, pre-smolts, and immature-smolts were extracted for each mesohabitat type by either main,

side channel, or split channel conditions and assigned a letter code. When two or more similar MHTs occurred within a site, the UAs, lengths and widths were averaged in order to facilitate assigning unique UAs, by discharge, to other MHTs between Keno and the estuary. The resulting MHT designations for their corresponding discharge versus UA relationships are presented in Table 4-6.

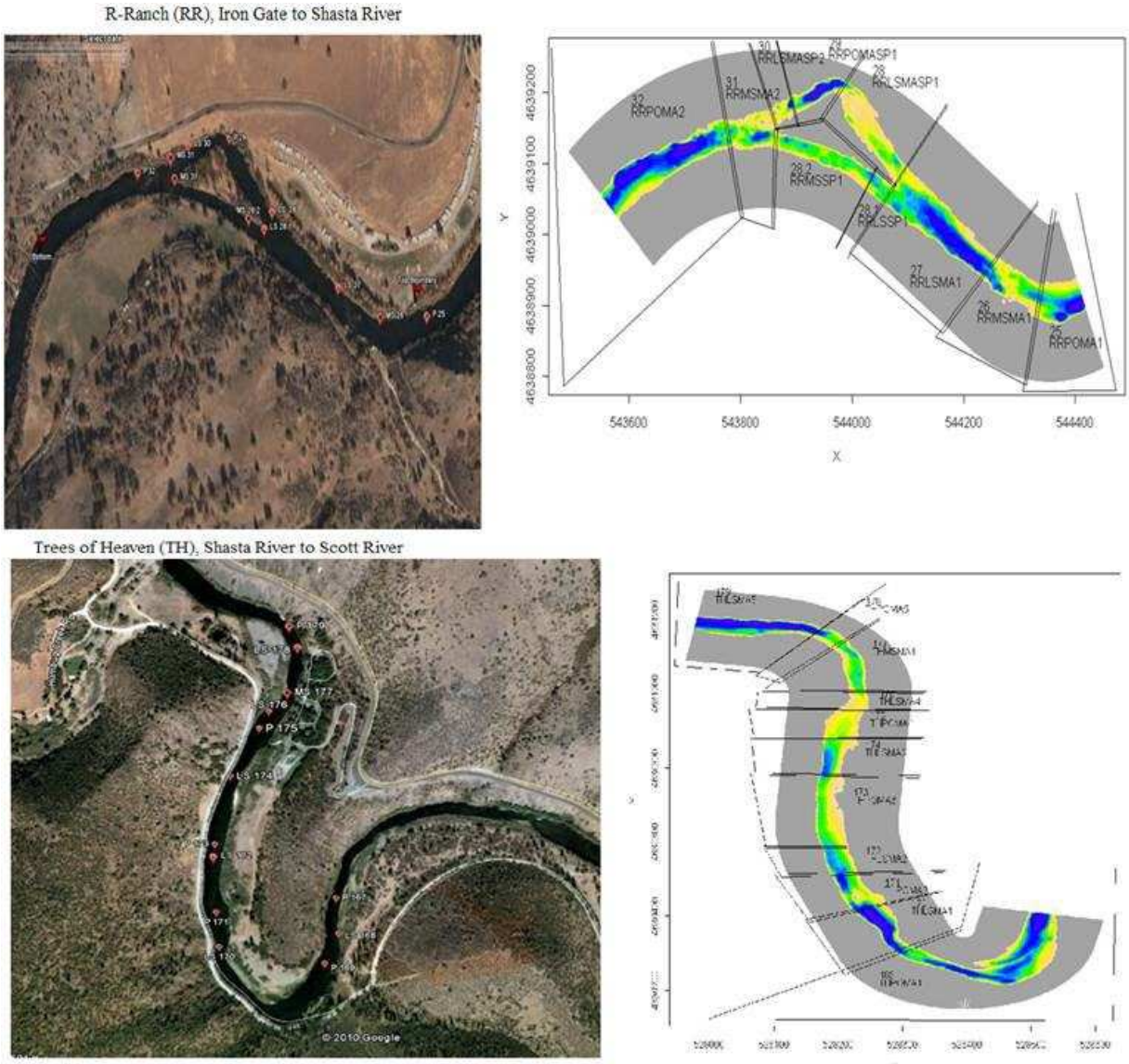


Figure 4-10. 2-D Hydrodynamic habitat sites: R-Ranch (RR), located in the hydrologic reach between Iron Gate dam and the Shasta River, and Trees of Heaven (TH), located between in the reach between the Shasta River and the Scott River.

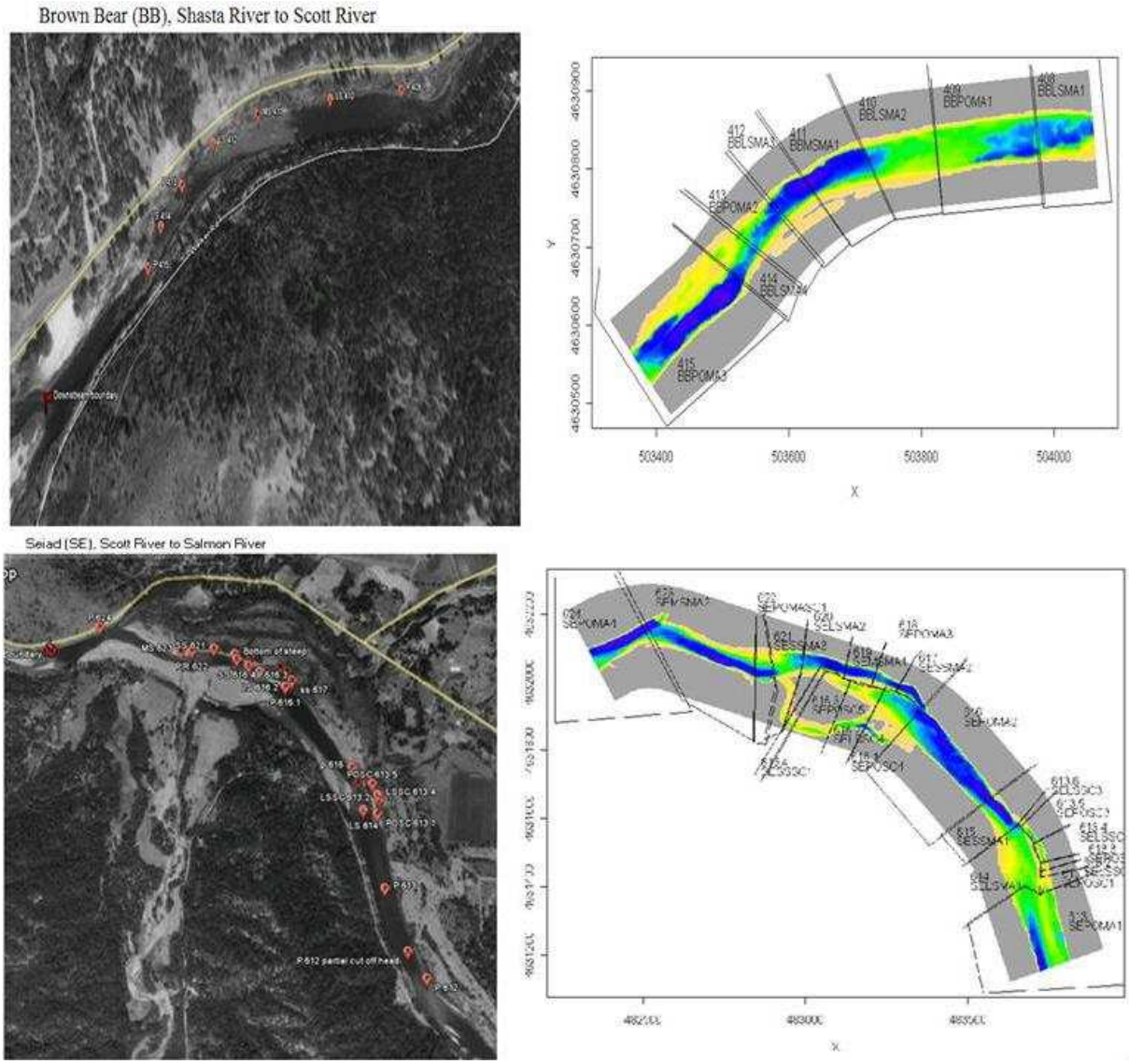


Figure 4-11. 2-D Hydrodynamic habitat sites: Brown Bear (BB), located in the hydrologic reach between the Shasta River and the Scott River, and Seiad (SE), located in the reach between the Scott River and the Salmon River.

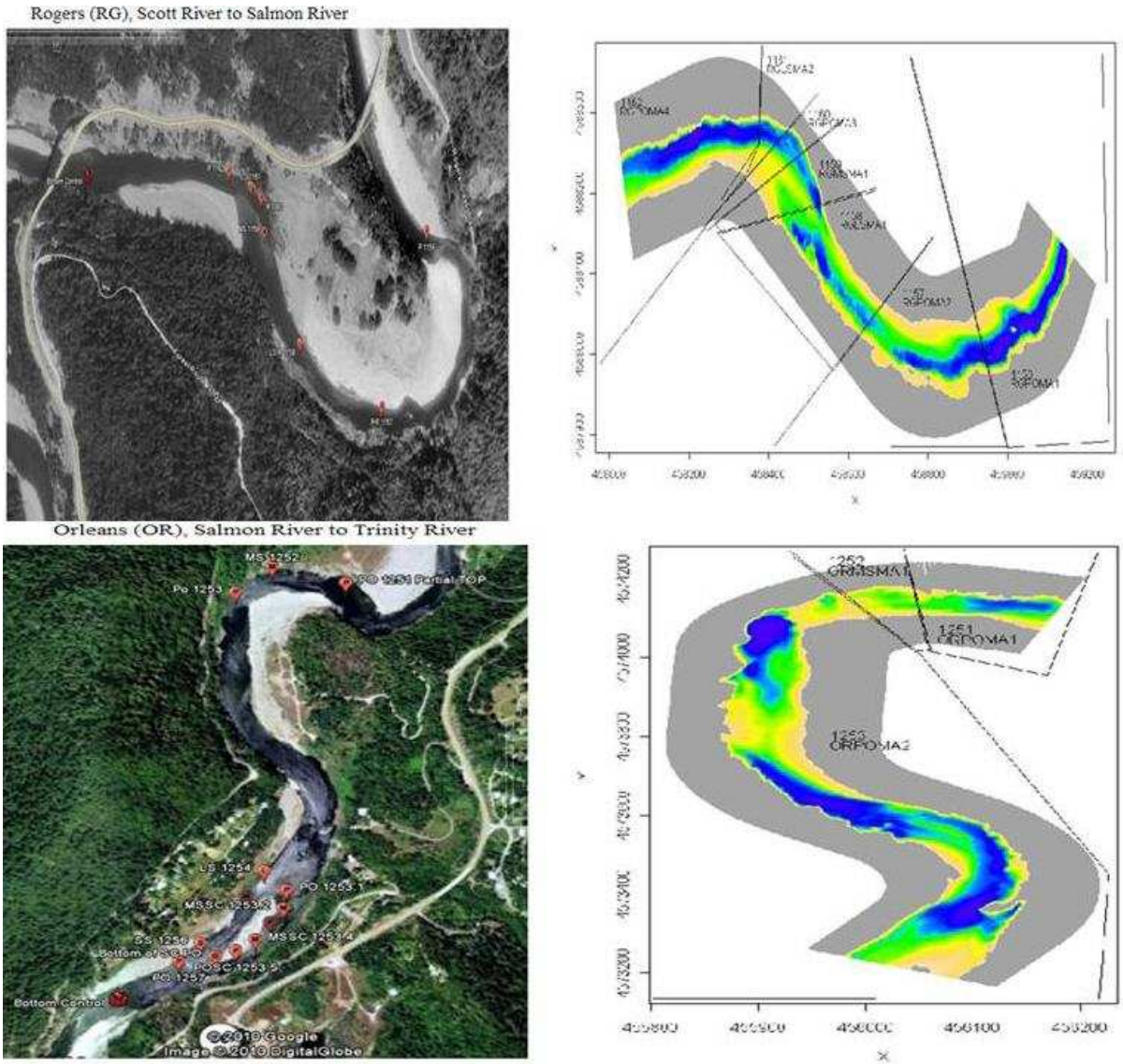


Figure 4-12. 2-D Hydrodynamic habitat sites: Rogers (RG), located in the hydrologic reach between the Scott River and the Salmon River and Orleans (OR), located in the reach between the Salmon River and the Trinity River.

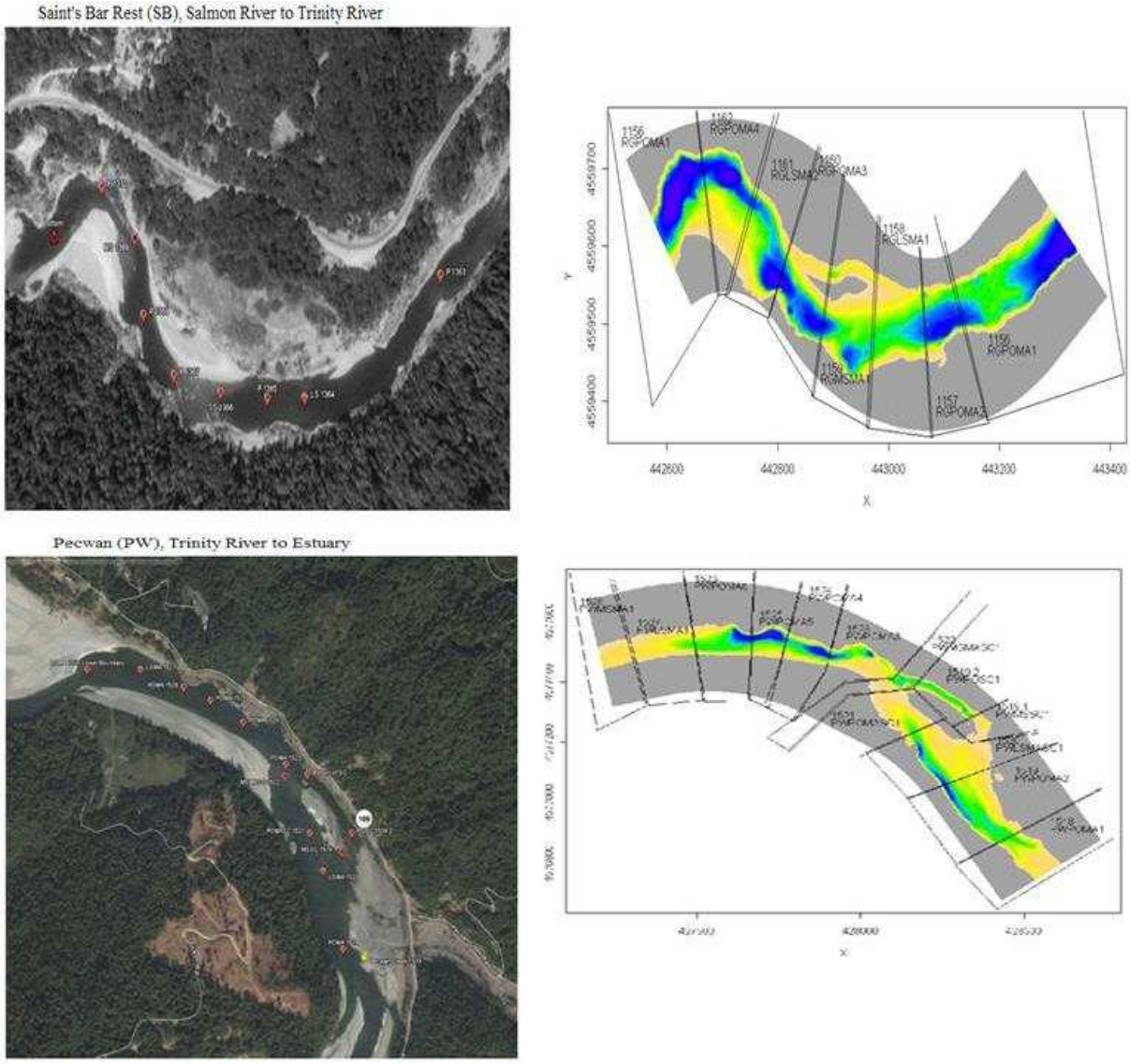


Figure 4-13. 2-D Hydrodynamic habitat sites: Saint's Bar Rest (SB), located in the hydrologic reach between the Salmon River and the Trinity River, and Pecwan (PW), located in the reach between the Trinity River and the Klamath estuary.

Table 4-6. Site name and MHT designations by hydrologic reach utilized to assign discharge versus UA relationships to MHTs between Keno and the Klamath estuary.

Iron Gate to Shasta River	Shasta River to Scott River	Scott River to Salmon River		Salmon River to Trinity River	Trinity River to Klamath Estuary
RRLSMA	THPOMA	SELSMA	RGPOMA	ORPOMA	PWPOMA
RRLSMASP	THLSMA	SELSSC	RGLSMA	ORMSMA	PWLSMA
RRLSSP	THMSMA	SEMSMA	RGMSMA	SBPOMA	PWLSMASC
RRMSMA	BBLSMA	SEPOMA		SBLSMA	PWMSMA
RRMSSP	BBMSMA	SEPOMASC		SBMSMA	PWMSMASC
RRPOMA	BBPOMA	SEPOSC		SBSSMA	PWMSSC
RRPOMASP		SESSMA			PWPOMASC
		SESSSC			PWPOSC

The entire Klamath River between Keno and the Estuary was classified based upon the MHTs and representative geomorphic type. However, not all of the MHTs had representative source discharge versus UA relationships in all geomorphic sections, so replacement source MHTs that were most similar based on professional judgment were used as replacements as shown in Tables 4-7 and 4-8.

Table 4-7. Target MHTs and source MHT replacements used to define Keno to Klamath River estuary MHT computational units in SALMOD II.

Target UA	Source UA Replacement
RRMSMASP	RRMSSP
RRSSMA	SESSMA
RRPOSP	RRPOMASP
RRSSMASP	SESSSC
RRSSSP	SESSSC
THSSMA	SESSMA
SELSMASC	SELSMA
SELSMA	RRLSMA
SEMSMASC	RRMSMA
SEMSSC	RRMSSP
SESSMASC	SESSMA
RGSSMA	RRLSMA
ORLSMA	SBLSMA
ORSSMA	SBSSMA

Table 4-8. The representative site designation, hydrologic reach, and combined target MHTs. A replacement MHT was used in the event that the target MHT did not have a discharge versus UA relationship.

Unit Number	Representative Site	Hydrologic Reach	MHT	Combined	MHT Replacement
101	RR	IG to SH	MSMA	RRMSMA	RRMSMA
102	RR	IG to SH	LSMA	RRLSMA	RRLSMA
103	RR	IG to SH	POMA	RRPOMA	RRPOMA
104	RR	IG to SH	LSMA	RRLSMA	RRLSMA
105	RR	IG to SH	MSMA	RRMSMA	RRMSMA
106	RR	IG to SH	LSMA	RRLSMA	RRLSMA
107	RR	IG to SH	POMA	RRPOMA	RRPOMA
108	RR	IG to SH	MSMA	RRMSMA	RRMSMA
109	RR	IG to SH	LSMA	RRLSMA	RRLSMA
110	RR	IG to SH	POMA	RRPOMA	RRPOMA
111	RR	IG to SH	LSMA	RRLSMA	RRLSMA
112	RR	IG to SH	MSMA	RRMSMA	RRMSMA
113	RR	IG to SH	LSMA	RRLSMA	RRLSMA
114	RR	IG to SH	MSMA	RRMSMA	RRMSMA
115	RR	IG to SH	LSMA	RRLSMA	RRLSMA
116	RR	IG to SH	MSMA	RRMSMA	RRMSMA
117	BB	IG to SH	SSMA	BBSSMA	SESSMA
118	BB	IG to SH	POMA	BBPOMA	BBPOMA
119	BB	IG to SH	SSMA	BBSSMA	SESSMA
120	BB	IG to SH	POMA	BBPOMA	BBPOMA
121	BB	IG to SH	POMA	BBPOMA	BBPOMA
122	BB	IG to SH	POMA	BBPOMA	BBPOMA
123	BB	IG to SH	LSMA	BBLSMA	BBLSMA
124	BB	IG to SH	POMA	BBPOMA	BBPOMA

4.4 HABITAT VERSUS DISCHARGE RANGE AND THE TRANSFER OF UA FROM SOURCE TO TARGET HYDROLOGIC REACH

The 2-D hydrodynamic habitat modeling results varied in terms of the discharge ranges modeled between sites. This difference in discharge range required that a standard set of discharge bins (values) and a set range of discharge magnitudes that encompassed the smallest and largest flows between all sites be constructed, for all life-stage relationships. Usable area versus flow from one site that differed from another was linearly interpolated so each discharge bin had a corresponding UA value. Whenever a discharge bin was either larger or smaller than a particular site's UA range, the last modeled habitat value (at the maximum simulated discharge) was extended to the upper discharge range needed as shown in the example in Table 4-9.

Table 4-9. Usable area by life-stage using consistent discharge bins and range showing the extension of UAs for discharges over a discharge range of 8,000 – 16,844 cfs.

Discharge (cfs)	MHT	Average Length (ft)	Average Width (ft)	Average Max Depth (ft)	Spawning (ft/ft²)	Fry (ft/ft²)	Pre-smolt (ft/ft²)	Immature-smolt (ft/ft²)
503	RRPOMA	506.8	134.0	7.5	26.00	10.00	129.00	134.00
713	RRPOMA	506.8	134.0	7.5	35.50	10.00	138.00	143.00
927	RRPOMA	506.8	134.0	7.5	43.00	10.00	140.50	145.50
999	RRPOMA	506.8	134.0	7.5	44.69	10.00	138.13	143.13
1,140	RRPOMA	506.8	134.0	7.5	48.00	10.00	133.50	138.50
1,156	RRPOMA	506.8	134.0	7.5	48.12	10.03	132.91	137.97
1,313	RRPOMA	506.8	134.0	7.5	49.37	10.34	127.00	132.69
1,393	RRPOMA	506.8	134.0	7.5	50.00	10.50	124.00	130.00
1,469	RRPOMA	506.8	134.0	7.5	49.85	10.50	117.72	123.57
1,483	RRPOMA	506.8	134.0	7.5	49.82	10.50	116.56	122.38
1,647	RRPOMA	506.8	134.0	7.5	49.50	10.50	103.00	108.50
1,900	RRPOMA	506.8	134.0	7.5	48.00	11.00	82.00	87.00
1,978	RRPOMA	506.8	134.0	7.5	47.20	11.27	77.44	82.04
2,083	RRPOMA	506.8	134.0	7.5	46.11	11.63	71.31	75.37
2,189	RRPOMA	506.8	134.0	7.5	45.02	11.99	65.12	68.63
2,191	RRPOMA	506.8	134.0	7.5	45.00	12.00	65.00	68.50
2,472	RRPOMA	506.8	134.0	7.5	40.65	13.45	53.41	56.91
2,482	RRPOMA	506.8	134.0	7.5	40.50	13.50	53.00	56.50
2,697	RRPOMA	506.8	134.0	7.5	36.44	14.24	45.61	49.48
2,773	RRPOMA	506.8	134.0	7.5	35.00	14.50	43.00	47.00
2,966	RRPOMA	506.8	134.0	7.5	32.02	15.16	40.35	44.68
3,064	RRPOMA	506.8	134.0	7.5	30.50	15.50	39.00	43.50
3,310	RRPOMA	506.8	134.0	7.5	27.64	16.32	37.77	41.46
3,365	RRPOMA	506.8	134.0	7.5	27.00	16.50	37.50	41.00
3,390	RRPOMA	506.8	134.0	7.5	26.79	16.55	37.41	40.95
3,924	RRPOMA	506.8	134.0	7.5	22.35	17.66	35.56	39.84
3,990	RRPOMA	506.8	134.0	7.5	21.80	17.80	35.33	39.70
4,086	RRPOMA	506.8	134.0	7.5	21.00	18.00	35.00	39.50
4,538	RRPOMA	506.8	134.0	7.5	17.29	18.31	34.69	39.50
4,817	RRPOMA	506.8	134.0	7.5	15.00	18.50	34.50	39.50
4,979	RRPOMA	506.8	134.0	7.5	14.00	18.39	34.61	39.61
5,498	RRPOMA	506.8	134.0	7.5	10.81	18.03	34.97	39.97
5,548	RRPOMA	506.8	134.0	7.5	10.50	18.00	35.00	40.00
5,968	RRPOMA	506.8	134.0	7.5	8.70	16.97	35.51	40.77
6,365	RRPOMA	506.8	134.0	7.5	7.00	16.00	36.00	41.50
6,459	RRPOMA	506.8	134.0	7.5	6.94	15.83	36.52	42.07
6,992	RRPOMA	506.8	134.0	7.5	6.62	14.85	39.45	45.33
7,183	RRPOMA	506.8	134.0	7.5	6.50	14.50	40.50	46.50
7,419	RRPOMA	506.8	134.0	7.5	6.36	13.92	41.08	47.22
7,871	RRPOMA	506.8	134.0	7.5	6.08	12.82	42.18	48.61
8,000	RRPOMA	506.8	134.0	7.5	6.00	12.50	42.50	49.00
8,380	RRPOMA	506.8	134.0	7.5	6.00	12.50	42.50	49.00
9,340	RRPOMA	506.8	134.0	7.5	6.00	12.50	42.50	49.00
10,301	RRPOMA	506.8	134.0	7.5	6.00	12.50	42.50	49.00
10,982	RRPOMA	506.8	134.0	7.5	6.00	12.50	42.50	49.00
16,844	RRPOMA	506.8	134.0	7.5	6.00	12.50	42.50	49.00

Once the UAs versus discharge relationships for each life- stages were standardized to discharge range, a scalar was developed in order to transfer a source MHT UA to a Target MHT. This scalar was based upon the hydrologic segment's proportions, from Keno to the Klamath estuary, using the average monthly discharge, averaged over 51 simulated water years based on the simulated hydrology under the No Dam Alternative. The resulting scalar (flow based proportions) allowed the adjustment of the discharge axis (X-Axis) when transferring from the source MHT UA to the Target MHT within specific hydrologic reaches as illustrated in Tables 4-10 and 4-11.

Table 4-10. Hydrologic reach and average monthly proportions used to scale UA discharge bins from one hydrologic reach to the other.

Hydro Reach Number	Hydro Reach	2D Site Representation	Average Monthly Proportion
1	Keno to JCB	-	0.12
2	JCB to Copco	-	0.01
3	Copco to IG	-	0.02
4	IG to SH	RR	0.02
5	SH to SC	TH/BB	0.06
6	SC to SA	SE/RG	0.19
7	SA to TR	SB/OR	0.27
8	TR to KR	PW	0.32

Table 4-11. Example site transfer of UA discharge bins from the Pecwan site "8" to Hydro Reach 7-1.

Pecwan (PW) WUA X-Axis							
8	7	6	5	4	3	2	1
503	365	272	243	235	226	220	159
713	518	386	345	333	321	312	226
927	673	501	449	433	417	406	293
999	726	540	483	466	449	437	316
1,140	828	616	552	532	513	499	361
1,156	840	625	559	540	520	506	366
1,313	954	710	635	613	591	574	416
1,393	1,012	753	674	650	627	609	441
1,469	1,067	794	711	686	661	643	465
1,483	1,077	802	718	692	667	649	469
1,647	1,196	891	797	769	741	721	521
1,900	1,380	1,027	919	887	855	831	601
1,978	1,437	1,070	957	924	890	865	626
2,083	1,513	1,126	1,008	973	937	911	659
2,189	1,590	1,184	1,059	1,022	985	958	693
2,191	1,592	1,185	1,060	1,023	985	959	694
2,472	1,796	1,337	1,196	1,154	1,112	1,082	782
2,482	1,803	1,342	1,201	1,159	1,116	1,086	786
2,697	1,959	1,458	1,305	1,259	1,213	1,180	854
2,773	2,014	1,499	1,342	1,295	1,247	1,213	878
2,966	2,155	1,604	1,435	1,385	1,334	1,298	939
3,064	2,226	1,657	1,483	1,431	1,378	1,341	970
3,310	2,405	1,790	1,602	1,545	1,489	1,448	1,048
3,365	2,444	1,820	1,628	1,571	1,514	1,472	1,065
3,390	2,463	1,833	1,640	1,583	1,525	1,483	1,073
3,924	2,851	2,122	1,899	1,832	1,765	1,717	1,242
3,990	2,899	2,158	1,931	1,863	1,795	1,746	1,263
4,086	2,968	2,209	1,977	1,908	1,838	1,788	1,293
4,538	3,297	2,454	2,196	2,119	2,041	1,985	1,436
4,817	3,499	2,605	2,331	2,249	2,167	2,108	1,525
4,979	3,617	2,692	2,409	2,325	2,239	2,178	1,576
5,498	3,994	2,973	2,660	2,567	2,473	2,406	1,740
5,548	4,030	3,000	2,685	2,590	2,495	2,427	1,756
5,968	4,335	3,227	2,888	2,787	2,684	2,611	1,889
6,365	4,624	3,442	3,080	2,972	2,863	2,785	2,015
6,459	4,692	3,493	3,125	3,016	2,905	2,826	2,045
6,992	5,079	3,781	3,383	3,265	3,145	3,059	2,213
7,183	5,218	3,884	3,476	3,354	3,231	3,143	2,274
7,419	5,389	4,012	3,590	3,464	3,337	3,246	2,348
7,871	5,718	4,256	3,809	3,675	3,540	3,444	2,492
8,000	5,812	4,326	3,871	3,735	3,598	3,500	2,532
8,380	6,088	4,531	4,055	3,913	3,769	3,666	2,653
9,340	6,785	5,050	4,520	4,361	4,201	4,086	2,957
10,301	7,483	5,570	4,985	4,810	4,633	4,507	3,261
10,982	7,978	5,939	5,314	5,128	4,940	4,805	3,476
16,844	12,237	9,108	8,151	7,865	7,576	7,370	5,332

4.4.1 Island MHT Usable Area (UA)

In order to account for variability between islands, UA versus discharge relationships for each life stage were assigned to each unique island MHT. This required calculating the life stage specific UA versus discharge relationship for each main channel MHT and each sub-channel MHT for each island, then computing the average life stage specific UA versus discharge of the main channel and adding it to the average life stage specific UA versus discharge relationship of the sub-channel. This procedure resulted in a life stage specific unique UA versus discharge relationship for each unique island MHT.

A 'Hydro-Geo-Scalar' (HGS) was developed for scaling the habitat versus flow relationship to account for the differences between the source 2D and target site specific unit widths. The HGS scalar (MHT Unit width/2D MHT width) was multiplied by each main and sub channel unit (Table 4-12). Unique, life stage specific habitat versus flow relationship lookup tables were then derived for each main channel and Island MHT (Table 4-13).

4.4.2 Existing Conditions

This section of the report describes the general life history periodicities for Chinook salmon. Much of the data and charts are based on Klamath River and tributary specific information assembled to populate SALMOD, calibrate the model and validate the output, with the intent of providing predictive capabilities that will inform ongoing and future management decisions.

4.4.2.1 Adult Migration

The adult Chinook Salmon life-history timing begins with entry through the Lower Klamath Basin, with Spring Chinook migrating between the months of April and July followed by the Fall Chinook migration during the period of August through mid-October (Figure 4-14).

A Late-Fall Chinook component also exists. A carcass of a spawned female Chinook was observed on February in Blue Creek, a tributary to the Lower Klamath River suggesting spawning of the Late-Fall Chinook run extends through January (Stern and Noble 1990).

Table 4-12. The calculations of UA as a function of flow were also adjusted for differences between the unit average width and the 2-D derived average width, for two different MHTs within the side channel portion of the island complex.

SCISL01		Unit	2-D Unit		
Spawning	SELSSC	Average	Avg		
Discharge	UA	Width	Width	HGS	UA
503	0.2	33	35.8	0.9	0.2
713	0.2				0.2
927	0.2				0.2
999	0.2				0.2
1140	0.6				0.6
1156	0.7				0.6
1313	1.5				1.3
1393	1.9				1.7
1469	2.3				2.1
1483	2.5				2.3
1647	4.6				4.3
1900	8.0				7.4
1978	9.0				8.3
2083	10.4				9.6
2189	11.2				10.3
2191	11.2				10.4
2472	13.3				12.3
2482	13.4				12.4
2697	15.0				13.9
2773	15.3				14.1
2966	16.0				14.8
3064	16.4				15.1
3310	17.3				16.0
3365	17.4				16.1
3390	17.5				16.1
3924	18.5				17.1
3990	18.6				17.1
4086	18.7				17.2
4538	19.1				17.6
4817	19.1				17.6
4979	19.1				17.6
5498	19.2				17.7
5548	19.3				17.7
5968	19.5				17.9
6365	19.6				18.1
6459	19.7				18.2
6992	19.6				18.0
7183	19.5				18.0
7419	19.5				18.0
7871	19.5				18.0
8000	19.5				18.0
8380	19.6				18.0
9340	19.3				17.8
10301	18.1				16.6
10982	18.1				16.6
16844	18.1				16.6

SCISL01		Unit	2-D Unit		
Spawning	SEPOSC	Average	Avg		
Discharge	UA	Width	Width	HGS	UA
503	1.4	35	45.6	0.8	1.1
713	1.4				1.1
927	1.4				1.1
999	1.4				1.1
1140	3.1				2.4
1156	3.3				2.5
1313	6.0				4.6
1393	6.9				5.3
1469	7.7				5.9
1483	8.0				6.1
1647	11.4				8.8
1900	16.7				12.8
1978	18.3				14.1
2083	20.5				15.7
2189	21.7				16.7
2191	21.7				16.7
2472	24.9				19.1
2482	25.1				19.2
2697	27.5				21.1
2773	28.2				21.7
2966	30.0				23.0
3064	30.9				23.7
3310	33.2				25.5
3365	33.5				25.7
3390	33.7				25.9
3924	37.2				28.6
3990	37.5				28.8
4086	37.9				29.1
4538	39.8				30.5
4817	39.9				30.7
4979	40.0				30.7
5498	40.3				30.9
5548	40.1				30.8
5968	38.4				29.4
6365	36.7				28.2
6459	36.3				27.9
6992	34.3				26.3
7183	33.6				25.8
7419	32.7				25.1
7871	31.6				24.2
8000	31.2				24.0
8380	30.3				23.2
9340	27.1				20.8
10301	23.6				18.1
10982	23.6				18.1
16844	23.6				18.1

Table 4-13. Final UA versus lookup table example, for the MHT island unit SCISL01 and side channel island Number 01.

SCISL01				
Discharge (cfs)	Spawning UA (ft/ft²)	Fry UA (ft/ft2)	Pre-smolt UA (ft/ft2)	Immature-smolt UA (ft/ft2)
503	34.6	9.6	69.5	73.7
713	33.9	9.0	61.2	64.9
927	33.2	9.6	56.2	59.7
999	33.4	9.6	54.7	58.2
1140	34.3	9.8	53.2	56.8
1156	34.4	9.9	53.2	56.7
1313	35.7	11.0	52.8	55.6
1393	36.2	11.6	52.5	55.0
1469	36.1	12.1	50.8	53.4
1483	36.2	12.2	50.6	53.2
1647	37.0	13.6	47.4	50.1
1900	37.0	15.6	46.7	48.9
1978	36.9	16.0	46.8	49.0
2083	36.8	16.5	46.9	49.1
2189	36.3	17.3	47.0	49.2
2191	36.2	17.3	47.0	49.2
2472	35.4	18.7	49.1	51.3
2482	35.4	18.8	49.1	51.3
2697	35.2	19.9	52.0	54.2
2773	35.0	20.2	52.4	54.4
2966	34.8	21.4	52.7	54.8
3064	34.8	21.9	52.8	55.0
3310	35.2	23.4	54.3	56.4
3365	35.2	23.7	54.6	56.7
3390	35.1	23.8	54.7	56.8
3924	34.5	26.5	57.4	59.6
3990	34.4	26.6	57.6	59.8
4086	34.2	26.9	57.9	60.1
4538	33.6	28.0	59.4	61.5
4817	33.0	28.6	59.9	62.1
4979	32.6	28.7	60.0	62.2
5498	31.5	29.1	60.5	62.5
5548	31.3	29.1	60.5	62.5
5968	30.0	27.5	59.0	61.1
6365	28.7	26.0	57.6	59.8
6459	28.5	25.8	57.5	59.6
6992	27.2	25.0	57.8	59.9
7183	26.7	24.7	57.9	59.9
7419	26.2	24.5	57.8	60.0
7871	25.3	24.3	57.7	60.3
8000	25.0	24.3	57.6	60.4
8380	24.8	24.2	56.9	59.8
9340	23.9	24.1	55.8	58.7
10301	22.6	24.2	54.4	57.4
10982	22.6	24.2	54.4	57.4
16844	22.6	24.2	54.4	57.4

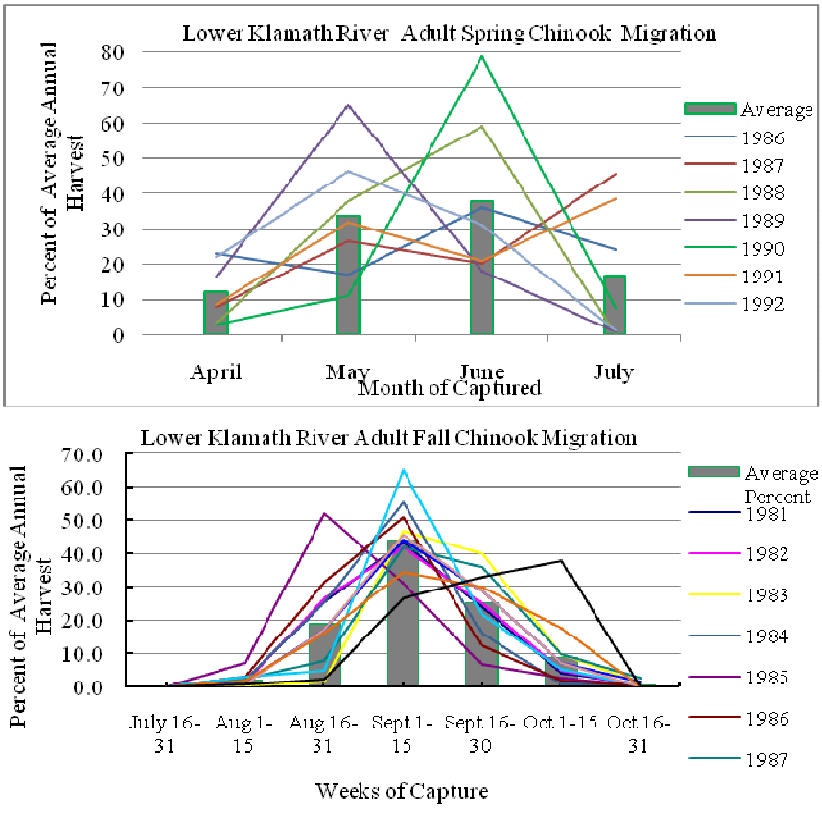


Figure 4-14. Adult Spring (top) and Fall Chinook Salmon (bottom) movement through the Lower Klamath River based on Yurok Tribe net harvest monitoring data (1986-1992).

Currently, the adult Fall Chinook entry into the upper Klamath River tributaries and Iron Gate hatchery begins in mid-September, peak in early October and conclude by the last week of November (Shaw et al. 1997). Historically, migration through Klamathon Racks, a weir operated in the mainstem Klamath River between Bogus Creek and the Shasta River, began in mid-August and peaked in mid-September, with the Shasta River counts peaking during the first week of October (Figure 4-15). This shift in timing is believed to be an artifact of higher fall temperatures associated with the construction of the Klamath River hydropower dams (Bartholow 2005).

4.4.2.2 Spawning

Presently, spawning in the mainstem Klamath River commences upon entry, starting in mid-October, peaking during the last week of October through the first week of November, and concluding by the end of November (Figure 4-16).

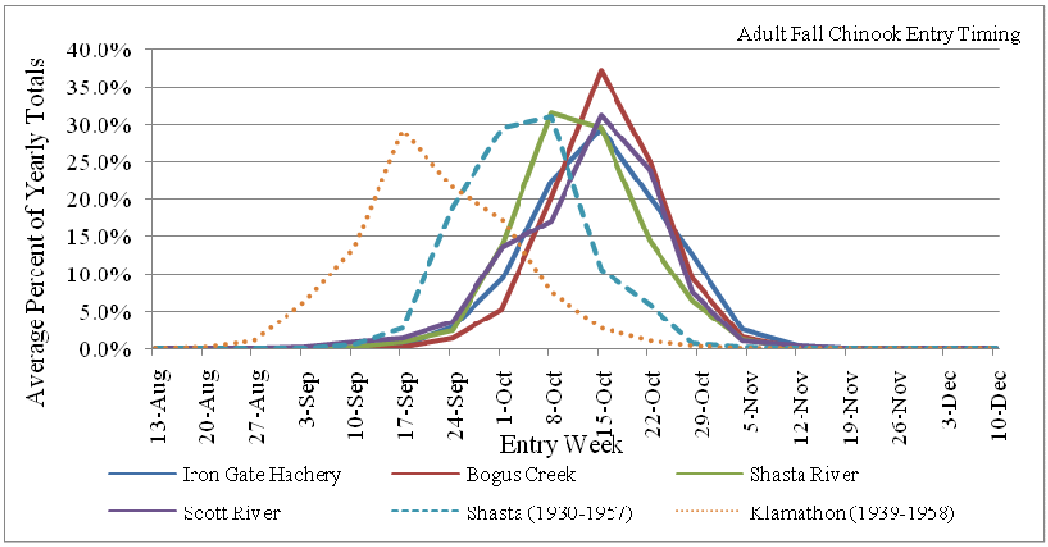


Figure 4-15. Adult Fall Chinook present timing into major tributaries and Iron Gate Hatchery and Historical timing at Klamathon and Shasta Racks.

4.4.2.3 Emergence

Emergence was estimated based on Daily Temperature Units (DTU), with accumulating DTUs for each average daily temperature unit above 32°F following the completion of redd construction. An accumulated DTU of 1,600 units is the estimated time of emergence (Piper et al. 1982). Using the average daily temperatures and weekly spawn timing for Fall Chinook, in the mainstem Klamath River, the estimated emergence time started in mid-February, peaked during the third week of March, and concluded by the first week of April (Figure 4-17).

4.4.2.4 Juvenile Outmigration

Upon emergence, yolk-sac depletion and buttoning up, the young-of-the-year (YOY) begins their dispersal downstream during the evening hours, but stop and rear in suitable habitat during the day. Outmigration traps in the mainstem Klamath River have demonstrated the outmigration timing and size distributions of fish as they migrate towards the ocean. Juvenile Chinook from the Shasta and Bogus Creek, tributaries in the upper 15 miles of the Klamath River, below Iron Gate Dam migrate between February and early April, with the majority of fish being captured at Big Bar from May through mid-July (Figure 4-18).

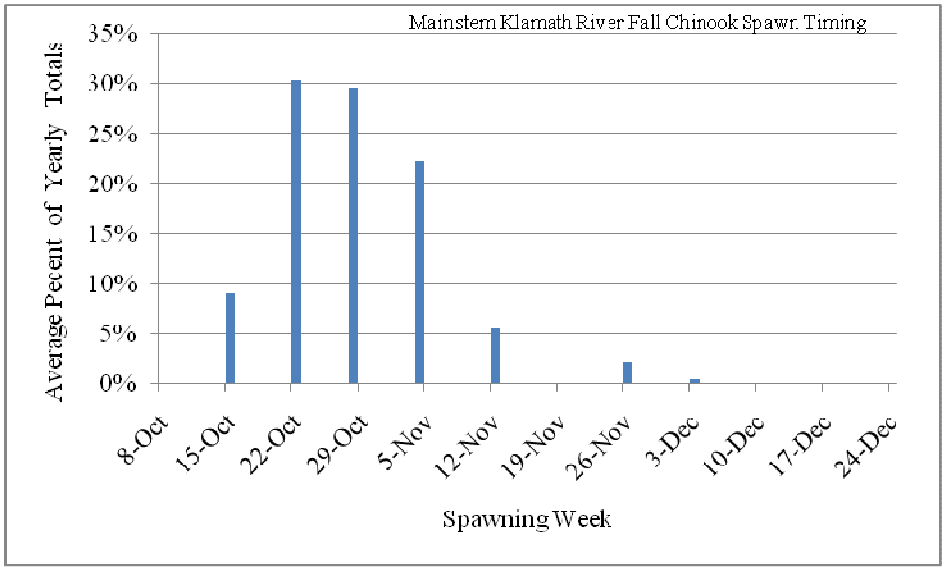


Figure 4-16. Klamath River mainstem Fall Chinook spawning timing based on weekly redd counts.

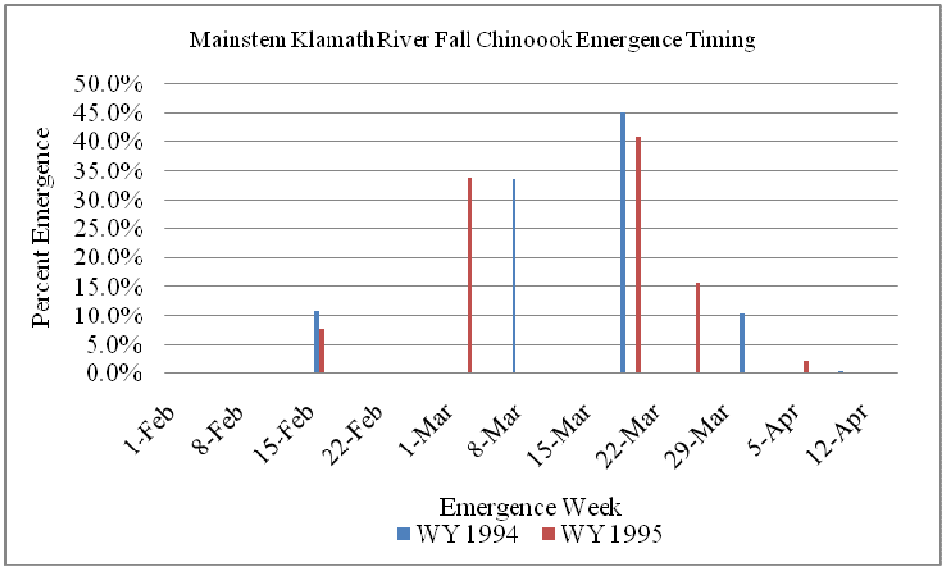


Figure 4-17. Emergence timing for Fall Chinook in the mainstem Klamath River based on DTUs.

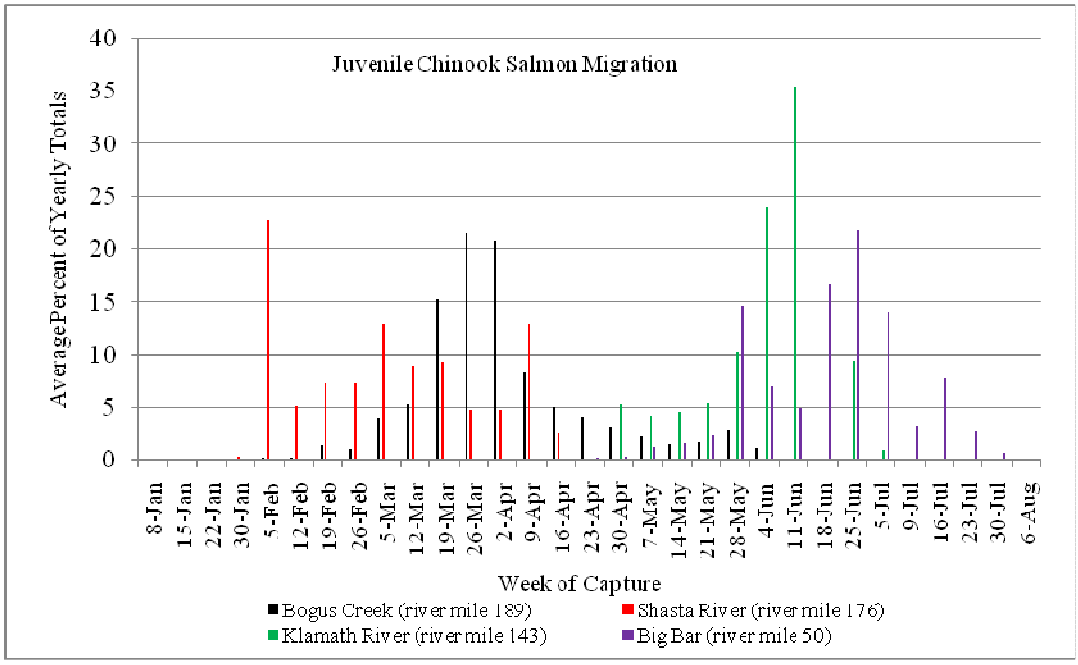


Figure 4-18. Juvenile Chinook Salmon outmigration observed from traps located at the mouths of Bogus Creek and Shasta River and the mainstem Klamath River at river miles 143 and 50.

If one assumes an average downstream migrant rate of 2.5 river miles a day, fish originating from Bogus Creek (river mile 189), or YOY emerging from the mainstem Klamath River near Bogus Creek would arrive at Big Bar (river mile 50) in approximately 56 days. These fish would first arrive at Big Bar in early May, peak in mid-June and completely pass the location by late July (Figure 4-19). This could help understand the bimodal distribution of fish occurrences observed at Big Bar, with the early peak of YOY Chinook being natural fish originating from Bogus, Shasta, mainstem Klamath River and Scott River, with the later peak dominated by Iron Gate hatchery releases. Based upon trap catches during the outmigration of juvenile salmon in the Klamath River, the weight to length relationship suggests that juvenile Chinook salmon exhibit slightly greater than isometric growth (Figure 4-20).

4.4.2.5 Dam Removal

Following dam removal, we expect that migration of adult Fall and Spring Chinook to once again replicate the historical timing presented in Figure 4-15, based on the historical counts at Klamathon and Shasta Racks.

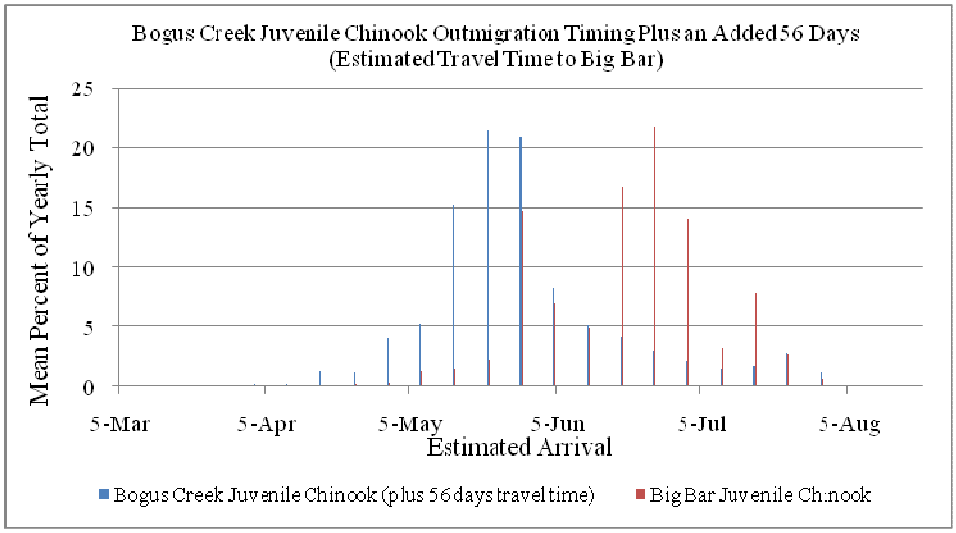


Figure 4-19. A hypothetical arrival time of Bogus Creek (river mile 189) and nearby Klamath River mainstem YOY arrival time at Big Bar (river mile 50).

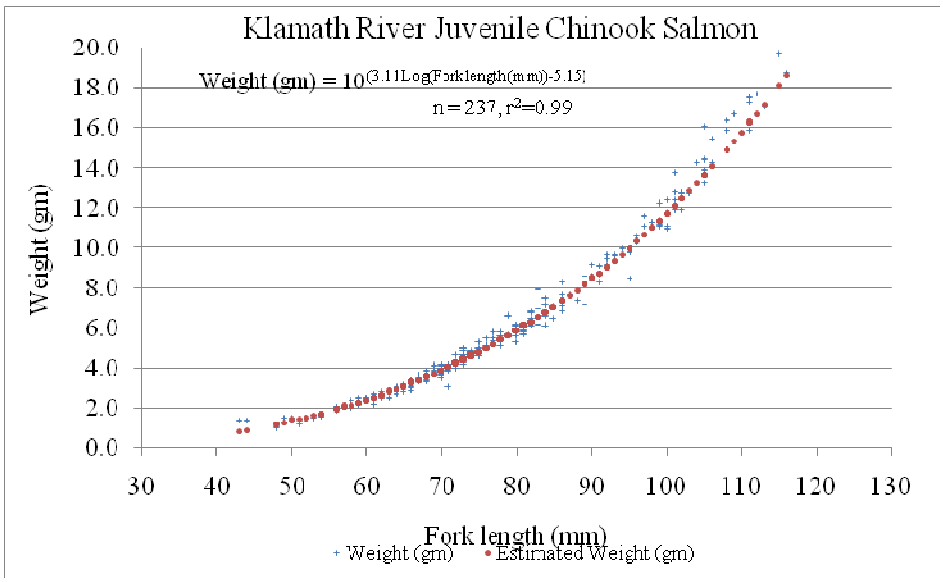


Figure 4-20. The juvenile length to weight relationship used in SALMOD was developed from data collected on the mainstem Klamath River (FWS data).

The distribution of spawners, within the mainstem Klamath River upstream of the existing Iron Gate dam was based upon the proportion of estimated spawning habitat availability as described above. The habitat conditions (i.e., the spatial mosaic of mesohabitats) above Iron Gate are very complex and contain extensive areas with excellent production potential. This is supported by existing fisheries inventories between the existing reservoirs where there is ample habitat to support a trophy Red band Trout population (Figure 4-21). However, the current reservoirs occupy some the lowest gradient and widest valley reaches of the entire mainstem. These sections of river had high sinuosity and complex channels capable of providing excellent salmonid spawning and rearing habitats (Figure 4-22).

Not only the habitat availability, but returning the system back to one that exhibits the natural hydrograph in terms of flow timing, duration, magnitude, frequency and rate of change coupled with reinitiating bedload transport through areas currently blocked by dams are expected to provide substantial beneficial effects on production, diversity and recovery.

Figure 4-21. Other than the 1-2 miles of high gradient habitat below J.C. Boyle reservoir, the mainstem Klamath River between and within the existing reservoirs offers excellent habitat for salmonids with high production potential.

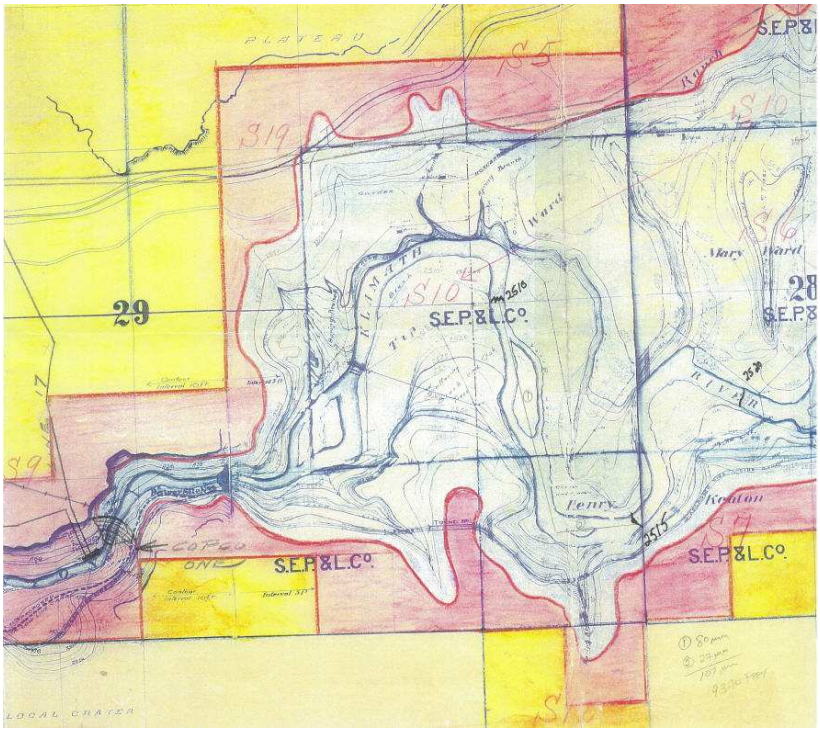


Figure 4-22. A reach of river presently beneath Copco reservoir showing a highly complex and sinuous channel, capable of high salmonid production potential.

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5. HEC5Q MODEL STATUS (CAMPBELL & PERRY)

5.1 BRIEF DESCRIPTION OF HEC5Q MODEL

The HEC5Q water quality model was developed by the US Army Corps of Engineers, Hydrologic Engineering Center (HEC) (USACE 1986). HEC5Q is the existing model used to predict mainstem Klamath River water temperatures and provides input data to SALMOD II and to the upper basin EDT model. More generally, HEC5Q provides estimates of water temperature conditions for all the life cycle modeling used in the assessments under all evaluated scenarios.

HEC5Q is a one-dimensional water quality model and outputs stream temperature predictions as daily averaged values that are homogenously mixed for a series of computational units that form the reservoir and stream network in the model (Hanna and Campbell 1999). Those computational units are averaged vertically in reservoirs (stacked slices) and longitudinally in streams (blocks in series). Details of the computational methods and historical calibration and validation within the Klamath River below Iron Gate Dam to the Scott River can be found in Hanna and Campbell (1999). Although originally calibrated for the Klamath River reach from Iron Gate Dam to Seiad Valley, CA, the model domain now covers the entire mainstem river from Link Dam downstream to the Pacific Ocean. The period of record for the existing model is 1961 through 2009. Although HEC5Q has inherent computational limitations and specific input requirements, we believe it is adequate in terms of its general utility in predicting overall trends in water temperatures that are based on changes in flow and/or ambient meteorology.

Currently, HEC5Q is undergoing review by USGS Water Resources in Portland, OR. Due to this review and discussion among scientists, HEC5Q is likely to undergo alterations to its parameterization, including re-calibration and validation prior to final model runs. Adjusting HEC5Q parameterization is warranted since the model's spatial domain has been extended considerably beyond its previous applications and more extensive spatial and temporal calibration and validation data. The structure of HEC5Q, inputs and outputs, and development of input data sets for hydrology and meteorology in response to simulated alternative management actions and climate change are discussed below.

5.1.1 HEC5Q Model Inputs and Outputs

Details of HEC5Q model inputs and data requirements are described in USACE (1986) and more specifically for the Iron Gate to Scott River reach of the Klamath River in Hanna and Campbell (1999). In general, the model requires flow, reservoir storage and outlet elevation, and five

meteorological related inputs: air temperature, dew point, precipitation, windspeed, and visibility as daily averages or daily cumulative totals. Initial conditions are fixed inputs at the top of the model network (Link Dam) and subsequent values are computed for all remaining computational elements and time steps. Initial conditions influence only the first few computational elements over the first few days of the simulations.

Model outputs are daily average water temperature (°C) at all control nodes (about 30 locations) in the model domain from Link Dam downstream through the reservoirs in series to the Pacific Ocean.

5.1.2 HEC5Q Model Limitations

HEC5Q is constrained by its implementation in FORTRAN in terms of the maximum number of computational elements as well as limitations on certain of its internal algorithm solutions. HEC5Q cannot reliably predict water temperature for impoundments with a retention time of less than one day, the model's time step. For this reason, J.C. Boyle Reservoir is depicted in the model network as a single river reach with depth, width, and length the same as the reservoir pool. HEC5Q does not capture diurnal variability in water temperature.

The process for converting meteorology and flow inputs to water temperature by HEC5Q is contained in the algorithm implemented in the algorithm "HEATX." The code within that executable program cannot be viewed, altered, or diagnosed and as such is not explicit in the model and is treated as a black-box algorithm.

The daily average temperature prediction at each computational unit is the only output results for temperature from the model. HEC5Q is considered a planning model, one that predicts general trends in temperature over long time scales. There may be substantial differences in temperature on any given day when predicted and measured temperatures are compared, but a review of the seasonal and annual trends support that the simulations of temperatures is adequately represented by the model.

5.1.3 HEC5Q Model Assumptions

HEC5Q assumes that all constituents are homogenously mixed from top to bottom and from side to side for any computational units within the model network. Reservoirs consist of stacked "slices" in the vertical dimension and one representative predicted temperature is assigned to that layer in a reservoir. In streams, the computation units are like boxes in series and again, each unit is homogenously mixed from top to bottom and from side to side with one predicted temperature.

5.2 HEC5Q MODEL, GCM INPUT DATA, AND INDEX SEQUENTIAL RUNS

Five climate change projections were selected to represent a range of possible future conditions for the Klamath Basin by the US Bureau of Reclamation Denver Technical Service Center. Details on how these GCM model outputs were selected can be found in Grieman (2010). The fish production modeling team will use only one of 10 realizations for each climate change scenario, representing the median condition for each GCM. For all our analyses, we used a shorthand convention to refer to the GCM projections utilized; MIUB and CCCMA are the drier/warmer and wetter/warmer projections, GFDL is the "median" or central tendency of the estimated increase in ambient air temperatures and precipitation ratio, and the NCAR and MRI are the drier/cooler and wetter/cooler projections (Reclamation 2010).

To develop input data sets for HEC5Q, output from GCM models needed to be calibrated against observed meteorological data used in HEC5Q. The GCM data were downscaled to historical PRISM data sets (Reclamation 2010). This process resulted in predicted air temperature and precipitation that was averaged over a broad geographic area and two elevation bands. In contrast, HEC5Q uses daily average point estimates for the required five meteorological input values at two locations: the Montague/Siskiyou and the Eureka/Arcata airports. Thus, the geographic scale and elevation differed between input data needed by HEC5Q and output data supplied by the GCM models. We attempted to identify meteorological stations similar in elevation to that used by GCM models, but none existed. Therefore, we adjusted GCM air temperatures by averaging the past 10 years of measured air temperatures at Montague/Siskiyou and Eureka/Arcata airport and comparing it to the first 10 years of the GCM predicted air temperatures (Table 5-1). GCM air temperatures were then adjusted by taking the difference between the past 10 years of measured air temperature at the two airport locations and the first 10 years of each of the climate change projections. For the inland meteorological location, Montague Siskiyou airport, the adjustment (Delta T) was 2.2°C. For the coastal meteorological location, Eureka/Arcata airport, the Delta T was 1.1°C.

Due to the differences in spatial scales and single versus multiple elevation bands for the GCM data sets versus HEC-5Q inputs, the temperature adjustments provided the most rational approach to linking these data. We believe this is further supported given similar adjustments that were made in applying GCM outputs to water temperature models for Klamath River tributaries (Flint and Flint 2009). For these models, linear regression between the PRISM and GCM data sets warranted an adjustment of 1.87 °C for the tributary models (personal communication, Lorraine Flint, 4 May 2010). Second, variation in air temperatures of selected GCM projections ranged from 1.4 – 2.2 °C (personal communication, David Raff, 23 October 2009).

Table 5-1. Comparison of measured air temperatures (°F) at Montague/Siskiyou (M/S) and Eureka/Arcata (E/A) Airports and 5 GCM projection predicted air temperatures for the Lower Klamath Basin.

Decade	**Measured**	**Projected**				
	M/S	CCCMA	GFDL	MIUB	MRI	NCAR
1999-2009	52					
2012-2021		48.8	47.8	48.8	47.1	47.2
	E/A	CCCMA	GFDL	MIUB	MRI	NCAR
1999-2009	51.2					
2012-2021		50	49	50	48.2	48.4

HEC5Q also requires dew point, visibility, wind speed, and water temperature of tributary inputs. Tributary water temperatures were supplied as output from the Flint and Flint (2009) temperature models applied to each GCM scenario. Dew point is typically calculated using daily minimum air temperature and those values were not provided in the GCM data sets. Therefore dew point record was calculated from average daily temperature (T) based on the following equation:

$$1.021T-5.97 \quad \text{for Eureka/Arcata}$$
$$0.5648T+7.12 \quad \text{for Montague/Siskiyou.}$$

Wind speed and visibility were derived from historical records from the Montague/Siskiyou and Eureka/Arcata airports and were averaged by day for available records. The resulting daily values were repeated in all of the individual years for the two meteorological locations in HEC5Q. Although these simulations derive from synthetically constructed input data, their utility is to project possible future thermal conditions. While none of the outputs are “real” in the sense that they fully describe future conditions, they can provide insights into how variability in future thermal conditions may or may not be ameliorated under the various alternatives being evaluated in the SD.

In addition to GCM simulations, the Bureau of Reclamation also simulated hydrology using historical water volumes and meteorology, but with simulated river flows estimated under the Dams In with KBRA and Dams Out alternatives. Therefore, we will also simulate river

temperatures using historical meteorology with the simulated hydrology provided by the Grieman (2010).

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6. LOWER BASIN TRIBUTARIES (HAMPTON & PERRY)

6.1 BRIEF DESCRIPTION OF MODEL

The Fall Chinook Life Cycle Model for the Secretarial Determination will simulate the annual number of adults returning to five natal tributaries of the Lower Klamath River: the Trinity, Salmon, Scott, and Shasta rivers and Bogus Creek. SALMOD II will then receive progeny of these spawners as age-0 juvenile Chinook salmon emigrating from the natal tributaries (hereafter, age-0 emigrants). This chapter develops the stock-recruitment models needed to produce age-0 emigrants from their parent stock.

The primary goal of this chapter is to 1) parameterize age-0 production curves for tributaries with sufficient empirical data and 2) develop approaches for parameterizing production curves for tributaries lacking data. We first estimate productivity (α) and capacity (β) parameters for each tributary. Next, we examined whether river flow and mean emigration date explained deviations from the average spawner-emigrant curve. Third, we investigated use of a habitat-based method for predicting capacity of tributaries from watershed area (Parken et al. 2006). Fourth, we discuss how the preceding information will be combined to quantify both productivity and capacity for tributaries of the Lower Klamath River. Last, we describe how KBRA activities will be translated into changes in productivity and capacity through time in response to restoration actions.

For the analysis of empirical data, we used mark-recapture abundance estimates of age-0 emigrant Chinook from trapping efforts on Bogus Creek, Shasta River, Scott River, and Trinity River and escapement estimates of Fall Chinook Salmon to each tributary. We chose to use the Ricker model for three reasons: First, the spawner-emigrant data for the Trinity River appeared consistent with a Ricker-type function. Second, the Ricker model can be cast in a generalized linear models framework allowing standard software packages to be used for parameter estimation, model comparison using Akaike's Information Criterion (AIC), inclusion of covariates, and simultaneous analysis of all tributaries. Last, the Ricker model has been used previously to analyze the stock-recruitment relationship for Klamath River Fall Chinook salmon, providing a basis for its use in this analysis (PFMC 2005).

6.2 MODEL INPUTS AND OUTPUTS

6.2.1 Inputs, Model Structure, and Model Selection

6.2.1.1 Spawner-emigrant Data

Annual abundance estimates of naturally produced age-0 emigrants were available for 21 years (emigration years 1989-2009), 10 years (2000-2009), 9 years (2001-2009), and 8 years respectively, for the Trinity River, Scott River, Shasta River, and Bogus Creek (Chamberlain and Williamson 2006; Chesney et al. 2009; Pinnix and Quinn 2009). Age-0 emigrant abundance was estimated via mark-recapture using weekly estimates of trap efficiency. Associated estimates of sampling error were also available, but were not explicitly included in this analysis. Spawner escapement data was obtained from the "Megatable," which collates tributary-specific escapement estimates from numerous sources (CDFG 2010). We included only naturally produced adults in the analysis and excluded jacks.

A number of details about the spawner-emigrant data should be kept in mind when interpreting findings from this analysis. First, age-0 abundance estimates from the Trinity River represent progeny of both naturally produced Spring and Fall Chinook. Therefore, we estimated age-0 abundance of Fall Chinook salmon by assuming that the relative abundance of age-0 Fall Chinook was directly proportional to fraction of the total Chinook escapement comprised of the Fall run. In addition, four years of Trinity River data were excluded from the analysis due to incomplete sampling of the juvenile salmon emigration (emigration years 1990, 1994, 2000, and 2006). Last, juvenile salmon trapping occurs at mile 4.75 on the Scott River. If substantial spawning occurs in the lower 4.75 miles of the Scott River *and* these spawners are included in escapement estimates, then age-0 emigrant production may appear low relative to spawner abundance.

6.2.1.2 The Ricker Model

We fit a Ricker Model of the following form

$$R_{y,T} = \alpha_T S_{y,T} e^{-\beta_T S_{y,T} + \varepsilon}$$

where $R_{y,T}$ is the number of age-0 Chinook salmon emigrating in year y from tributary T, $S_{y,T}$ is the number of spawners in tributary T, ε is lognormally distributed error with mean 0 and standard deviation σ, and α_T and β_T are tributary-specific parameters of the stock-recruitment curve to be estimated from the spawner and emigrant data.

The parameter α is considered the "productivity" parameter while β_T is regarded as the "capacity" parameter. Specifically, α quantifies slope of the production curve at the origin; that is, the number of age-0 emigrants produced per spawner at low spawner abundance, when density dependence is absent. In contrast, β controls the degree of density dependence as the leveling off, or decline in production beyond the escapement that produces maximum age-0 abundance. Because β is difficult to interpret biologically, we use the biological reference points $S_{\max}$ and $R_{\max}$ as a measure of a tributary's capacity. $S_{\max}$ and $R_{\max}$ quantify the peak of the spawner-emigrant curve – the abundance of spawners that produces the maximum number of age-0 emigrants. $S_{\max}$ is estimated as $1/\beta$. At spawner levels below $S_{\max}$, increasing spawners increases abundance of juveniles, but beyond $S_{\max}$, further increases in spawner abundance does not increase juvenile production due to density dependence processes (e.g., redd superimposition or competition among juveniles).

The Ricker model in a linear form is

$$\ln\left(R_{y,T}\right) = \ln\left(\alpha_T\right) + \ln\left(S_{y,T}\right) - \beta_T S_{y,T} + \varepsilon$$

and parameters can be estimated using standard linear models. Considering a single tributary, the linear model is fit using a generalized linear model from the Gaussian family with a log link function as

$$\ln\left(R_y\right) = \theta_0 + \ln\left(S_y\right) + \theta_1 S_y + \varepsilon$$

where $\hat{\alpha} = \exp(\hat{\theta}_0)$, $\hat{\beta} = -\hat{\theta}_1$, and $\ln(S_T)$ is coded as an offset (i.e., its slope is fixed to 1).

6.2.1.3 Modeling Productivity as a Function of Covariates

We incorporated a number of covariates into the Ricker model to quantify factors affecting production of juvenile salmon. First, we included the mean day of emigration as a potential factor affecting productivity. Assuming a constant instantaneous rate of mortality of juveniles, the fraction of fish surviving to emigration from a stream depends on residence time within the stream. A population that exits a tributary predominantly as fry shortly after emergence will experience less total mortality within that tributary relative to a stream where juveniles spend considerable time rearing and emigrate as larger parr. Under this hypothesis, we would expect a positive relation between mean emigration date and mean size of juvenile emigrants, and a negative relationship between α (an index of survival) and mean emigration date.

To examine effects of emigration timing on survival, the mean emigration date for each year and tributary ($d_{y,T}$) was calculated as a weighted average with the weights equal to the fraction of total estimated abundance of age-0 juveniles emigrating in each week. The mean annual migration date was then centered on the mean migration date across all years and tributaries (i.e., the grand mean was subtracted from $d_{y,T}$). Using this approach, α estimates the productivity relative to a population with a mean emigration date of May 16 (the overall mean emigration date). The effect of different mean migration dates on productivity is then estimated relative to the grand mean.

We identified two critical periods during which river flow could affect abundance of age-0 emigrants: the spawning period (Oct.-Nov.) and the egg incubation period (Dec.-Jan.). We hypothesized that mean flows during the spawning period and maximum flows during the egg incubation period could have opposite effects on production of juvenile salmon. For example, higher mean flows during the spawning period could increase available spawning habitat, thereby reducing competition for prime spawning area, minimizing redd superimposition, and increasing egg survival. In contrast, eggs are vulnerable to high-flow events during the incubation period and we suspect that high maximum flows during this period could decrease egg survival.

To examine effects of river discharge on survival, we calculated mean and maximum daily discharge for each year and tributary during each critical period described above. Next, for each tributary we standardized flow covariates by subtracting each observation from the 20-year mean (1989-2009) of each seasonal period and then diving by standard deviation. Standardizing rescales variables to a mean of zero and standard deviation of one. Since each tributary exhibits different magnitudes of discharge, standardizing within each tributary "normalizes" discharge covariates to the same relative scale (Figure 6-1). This approach enabled us to quantify effects of flow simultaneously over all tributaries. Using standardized covariates, α_T and β_T estimate the productivity and capacity of each tributary under mean flow conditions. Because Bogus Creek lacks a discharge gage, we used the average standardized flows of the Scott and Shasta rivers based on the observation that deviations in mean and peak discharge was correlated among watersheds (Figure 6-1).

With covariates described above, the Ricker model and associated linear model are

$$R_{y,T} = \alpha_T S_{y,T} e^{-\beta_T S_{y,T} + \sum \theta_j x_{y,T,j} + \varepsilon} \text{ and}$$

$$\ln\left(R_{y,T}\right) = \theta_0 + \ln\left(S_{y,T}\right) + \theta_1 S_{y,T} + \sum \theta_j x_{y,T,j} + \varepsilon$$

where x_j is the jth covariate (j = 1,…,3) and θ_j is the slope parameter for the jth covariate.

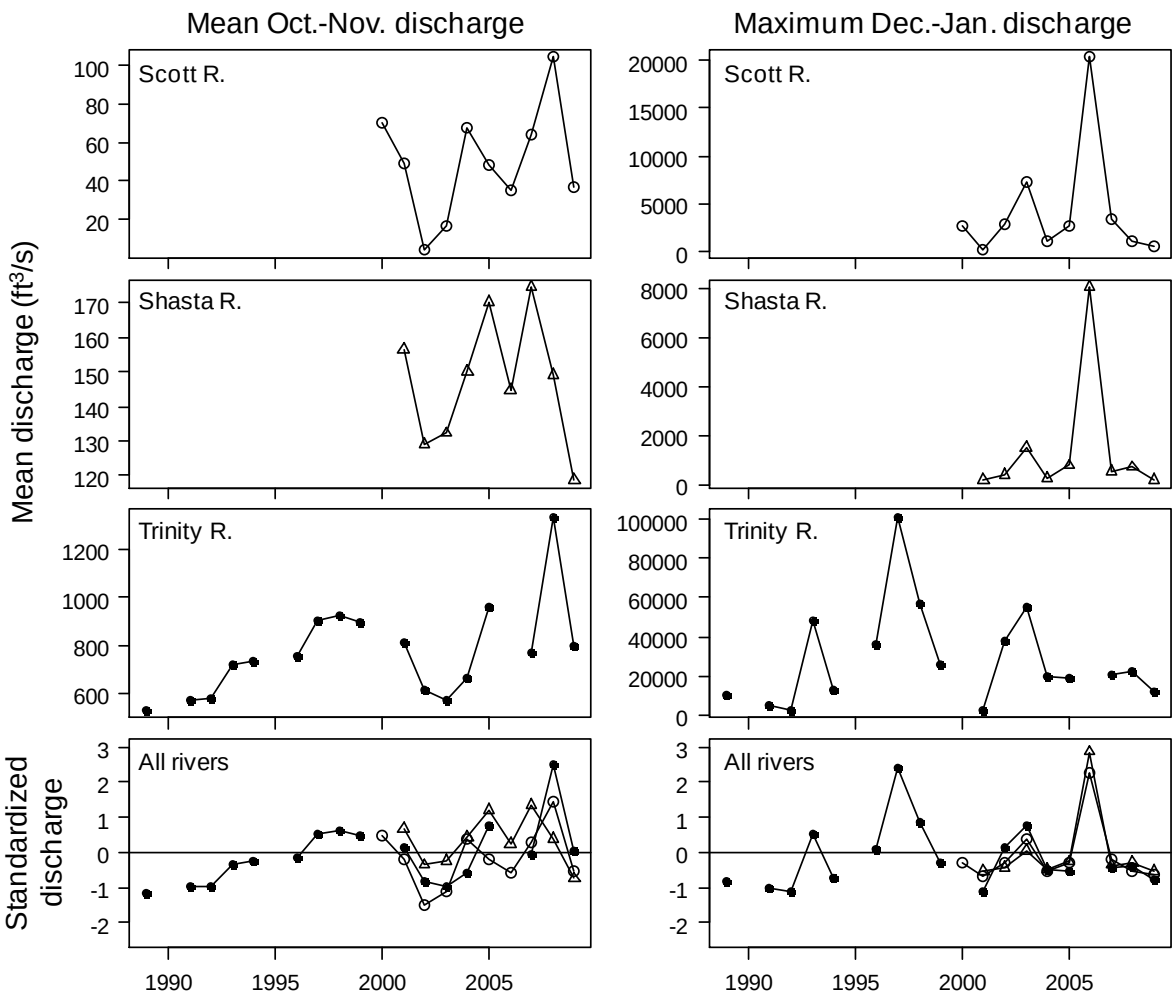

Figure 6-1. Annual mean discharge during Oct.-Nov. and annual maximum discharge during Dec.-Jan in unstandardized and standardized form.

6.2.1.4 Model Selection

We constructed a number of models to test biological hypotheses and identify the model structure best supported by the spawner-emigrant data:

<u>Model 1, The "Base" Model</u>: This model fits separate spawner-emigrant curves to each tributary. This model is formed by including tributary as a categorical main effect, which estimates tributary-specific α parameters, and a tributary $\times$ S_T interaction term, which estimates tributary-specific β parameters. Tributary-specific β parameters were retained in all subsequent models

because we expect the capacity of each tributary to differ due to considerable differences in watershed size.

Model 2, The Full Model: This model assumes α, β, and the effect of covariates on production (α) differs among tributaries. This model is fit by adding to Model 1 the three covariates (two flow variables and mean emigration date) as well as the interaction of tributary with each covariate.

Model 3, Effect of covariates similar among tributaries: This model assumes that flow variables and emigration date affect productivity similarly across all tributaries. This model is formed by dropping the interaction of tributary with each covariate from Model 2 and fitting a common slope for each covariate across all tributaries.

Model 4, No tributary differences in productivity: This model assumes no productivity differences among tributaries remain after accounting for effects of flow and emigration date. This model is constructed by dropping the main effect of tributary from Model 3.

Akaike's Information Criterion (AIC) was used to rank the models and select the best-fit model. In general, AIC selects models on the basis of parsimony by balancing model fit (*sensu* R^2) with model complexity (number of parameters; Burnham and Anderson, 2002). The lowest-AIC model is considered the best-fit model, models within 2 AIC (ΔAIC = 2) are good competing models, and models with ΔAIC > 10 have little support. We used the lowest-AIC model for inference.

6.2.2 Model Output

6.2.2.1 Spawner-emigrant relations for the base model

For the Scott River, Shasta River, and Bogus Creek, emigrant abundance increased linearly with little evidence of density dependence (Figure 6-2). Confidence intervals of $\hat{\beta}_T$ for these tributaries overlapped zero, as might be expected from lack of data at high spawner levels with which to estimate capacity of these streams (Table 6-1). In contrast, the spawner-emigrant data for the Trinity River showed evidence of declining emigrant recruitment at high spawner abundance, and confidence intervals for $\hat{\beta}_T$ did not encompass zero (Figure 6-2, Table 6-1). Estimates of α suggest differences in productivity among tributaries, with Bogus Creek producing the highest number of emigrants per spawner (at low spawner abundance) followed by the Shasta, Trinity, and Scott rivers (Table 6-1).

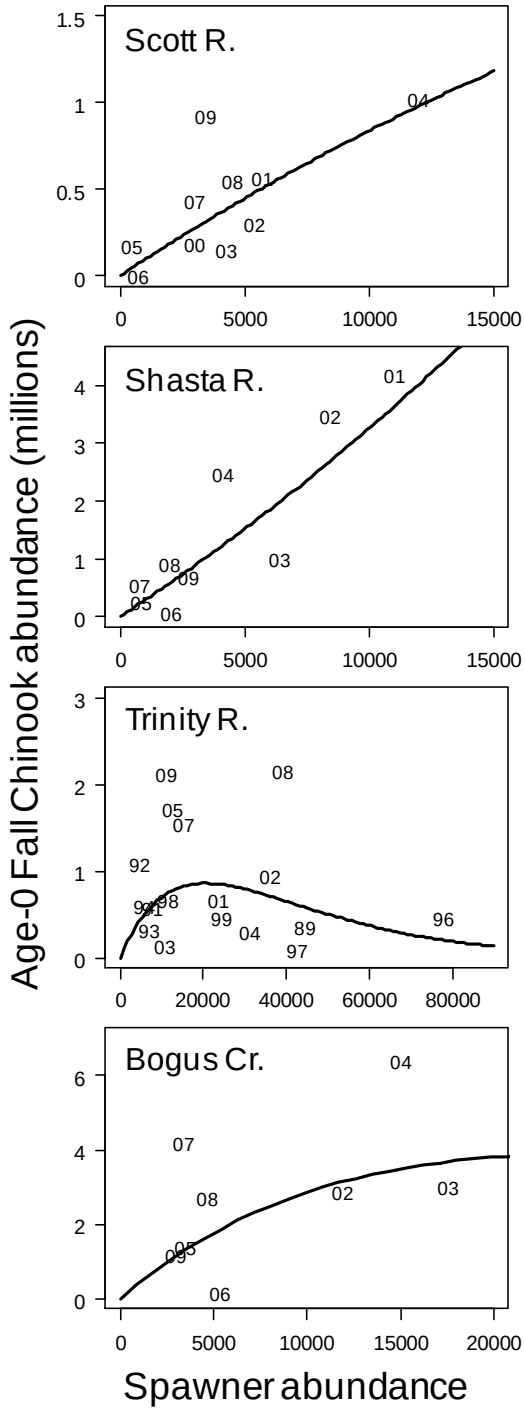

Figure 6-2. The Ricker model without covariates fit to spawner-emigrant data of Fall Chinook salmon in four tributaries of the lower Klamath River. Note the difference in x- and y-axis scales. Symbols represent year of emigration of juvenile salmon.

Table 6-1. Parameter estimates of the Ricker model fit simultaneously to spawner-emigrant data for four tributaries of the lower Klamath River.

Tributary	Parameter	Estimate	SE	95% Confidence Interval
Shasta River	α	283.1	141.4	5.95, 560.2
	β	-1.41×10^{-5}	9.14×10^{-5}	-1.93×10^{-4}, 1.65×10^{-4}
Scott River	α	94.8	43.6	9.3, 180.3
	β	1.25×10^{-5}	9.62×10^{-5}	-1.76×10^{-4}, 2.01×10^{-4}
Trinity River	α	101.9	47.8	8.2, 195.6
	β	4.04×10^{-5}	1.32×10^{-5}	1.45×10^{-5}, 6.63×10^{-5}
Bogus Creek	α	429.5	251.8	-64.0, 923.
	β	4.08×10^{-5}	6.02×10^{-5}	-7.72×10^{-5}, 1.59×10^{-4}
All	σ	0.934		

6.2.2.2 Spawner-emigrant relations with environmental covariates

We found that including covariates in the Ricker model accounted for much of the deviations from the mean production curves. Although adding covariates and their interaction with tributary to the base model increased the number of parameters from 9 to 21, AIC decreased from 119.8 to 84.3, substantially improving model fit (Table 6-2). Eliminating the interaction terms from Model 2 further improved model fit, reducing AIC from 84.3 to 76.8. This finding supports the hypothesis that mean discharge during spawning, maximum discharge during egg incubation, and mean date of emigration had a common effect on productivity of all tributaries. Dropping the main effect of tributary from Model 3 further reduced AIC, resulting in the best-fit, lowest-AIC model. This finding suggests that variability in productivity among tributaries can be adequately explained by river flows and emigration timing (Model 4, Table 6-2). However, Model 3 is within 2 AIC units of Model 4, providing some evidence that variation in productivity among tributaries is not fully explained by the covariates.

Table 6-2. Comparison of the best-fit Ricker model (i.e., ΔAIC = 0) with models including tributary-specific covariate effects (Model 2), constant covariate effects among tributaries (Model 3), and no differences in productivity among tributaries after accounting for the covariates (Model 4).

Model	**Number of parameters**	**Deviance**	**AIC**	**ΔAIC**
1) Base model (no covariates)	9	101.8	119.8	44.0
2) Full model (tributary-specific covariate effects)	21	42.3	84.3	8.5
3) Constant covariate effects among tributaries	12	52.8	76.8	1.0
4) No productivity difference among tributaries	9	57.8	75.8	0.0

All covariates explained significant variation in age-0 emigrant abundance and none could be dropped from Model 4. When each covariate was dropped from Model 4, model fit worsened significantly (for mean Oct.-Nov. flow, $F_{1,33} = 14.8$, $P = 0.0005$; for maximum Dec.-Jan. flow, $F_{1,33} = 31.5$, $P < 0.0001$; and for mean emigration date, $F_{1,33} = 16.8$, $P = 0.0002$). Based on these findings, we used Model 4 to understand how covariates affect abundance of age-0 Fall Chinook emigrants. Without covariates, the base Ricker model explained 53.4% of the total variation in emigrant abundance, whereas the best-fit model with covariates explained 84.4% of the total variation (Figure 6-3).

Maximum Dec.-Jan. flow was negatively associated with emigrant abundance whereas mean Oct.-Nov. flow was positively correlated with emigrant abundance (Table 6-3, Figure 6-4). The magnitude of the slope parameter for Dec.-Jan flow (θ_{DJ}) is larger than the slope for Oct.-Nov flow (θ_{ON}), indicating that maximum flows during the egg incubation period (Dec.-Jan.) are associated with larger deviations from the spawner-emigrant curve than are flows during the spawning period (Oct.-Nov.; Table 6-3). In addition, mean emigration date was negatively associated with abundance, indicating that earlier migration dates increased productivity, in terms of the number of juveniles produced per spawner (Table 6-3).

Slope parameters can be interpreted biologically in terms of their effect on productivity. Since the Ricker model can be written as $R = (\alpha e^{\theta_j Q_j}) S e^{-\beta S + \varepsilon}$, the term $e^{\theta_j Q_j}$ estimates the proportional change in productivity at a given level of the covariate. For example, spates > 2 SD above average maximum flows during the egg incubation period (Dec.-Jan.) occurred in 1997 and in 2006 (Figure 6-1) and were associated with large negative residuals from the spawner-emigrant curves (Figure 6-2). Thus, for the Shasta River, the 2006 flood event (2.86 SDs above average)

is estimated to have reduced productivity to only 19% of that observed in a year with average maximum flows during the incubation period (i.e., exp(-0.579*2.86) = 0.19).

We also found that the mean date of emigration deviated considerably among streams from the overall mean of May 16 (Table 6-4), accounting for much of the observed difference in α estimated under the base model (Table 6-1). These findings suggest that residence time within tributaries influences total mortality and is consistent with the notion of fish experiencing a constant instantaneous rate of mortality with respect to time (Figure 6-5)

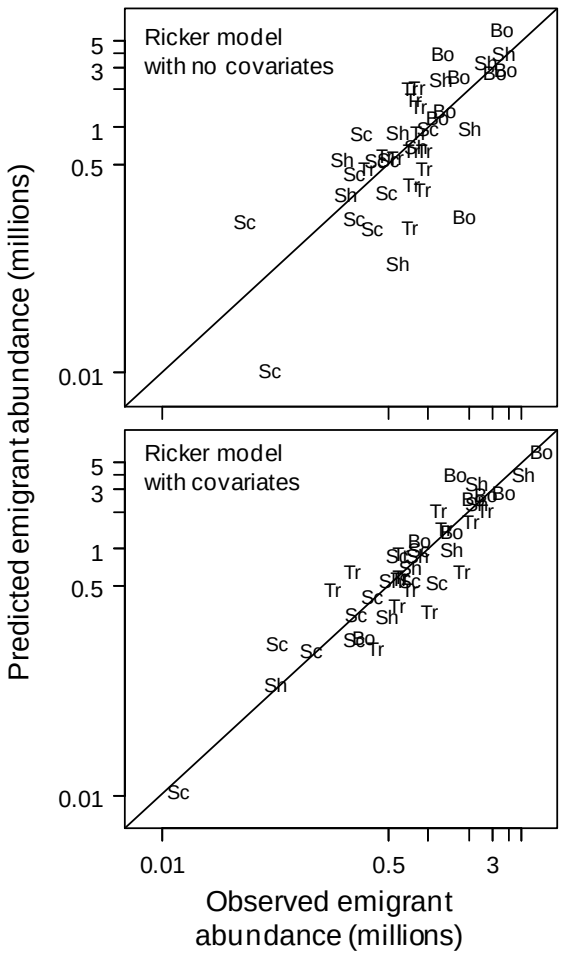

Figure 6-3. Observed versus predicted emigrant abundance for the Ricker model without covariates and the Ricker model including mean Oct.-Nov discharge, maximum Dec.-Jan. discharge, and mean emigration date of age-0 Chinook salmon. The 1:1 reference line shows where predicted abundance equals observed abundance. Symbols represent each tributary: Sc = Scott River, Sh = Shasta River, Tr = Trinity River, and Bo = Bogus Creek.

Table 6-3. Parameter estimates of the Ricker model fit simultaneously to spawner-emigrant data for three tributaries of the lower Klamath River.

Tributary or Flow Variable	**Parameter**	**Estimate**	**SE**	**95% Confidence Interval**
All rivers	α	171.8	24.9	123.0, 220.6
Scott River	β	1.31×10^{-4}	4.04×10^{-5}	2.10×10^{-4}, 5.13×10^{-5}
	S_{max}	7656	2371	3009, 12303
Shasta River	β	1.15×10^{-6}	4.68×10^{-5}	-5.28×10^{-5}, 1.31×10^{-4}
	S_{max}	25725	30953	-34943, 86393
Trinity River	β	4.16×10^{-5}	7.03×10^{-6}	5.54×10^{-5}, 2.79×10^{-5}
	S_{max}	24012	4053	16068, 31956
Bogus Creek	β	3.89×10^{-5}	2.64×10^{-5}	5.07×10^{-5}, 5.30×10^{-5}
	S_{max}	>500,000	>1,000,000	<0, >0
Mean Oct.-Nov. *Q*	θ_{ON}	0.4151	0.1079	0.204, 0.627
Max. Dec.-Jan. *Q*	θ_{DJ}	-0.5790	0.1032	-0.781, -0.377
Mean emigration date	θ_d	-0.0139	0.0034	-0.002, -0.007
	σ	0.298		

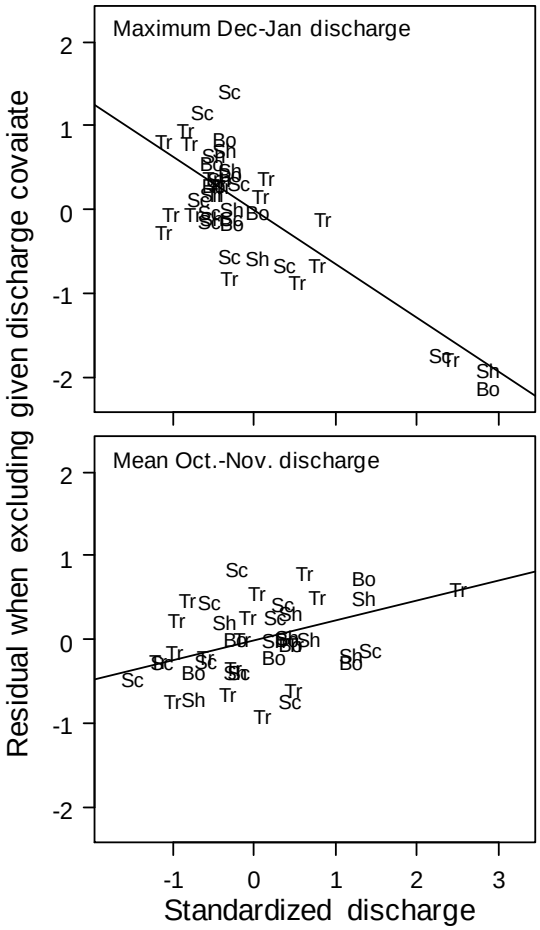

Figure 6-4. Residuals from the Ricker model plotted against standardized discharge for the Dec.-Jan. period and Oct.-Nov. period. Symbols represent each tributary: Sc = Scott River, Sh = Shasta River, Tr = Trinity River, and Bo = Bogus Creek.

Table 6-4. Mean emigration date for the period of record and productivity of each tributary (α) after accounting for the effect of differences in mean emigration date among tributaries.

Tributary	**Mean emigration date (Standard deviation)**	**Estimated productivity, α**
Scott River	May 24 (23.0 days)	153.1
Shasta River	April 2 (16.8 days)	314.2
Trinity River	June 27 (23.8 days)	95.5
Bogus Creek	April 10 (5.7 days)	281.6

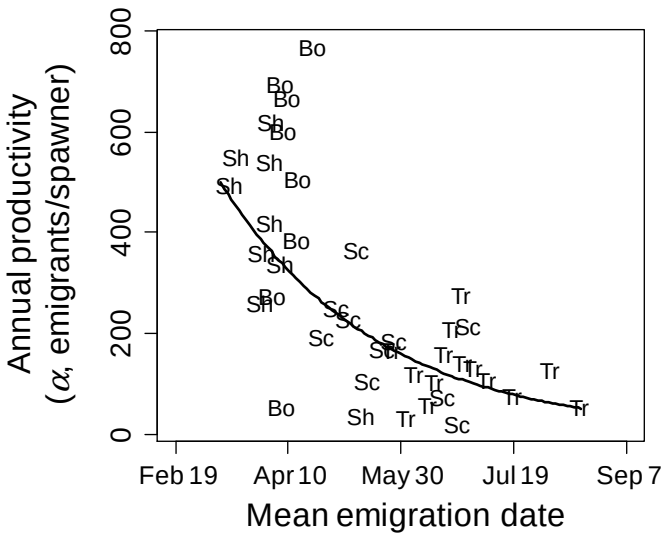

Figure 6-5. Estimated annual productivity as a function of mean emigration date. Symbols represent each tributary: Sc = Scott River, Sh = Shasta River, Tr = Trinity River, and Bo = Bogus Creek.

6.2.2.3 Predicting capacity and productivity

One major challenge in developing juvenile production curves for Lower Klamath River tributaries is the lack of emigrant abundance estimates for the Salmon River, and the lack of contrast in spawner abundance for tributaries with both spawner and age-0 emigrant data. For example, capacity, as estimated by S_{max} (the spawner level that generates the maximum number of age-0 juveniles, on average), was not significantly different from zero for the Shasta River and Bogus Creek (Table 6-3). Here we investigate the use of emigration timing data and watershed area to estimate productivity and capacity, respectively, for streams that lack sufficient empirical data with which to fully describe their spawner-emigrant relationship. To predict capacity, we investigated use of a habitat-based method for estimating S_{max} (Parken et al. 2006). For productivity, we investigated the use of emigration timing data as a means of estimating α for the Salmon River. Although the Salmon River lacks mark-recapture estimates of juvenile abundance, consistent trapping efforts have occurred, providing information about emigration timing. Our analysis above suggests that emigration timing can be used to infer the productivity for the Salmon River.

Parken et al. (2006) fit a model of the form:

$$S_{\max} = ax^b$$

where $S_{\max} = 1/\beta$ is the spawner abundance producing the maximum number of recruits as estimated by Ricker models fit separately to 25 Chinook salmon stocks, x is the watershed area (km^2) downstream of major migration barriers, and a and b are fitted coefficients. We used estimated coefficients for ocean-type Chinook salmon ($\ln(a) = 2.11$ and $b = 0.965$), which explained 84% of the variation in $S_{\max}$ for watersheds ranging in size from 176 km^2 to 7,611 km^2.

For the Scott and Trinity Rivers, $S_{\max}$ predicted from watershed area (Table 6-5) was larger than estimated from juvenile abundance data and fell just outside the upper bound of the 95% confidence interval (Table 6-3). For the Shasta River and Bogus Creek, we could not compare estimates of $S_{\max}$ between methods due to the wide confidence intervals for $S_{\max}$ (Table 6-3). Although the habitat-based model predicted larger $S_{\max}$ for the Scott and Trinity rivers, the relative difference among tributaries is similar to empirical estimates. For example, the habitat based model predicts that $S_{\max}$ of the Trinity River is 2.6 times larger than for the Scott River, while the Ricker model estimates $S_{\max}$ for the Trinity is 3.1 time larger than for Scott River. Furthermore, production curves using estimated α but predicted $S_{\max}$ from watershed area appeared consistent with the data, with exception of Bogus Creek (Figure 6-6). Spawning and juvenile production in Bogus Creek is largely supported by Iron Gate Hatchery, and observed production is therefore much higher than expected given the small size of this watershed (Figure 6-6).

Table 6-5. Predictions of $S_{\max}$, the spawner abundance producing maximum recruitment, using the habitat-based model of Parken et al. (2006) for tributaries of the Lower Klamath River.

Tributary	Watershed area (km^2)	Area upstream of migration barriers	Accessible Watershed Area	$S_{\max}$
Scott R.	2,077	0	2,077	13,114
Shasta R.	2,049	348	1,700	10,811
Trinity R.	7,604	1,865	5,739	34,968
Bogus Cr.	140	0	140	969
Salmon R.	1,937	0	1,937	12,260

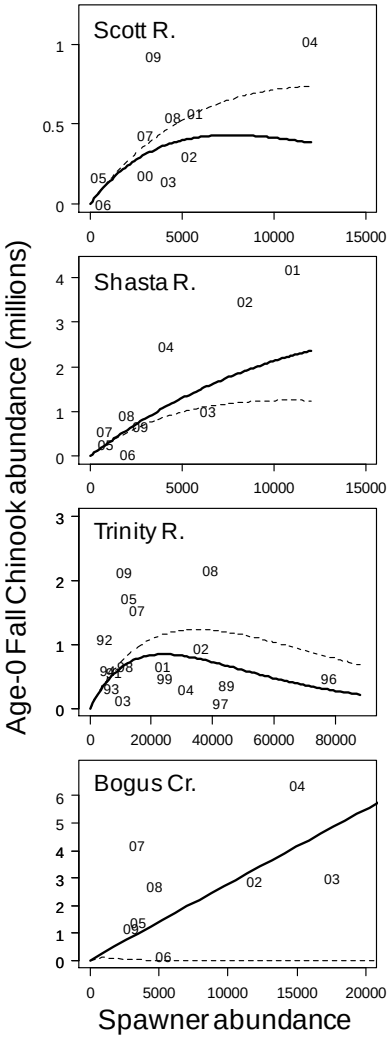

Figure 6-6. The estimated spawner-emigrant curve based on Model 4 compared to using estimates of S_{max} based on watershed area (dashed line) shown against spawner-emigrant data for four tributaries of the Lower Klamath River. Note the different x- and y-axis scales. Symbols represent year of emigration of juvenile salmon.

Although the habitat-based model may be used to predict capacity, estimates of productivity are also needed to construct spawner-emigrant relationships for the Salmon River. We suggest that emigration timing data could be used to predict productivity using parameter estimates from our previous analysis for the effect of emigration date on productivity (Table 6-3). Given an estimate of mean emigration date from a tributary, productivity can be estimated as

$$\alpha_{T,d} = \alpha_{d=\textbf{May 15}} \exp\left(\theta_d (\bar{d}_T - 136)\right)$$

where $\alpha_{T,d}$ is the productivity for a population with mean emigration date d in tributary T, $\alpha_{d = \text{May 16}}$ is the expected productivity for a mean emigration date of May 15 ($\alpha_{d = \text{May 16}}$ = 171.8 from Table 6-3), θ_d is the instantaneous rate of change in productivity with respect to emigration date (θ_d = -0.0139 from Table 6-3), $\bar{d}_T$ is the mean annual emigration date for tributary T (in Julian days), and 136 = May 16 in Julian Days.

Five years of juvenile trapping data for the Salmon River (2001 – 2005) were used to estimate the mean annual emigration date. The mean emigration date was estimated as the mean Julian week weighted by the fraction of fish captured each week. Over the five years, the mean emigration date was day 192 (July 11, standard deviation = 12 days). This emigration date yields a productivity estimate of 78.8, which is most similar to that estimated for Trinity River, which had the latest mean emigration date among the four tributaries in our Ricker model analysis (Table 6-4). The production curve using this productivity estimate along with $S_{\max}$ from Table 6-5 suggests a maximum emigration of about 350,000 juvenile Chinook salmon ($R_{\max}$) at a spawner level of 12,260 salmon ($S_{\max}$; Figure 6-7). Plotting predicted juvenile production relative to 30 years of observed escapements to the Salmon River suggests that spawning escapement under this particular model is below the capacity of the basin to produce juvenile emigrants (Figure 6-5). This finding is consistent with observations from other watersheds (e.g., the Shasta River) where spawner levels were too low to provide strong evidence of density dependence.

Although we used point estimates of productivity and capacity parameters to generate the production curve for the Salmon River, there is considerable uncertainty in these estimates. When used for simulation, uncertainty will be incorporated by sampling productivity, capacity, and mean emigration dates from a distribution of possible values. Year-to-year variation in mean emigration dates, and standard errors of parameters from our models and Parken et al.'s analysis provide the basis for incorporating uncertainty into predictions of juvenile salmon emigrations from tributaries into the Lower Klamath River.

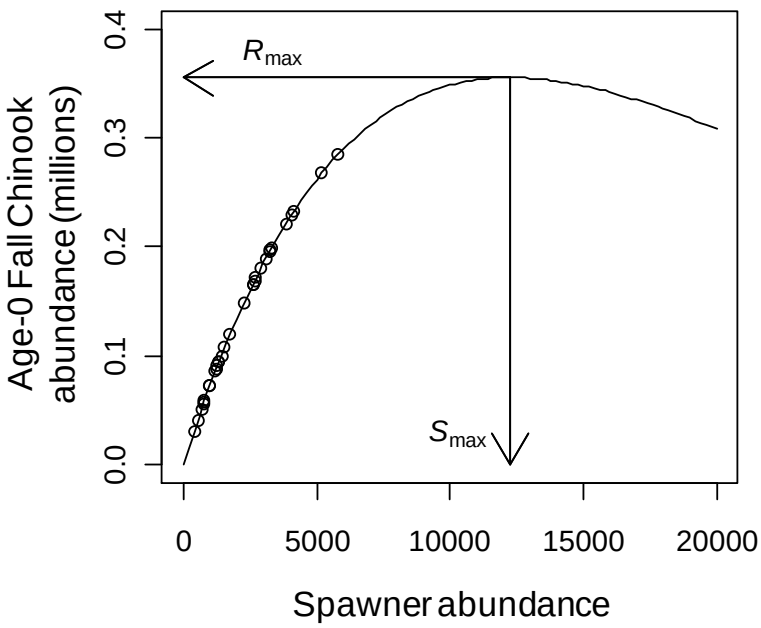

Figure 6-7. Spawner-emigrant curve for the Salmon River based on using watershed area to predict S_{max} and mean emigration date of juveniles to predict productivity (i.e., α = slope at the origin). Circles show predicted juvenile abundance based on observed estimates of spawners from 1978 – 2008.

6.2.3 KBRA habitat restoration actions and their effects on productivity

Part III of the Klamath Basin Restoration Agreement (KBRA) provides for establishment of a Fisheries Program which includes provisions and funding for development of a Fisheries Restoration Plan. Phase 1 of the Fisheries Restoration Plan is intended to establish habitat restoration priorities during the first 10 years of the agreement prior to the actual start of dam removal. Substantial funds are targeted for aquatic and upland habitat restoration projects within the Shasta, Scott and Salmon rivers and those smaller tributary streams that provide important habitat for anadromous salmonids which also includes Bogus Creek (KBRA 2010; Appendix C-2).

Since the Fisheries Restoration Plan has yet to be developed, specific restoration projects within the each of the tributary streams currently included in the model have yet to be identified. To develop a list of potential habitat restoration actions, local federal and state agency and tribal biologists formed a collaborative working group to identify habitat restoration actions that they believed were necessary to improve conditions for anadromous salmonids within the context of the KBRA. This collaborative working group included participants from the National Marine Fisheries Service, U.S. Fish and Wildlife Service, U.S. Forest Service, California Department of

Fish and Game, Yurok Tribal Fisheries Department and the Karuk Tribe's Department of Natural Resources. Stillwater Sciences assisted the working group in this process by providing additional expertise, developing the list of habitat restoration actions, estimating costs for implementing those actions, and assimilating comments and incorporating additional habitat restoration actions that were identified and prioritized by the work group. Stillwater Sciences (2010) provides a full description of this process as well as a summary of all of the KBRA related habitat restoration actions that were identified for the Klamath River and tributary streams downstream of Iron Gate Dam.

Habitat restoration actions were specifically identified for the three major tributary streams that are incorporated into the fish production model under the KBRA. These include the Shasta, Scott, and Salmon rivers. The Trinity River, which is the largest tributary to the Klamath entering at river mile 44, is excluded from the KBRA because a major watershed restoration program is already in progress in that watershed. Specific habitat restoration projects were not identified for smaller tributary streams similar in size to Bogus Creek; rather, these smaller tributaries were combined into larger geographic areas. Table 6-6 provides a summary of the dollar amounts that would become available for aquatic and upland restoration actions within the Shasta, Scott and Salmon watersheds under the KBRA.

Table 6-6. Summary of the cost estimates for restoration actions in the Shasta, Scott and Salmon rivers as described in Appendix C-2 of the KBRA.

Tributary	Aquatic Habitat Restoration	Upland Habitat Restoration	Total
Shasta R.	$23,625,000	$1,680,000	$25,305,000
Scott R.	$21,750,000	$3,410,000	$25,160,000
Salmon R.	$4,320,000	$5,560,000	$9,880,000

The types of aquatic habitat restoration actions that were identified and prioritized by the working group for the Shasta, Scott, and Salmon rivers include a range of activities, some of which have a greater certainty of being implemented, while others may be controversial in nature and will likely require private landowner cooperation. Therefore, implementation of these types of actions is less certain. Regardless of these uncertainties, for purposes of this model we assume that all of the habitat restoration actions identified will be implemented by 2021 as described in the KBRA. Tables 6.7, 6.8, and 6.9 provide a summary of the high priority aquatic and upland habitat restoration actions that were identified for the Shasta, Scott, and Salmon rivers by the working group, respectively.

Table 6-7. Summary of potential habitat restoration actions for the Shasta River Watershed developed by the collaborative work group comprised of federal, state, and tribal representatives.

Action	Description	Number or Length of restoration Action	Cost Estimate
Placement of Large Wood	Strategic placement of large wood and engineered log jams to improve instream habitat complexity, create off-channel habitat, and improve floodplain connectivity.	23 Miles (30 log jams/mile)	$1,978,000
Stream Channel and Floodplain Restoration	Restoration of stream channels and floodplains to recreate complex meandering floodplains with off-channel habitats and mature native riparian forest communities and improve instream habitat diversity.	0.7 Miles	$1,890,000
Impliment Water Conservation Actions	Identify and implement improved tailwater reduction and irrigation delivery systems to improve instream flow and water quality, particularly water temperature.	Could include a variety of project types	$2,000,000
Purchase of Conservation Easements and/or Water Rights	Stragically purchase conservation easments and/or water rights from willing sellers to improve habitat and insteam flow, maximize cold water refugia, and improve fish passage conditions.	Approximately 3,500 acrers of conservation easment, and 1,500 acers of land purchase	$14,000,000
Improve Fish Passage	Identify, prioritize and remove all fish passage barriers to comply with NOAA's Guidelines for Salmonid Passage at Stream Crossings	Improve fish passage at 5 existing irrigation diversions	$3,750,000
Riparian Habitat Easement Program	Expand riparian habitat easement programs; identify priority floodplain areas that provide setback opportunities in cooperation with landowners; employ voluntary riparian easement programs to lease/acquire riparian easements prioritized for restoration	0.9 Miles	$922,500
Cattle Exclusion Projects	Exclude or manage cattle from riparian areas to allow for revegetation and reestablishment of riparian forest. Provide protection to known spawning areas and redds by excluding livestock and mechanized equipment, and by enhancing adjacent habitat for juvenile holding and rearing. Could include fencing, or other methods.	232,320 feet	$717,869
		Total =	$25,258,369

Table 6-8. Summary of potential habitat restoration actions for the Scott River Watershed developed by the collaborative work group comprised of federal, state, and tribal representatives.

Action	Description	Number or Length of restoration Action	Cost Estimate
Placement of Large Wood	Strategic placement of large wood and engineered log jams to improve instream habitat complexity, create off-channel habitat, and improve floodplain connectivity.	19 Miles (30 log jams/mile)	$1,634,000
Stream Channel and Floodplain Restoration	Restoration of stream channels and floodplains to recreate complex meandering floodplains with off-channel habitats and mature native riparian forest communities and improve instream habitat diversity. May include construction of levee setbacks in some locations for floodplain restoration in areas that are heavily degraded by historic disturbance.	2.26 Miles	$6,102,000
Purchase of Conservation Easements and/or Water Rights	Strategically purchase conservation easments and/or water rights from willing sellers to improve hydraulic function and habitat conditions for aquatic resources. Use results from groundwater studies and SWRCB forward-looking infrared (FLIR) studies to identify groundwater-cold water spring relationships, and to focus restoration activities on reaches with detected cold water presence or cold water accretion.	Approximately 3,500 acrers of conservation easment, and 1,500 acers of land purchase	$14,000,000
Cattle Exclusion Projects	Exclude or manage livestock from channels, narrow channels, and stabilize and protect channels.	274,560 Feet	$848,390
Reduce Road Related Erosion	Monitor and treat road-caused sediment discharges from public and private roads in the Scott River Basin; use the California Salmonid Stream Habitat Restoration Manual Scott River TMDL Implementation Plan, and the 5 Counties Road Maintenance Manual for guidance.	141 Projects	$2,353,995
Restore Natural Fire to the Landscape	Restore natural fire regime through thinning, prescribed burning, and fire use on fire prone watersheds, especially those watersheds that support salmonids.	1,050 Acres	$207,900
		Total =	$25,146,285

Table 6-9. Summary of potential habitat restoration actions for the Salmon River Watershed developed by the collaborative work group comprised of federal, state, and tribal representatives.

Action	Description	Number or Length of restoration Action	Cost Estimate
Placement of Large Wood	Strategic placement of large wood and engineered log jams to improve instream habitat complexity, create off-channel habitat, and improve floodplain connectivity.	31.5 Miles (30 log jams/mile)	$2,709,000
Stream Channel and Floodplain Restoration	Restoration of stream channels and floodplains to recreate complex meandering floodplains with off-channel habitats and mature native riparian forest communities and improve instream habitat diversity.	0.6 Miles	$1,620,000
Restoration of Riparian Zones	Improve existing riparian zones through plantings, release of conifers, and control and removal of non-native competitors	370 Acres	$1,404,160
Restore Natural Fire to the Landscape	Restore natural fire regime through thinning, prescribed burning, and fire use on fire prone watersheds, especially those watersheds that support salmonids.	10,000 Acres	$1,980,000
Reduce Road Related Erosion	Decommission and upgrade roads and decrease road densities in areas with high risk for failure.	59.5 Miles	$2,380,000
		Total =	$10,093,160

Specific habitat restoration actions have not been developed for Bogus Creek and most of the watershed that is accessible to Chinook salmon is under private ownership. Although some habitat restoration actions and water conservation projects are currently planned, we anticipate that these actions will benefit coho salmon and steelhead trout to a much greater degree than fall Chinook salmon. In addition, because of its proximity to Iron Gate Hatchery, large numbers of hatchery origin Chinook salmon stray into Bogus Creek each year and this further complicates development of stock recruitment relationships in this watershed. Therefore, we assume that KBRA habitat restoration actions will have negligible affects to fall Chinook salmon production in that watershed.

A challenge for the fish production model is to describe how implementation of future KBRA habitat restoration actions might affect either the productivity (α) or capacity (β) parameters used within the Ricker Model for fall-run Chinook salmon for each of the five tributary streams currently included as nodes for SALMOD II. Restorations actions identified thus far would most influence habitat quality, rather than quantity. Therefore, we envision that productivity (α) will increase over time as restoration actions are implemented, whereas capacity would remain static (β). Many of the habitat restoration actions, such as placement of large wood, are anticipated to provide almost immediate benefits to salmon production, while others actions will likely require decades of maturation (restoration of floodplains and riparian forests) before benefits to salmonid habitats are fully realized.

Therefore, for purposes of the model we assume that substantial improvements in salmon habitat will be achieved in the Shasta, Scott and Salmon rivers beginning in 2021, when construction of habitat restoration projects if projected to be complete. These improvements are assumed to result in a substantial increase in productivity almost immediately. As these and other restoration projects mature we anticipate that further increases in productivity will continue gradually over the duration of the 50 years until such point that total productivity has reached equilibrium with improved habitat conditions (Figure 6-8).

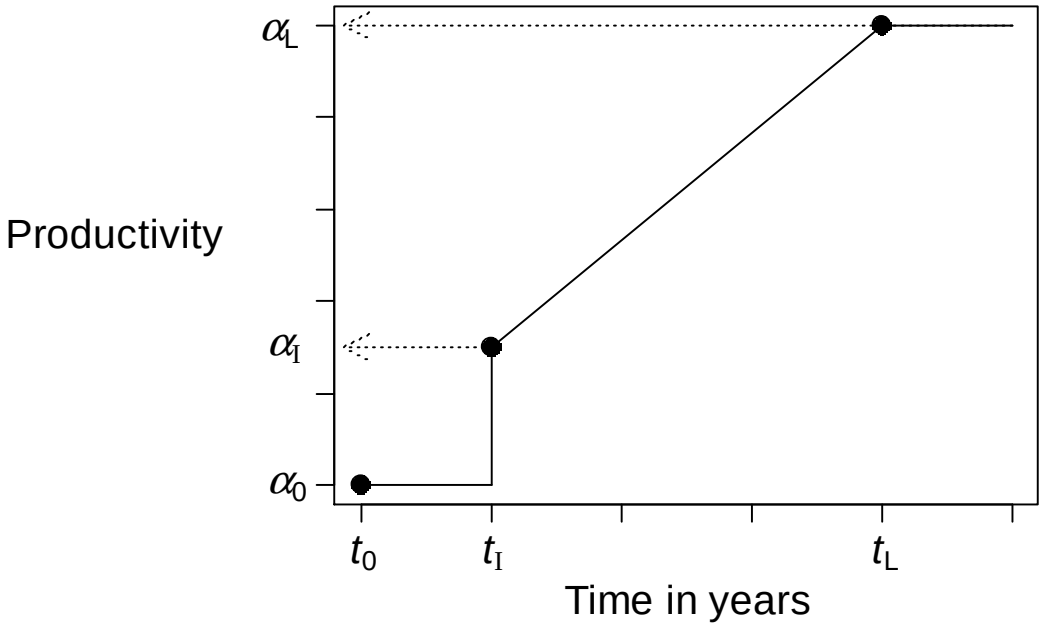

Figure 6-8. Conceptual model illustrating how KBRA activities in lower Klamath River tributaries are hypothesized to improve stream productivity. Productivity is defined in terms of *a*, the number of juveniles produced per spawner at low spawner abundance. KBRA activities are expected to result in both "immediate" improvements in productivity (a_I) t_I years after implementation and long-term improvements (a_L) that gradually increase productivity until t_L years after implementation. Increases in productivity are defined relative to the baseline productivity (a_0) under current conditions (e.g., $a_L = 1.5\ a_0$).

In addition to actions anticipated under the KBRA, there is a host of other restoration programs that are currently active within the Klamath River basin and we acknowledge that these activities may continue into the future regardless of the outcome of the Secretarial Determination process.

It is entirely possible that these actions may also result in gradual improvements to productivity over time. However, the purpose of the FPM is to describe the benefits of the KBRA and KHSA (dam removal) and the relative benefits that these two agreements may provide to fall Chinook salmon. Therefore, although existing restoration efforts may gradually improve habitat conditions into the future, at this time we have chosen to assume that current conditions will persist into the future for this analysis.

6.3 MODEL ASSUMPTIONS

6.3.1 Assumptions of Spawner-Emigrant Analysis

- Because age-0 Chinook salmon of both Fall and Spring run could not be distinguished in the Trinity River, we adjusted total abundance to an estimate of Fall run abundance by using the fraction of total escapement comprised of the Fall run. Thus, we make the assumption that relative abundance of age-0 Fall Chinook in the Trinity River was directly proportional to fraction of the total Chinook escapement comprised of the Fall run.
- We excluded flow during February – June period from the analysis, thereby making the implicit assumption that river flows during this period have little influence on abundance. We excluded flow covariates during this period for two reasons. First, the logarithm of Dec.-Jan. maximum flows was positively correlated with log-mean flows in Dec.-Jan, Feb.-Mar., and Apr.-May periods ($r > 0.85$). Thus, maximum Dec.-Jan. flows capture much of the information contained in river flows during latter periods. Second, once fish begin emigrating from tributaries, river flow affects only that fraction of the population remaining within each river. Since fish began emigrating from tributaries as early as mid-February, and emigration timing varied among streams, it is difficult to quantify population-level effects due to mean tributary flows after emigration begins. In contrast, flows during spawning (Oct.-Nov.) and incubation (Dec.-Jan.) affects the entire population within all tributaries, providing a better understanding of the influence of river discharge at the population level.

6.3.2 Assumptions of Watershed Area model for predicting capacity

- All watersheds in the analysis were north of the Klamath River, ranging from Oregon through Alaska. We assume that the relationship holds for watersheds outside of this range.
- The model estimates S_{max} for the "average" watershed and unique characteristics that may increase or decrease capacity are not captured.
- The model was used to estimate the spawner levels that maximize recruitment to adulthood rather than recruitment to juvenile life stages. We therefore assume S_{max} as

predicted from the watershed model is spawner level that maximizes age 0-emigrant recruitment.

6.3.3 Assumptions about emigration timing and size at emigration

- We plan to use historical emigration timing and size-at-emigration for population projection into the future. This approach assumes emigration timing and size-at-emigration will remain unchanged in the future.

6.4 MODEL DISCUSSION

Our analysis provides insight into the effects of river flows on recruitment of juvenile salmon. These findings will be incorporated into the life-cycle simulation model to understand the effect of climate-driven river flows on recruitment of juvenile salmon. For example, by incorporating effects of mid-winter spates on productivity, the recruitment of juveniles in tributaries will be sensitive to climate-driven changes in the frequency, magnitude, and timing of flood events.

One major hurdle that remains is translating our findings from observed flows to simulated river flows, and from the lower Klamath Basin to the upper basin. First, only discharge of the mainstem Klamath River has been simulated under climate change, and simulated tributary flows are lacking. Second, river flows are simulated on a monthly time step, consistent with output of global climate change models (GCMs), and then disaggregated to a daily time step. At this point, it is unclear whether simulated daily maximum flows adequately represent peak daily flows in observed data. Third, due to differences in geomorphic characteristics between the upper and lower basin, we are actively debating alternative approaches for inferring flow-related effects on productivity in the upper basin from our findings in the Lower Klamath tributaries. While timing of peak flows between the upper and lower basin are similar, presumably due to basin-scale weather events, relative peak flows in tributaries of the upper basin are of lower magnitude than in the lower basin.

Our current plan for implementing flow effects on productivity in the simulation model involves mapping observed flow data in different tributaries to an index site in the mainstem Klamath River. First, mean discharge during periods of interest (spawning and incubation) will be used to drive production, rather than relying on maximum daily flows from simulated data. We found that maximum daily discharge during the spawning period (Dec. – Jan.) was highly correlated with mean discharge (r = 0.98) of tributaries, so the mean should capture variation in maximum daily flows. Second, we will relate tributary flow covariates to a discharge gauging station on the mainstem Klamath River (e.g., Klamath River at Seiad). Given the high correlation of flows among tributaries (Figure 6-1), we expect that tributary-specific flows will be strongly related to

flows of the Klamath River. Regression models can then be used to calculate discharge of the tributaries given simulated discharge on the mainstem Klamath River. Uncertainty in these regression models will be carried forth as stochasticity in the simulation model. Last, discharge data from the upper basin tributaries will be compared to lower basin tributaries to develop an appropriate translation of flow effects on productivity in the upper basin. One alternative is to develop flow covariates for all tributaries that scale appropriately with the estimated stock-recruitment parameters in the lower basin. A second alternative is to directly scale the productivity parameters from the lower basin to account for differences in geomorphic characteristics between upper and lower basin watersheds. For example, lower relative peak flow in the upper basin suggests that a flood of given standardized magnitude would have less effect on recruitment in upper basin tributaries; i.e., a shallower slope. Thus, differences in relative magnitude of peak flows could be used to adjust the slope from the lower basin to an appropriate value for the upper basin.

In addition to abundance of juveniles entering the mainstem Klamath River from tributaries, SALMOD II requires specification of temporal (weekly) and life-stage (fry and juvenile) distributions. Weekly abundance and size estimates from trapping data provide the information needed to specify these distributions. We will use annual variation in the mean and standard deviation of emigration time and size-at-emigration to parameterize distributions from which these values will be drawn for the simulation. Thus, while juvenile abundance will be sensitive to the environment through river flows and emigration timing, variation in emigration timing and size-at-emigration will rely solely on historical empirical data.

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7. OCEAN PHASE HARVEST AND ESCAPEMENT (HENDRIX & LINDLEY)

7.1 BRIEF DESCRIPTION OF MODEL

The ocean component of the model incorporates mortality from entry in the estuary through return to the estuary as a mature adult. Survival from the estuary to age 3 is incorporated in the model as a Normal random variable with mean 0 and range of variability that is consistent with historical early ocean survival on the Klamath River. We use the Klamath Harvest Rate Model (KHRM) that was developed by NMFS SWFSC (Mohr in prep) and calculates all sources of mortality starting at age 3. Harvest is modeled using the KHRM, a spatially and temporally aggregated version of the Klamath Ocean Harvest Model (KOHM). The KOHM, described in detail by Prager and Mohr (2001) and Mohr (in prep) takes as input the abundance of age 3, 4 and 5 Chinook in the ocean on September 1, and projects this population through the processes of natural mortality, ocean fishing, maturation and entry to the river, and river fisheries (Figure 7-1). Mature fish that avoid impact by river fisheries are passed on to the river migration model, and immature survivors are advanced one year in age and subjected to the harvest model in the next year.

7.2 MODEL INPUTS AND OUTPUTS

The ocean model takes the numbers of juveniles entering the estuary from each source population as the input. The first part of the model applies a mortality rate to Type I Chinook leaving the estuary until the beginning of their third year, when they are passed to the KHRM (the KRHM increments each year on September 1). The KHRM determines the fate of age 3, 4, and 5 year olds. The fates are: 1) natural mortality over the winter, 2) harvest in one of the fisheries over the summer, 3) maturation and return to the Klamath River; or 4) remain in the ocean. All age 5 Klamath River fall Chinook mature and return to the river. The outputs of the ocean and harvest component of the model is the abundance of mature adults in the estuary by age and source population, and the harvest in each year. The mature adults that escape the fishery then begin their migration up the Klamath River.

7.3 MODEL ASSUMPTIONS

For the early ocean survival portion of the model, we derived an estimate of the proportion of Iron Gate Hatchery (IGH) and Trinity River Hatchery (TRH) survival attributable to a common source of variability (described below); therefore, we assume that any variability common to both IGH and TRH is due to the estuary and ocean portion of their overlapping outmigration.

The major assumptions in the KHRM are 1) that the biological parameters (e.g., mortality rates, maturation rates, and out of basin straying rates) in the model are accurate, 2) that the fishery parameters (i.e., shaker mortality, gear vulnerability, etc) are accurate, and 3) that the model structure adequately reflects the harvest rate decision process (i.e., the *F* control rule is an adequate function for translating expected abundance to fishing effort).

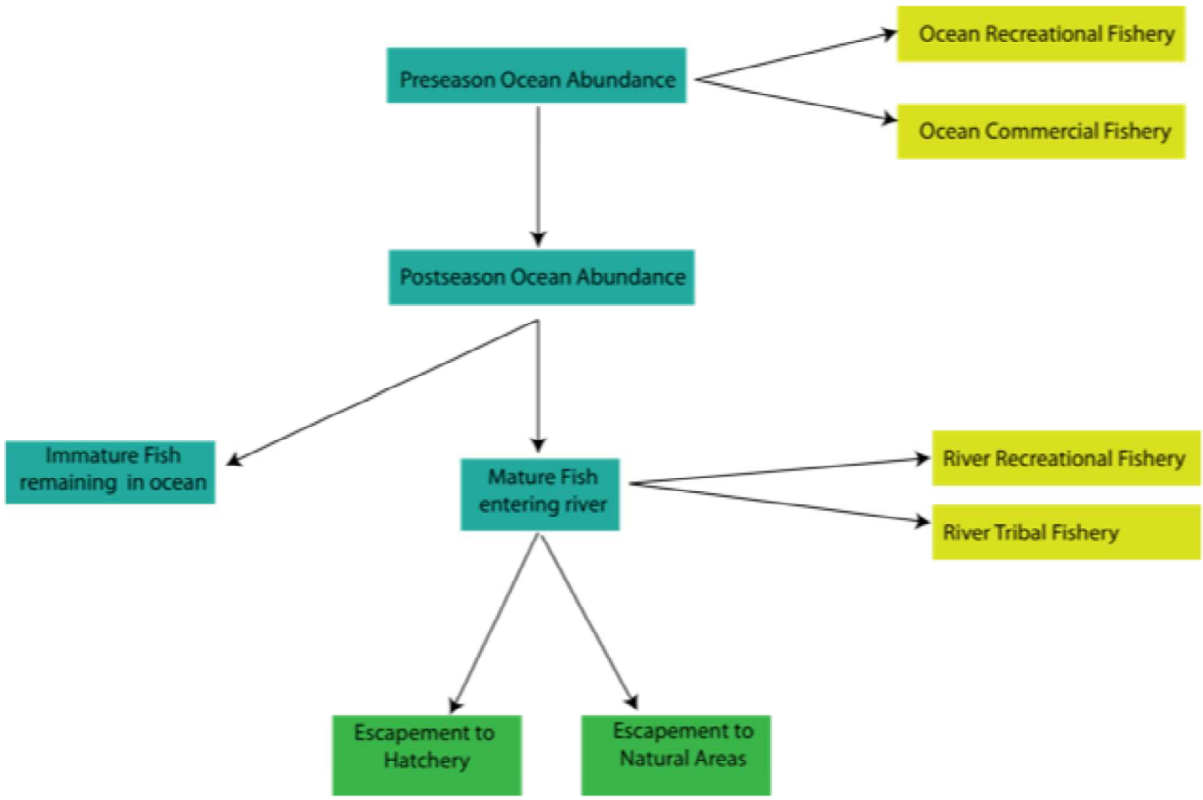

Figure 7-1. Movement of salmon through the Klamath Harvest Rate Model.

The distribution of the pre-season abundance among fates is controlled by management, fishery and biological parameters. The management parameters include the spawner reduction rate and the harvest allocations. The fishery parameters include age and sector-specific vulnerabilities, proportions legal (young fish are not all large enough to retain), shaker mortality rates (hook-and-release), and drop-off mortality rates (mortality due to contacting gear but not associated with harvest or intentional release). The biological parameters include age-specific ocean survival, maturation, and the proportion of spawners using natural areas. In our use of the model, we know the proportions of fish of various origins (specific hatcheries and natural areas) at each age, and assume that they do not differ in their management or biological parameters and that they return to their origin.

7.4 MODEL DISCUSSION

7.4.1 Early Ocean Survival

The Salmon Technical Team (STT) of the Pacific Fishery Management Council (PFMC) conducted an analysis of the stock recruitment relationships for the grouped stock of Klamath and Trinity wild fall Chinook (STT 2005). The recruitment was defined as the number of fish at ages 3, 4, and 5 that would have been expected to spawn in the absence of fishing. Two models were hypothesized: Model 1) a Ricker model in which recruitment was a function of parent stock size; and Model 2) a Ricker model in which recruitment was a function of parent stock size and an index of freshwater and nearshore survival.

The model including the survival index provided a better explanation in the patterns of stock recruitment (STT 2005). This result suggested that the hatchery derived survival index could be used to explain annual variability in the production of natural stocks. The patterns in log survival rate estimates from release to age 2 were similar between IGH and TRH for brood years 1979 to 2000 (Figure 7-2), which suggests that factors common to both rivers are responsible for much of the variability in the survival index. A possible source of the common signature in IGH and TRH fish is experiencing common estuary and early ocean survival.

The STT conducted a correlation analysis between survival rates of CWT release groups and freshwater flows during outmigration. The strongest relationship was found between releases from IGH and flows in months following release. The STT (2005) found that the correlation was not significant and the R^2 were 0.25 or less. This result is not surprising given the amount of variability attributable to factors common to both TRH and IGH; however, it does suggest that portions of the variability in the IGH survival can be attributed to flows during outmigration.

A second correlation analysis was conducted between Model 1 residuals (recruitment a function of spawner stock size only) and flows during both the fall and winter by STT (2005), and the residuals were significantly correlated with stream flow during migration and spawning. This is consistent with the analysis conducted by Dr. Russell Perry (Chapter 6) in which December flows were important covariates for describing annual variability in juvenile production in Bogus Creek, Scott River, Shasta River, and Trinity River.

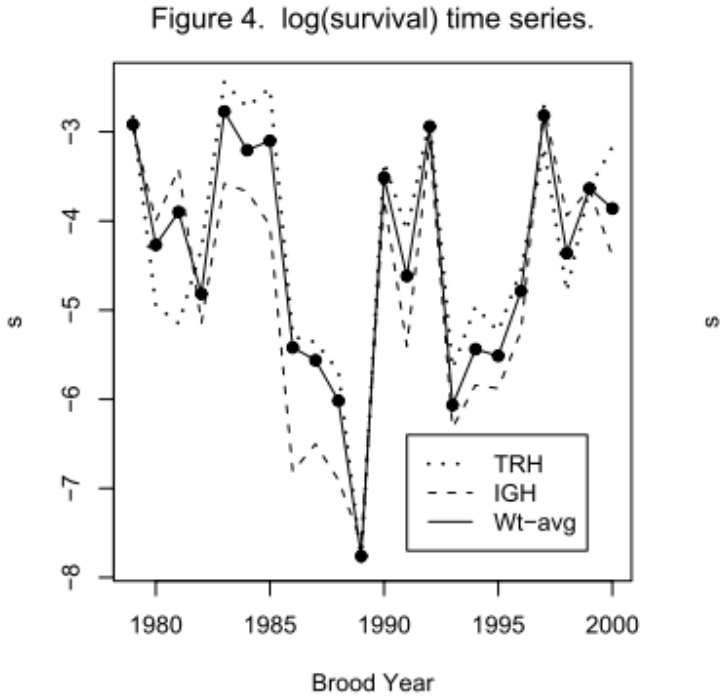

Figure 7-2. Log survival rate (s) from release in May to August for fingerling releases in brood years 1979 to 2000 at Trinity River Hatchery (TRH) and Iron Gate Hatchery (IGH). A weighted average (Wt-avg) using natural spawner abundances was computed by the Salmon Technical Team of PFMC. Original Figure 4 from STT (2005).

We quantified the amount of variability in log survival (s) attributable to the common estuary and ocean by fitting a random effects model:

$$s_{i,j} = \beta_i + \gamma_j + \varepsilon_{i,j},$$

where $s_{i,j}$ is the log survival rate in year j, hatchery i = 1,2, β_i = the average log survival rate for hatchery i, γ_j is the random effect for year j, and $\varepsilon_{i,j}$ is the residual error for hatchery i in year j. The random effects model was fit in R using the package lme4 (R Core Development Team 2010). The results of fitting this model provided an estimate of the average IGH log survival rate (β_{IGH}), the difference in survival from IGH by TRH (β_{TRH}*), an estimate of the variance on the random effect for each year (common variability attributable to the estuary and ocean) and residual variability (Table 7-1).

Table 7-1. Parameter estimates from random effects model of Iron Gate Hatchery (IGH) and Trinity River Hatchery (TRH) log survival rate from release to age 2 for brood years 1979 to 2000.

Model Term	Fixed or Random	Estimate
β_{IGH} (Intercept)	Fixed	-4.7668 (SE = 0.299)
β_{TRH}*	Fixed	0.4687 (SE = 0.185)
Year	Random	Variance = 1.59
Residual	Random	Variance = 0.379

*Note: the β_{TRH} term is the change relative to the Intercept

The random effects model indicated that the mean log survival rate of TRH was higher than IGH releases by 0.469 for fingerling releases from 1979 to 2000 (Table 7-2). Further, the majority of the variability is in the Year random effect, which can be characterized by a Normal distribution with mean of 0 and variance of 1.59 (i.e., $\gamma_j \sim N(0,1.59)$. The residual error attributable to annual differences unique to each hatchery can be characterized with a Normal distribution with mean of 0 and variance of 0.379 (i.e., $\varepsilon_{i,j} \sim N(0,0.379)$. Note that in the random effects model, the amount of total variance attributable to the Year random effect is approximately 81% (1.59/[1.59 + 0.379]).

We are also interested in the residual variability (attributable to annual variability specific to each hatchery), but not for the ocean portion of the model. The residual variability for IGH may provide some insights into patterns in survival that can be attributed to Klamath River outmigrant conditions (e.g., Klamath River flows during outmigration, temperatures during outmigration, etc.). We have yet to analyze the residuals for such patterns, however.

The STT (2005) stock recruitment analysis defined recruitment as the number of fish at ages 3, 4, and 5 that would have been expected to spawn in the absence of fishing. The data provided in STT (2005) include an estimate of the number of natural fall Chinook at age 3 for each brood year. We are in the process of using these data to construct a stock recruitment relationship from spawner to age 3 and incorporating an indicator of early ocean survival that is slightly different from the STT (2005) survival index. Our analysis uses a linear model for the stock recruitment relationship (i.e., the linear form of the Ricker stock production equation) with a covariate for ocean effects. The annual ocean effect covariate is modeled as an uncertain value (i.e., errors in variables regression). We use a second stage in the regression which has the same form as the analysis performed above, namely the early ocean survival is a random effects component to the observed Iron Gate and Trinity hatchery survival rates. The results of this analysis will be used

to quantify the effects of estuary and ocean survival on the stock production relationship from spawner to age 3.

7.4.2 Harvest Model

The mathematics of the KHRM are fairly simple and straightforward, although conservation constraints can complicate things to some extent. The first step of the projection is to determine the overall spawner reduction rate (SRR), which is a function of pre-season ocean abundance. Abundance is known exactly in our model but estimated in reality.

The level of harvest is determined by a fisheries control rule, (*F*-control rule) that can be defined explicitly to test alternative fisheries management approaches (Figure 7-3). The *F* control rule specifies the allowable fishing mortality rate as a function of the natural area spawners in the absence of fisheries. The form of this function is under revision at the moment, and our version of the KHRM includes options for using the existing control rule that varies the SRR such that escapement will be about 40,000 spawners unless this can't be achieved in the absence of fishing or if other constraints limit fishing (in which case the escapement could be higher). The Pacific Fisheries Management Council is considering other control rules that would allow some fishing when preseason abundance is lower than the threshold that would allow fishing under the current rule. We include two possible versions of this new control rule.

Once the SRR is determined, the catch and impacts are apportioned among fishing sectors--ocean commercial, ocean recreational, river tribal, and river recreational. The shares of each fishery can be varied, but are typically governed by a 50-50 split between the river tribal and all other fisheries, and a 20% share of the non-tribal harvest allocated to river recreational sector.

Complications arise because of several potential constraints. One constraint, intended to protect ESA-protected California Coastal Chinook, limits age 4 harvest rates to 16%. Another constraint is that the SRR cannot exceed 66%, no matter how large the preseason abundance. Finally, while the river harvest is allocated 20% of the catch, the fishery is not capable of achieving this harvest rate when the river run is over a certain size, and subsequently escapement may be larger in practice than would otherwise be allowed. In the model, all of these constraints can be adjusted, although we use the values typically used by the PFMC in their annual assessment cycle.

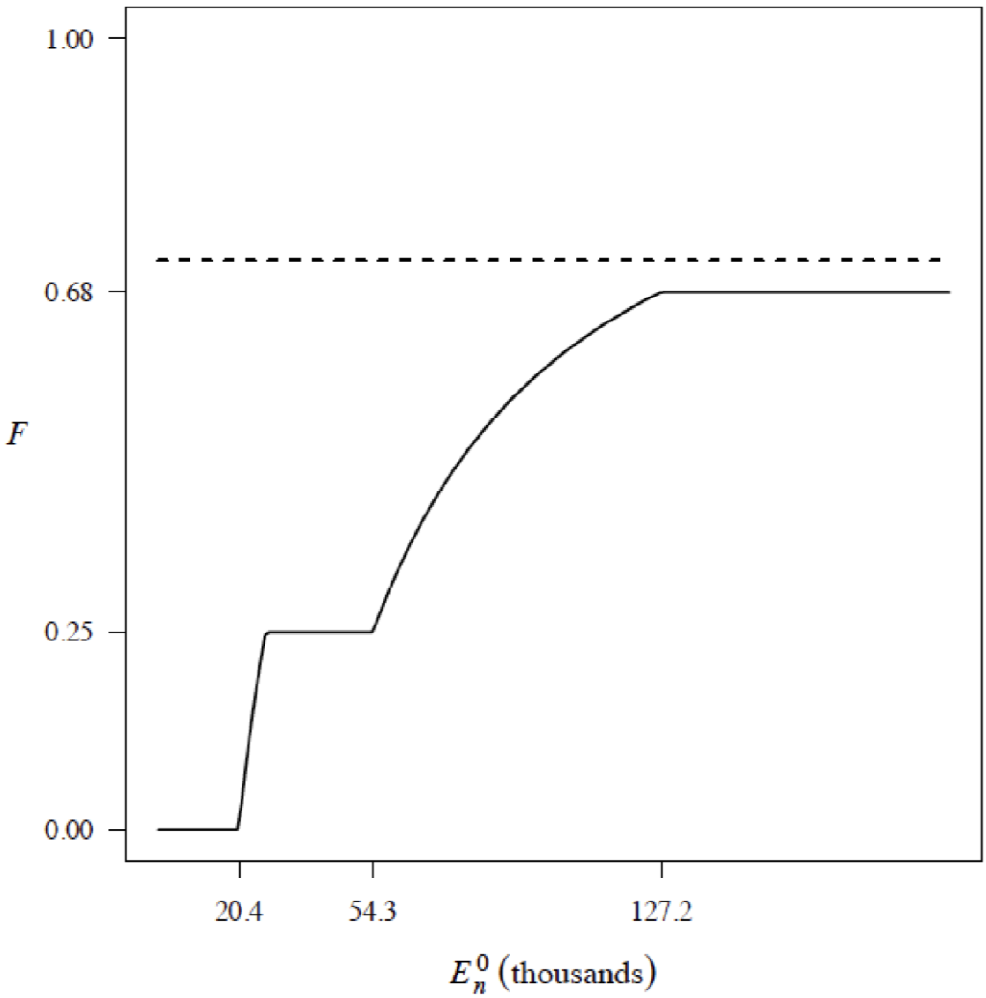

Figure 7-3. The spawner reduction rate (*F*) is a function of pre-season ocean abundance of three, four, and five year-old fish (E^0_n). *F* is capped at 0.68, which is 95% of the *F* that would yield the spawning biomass that generates maximum sustainable yield

7.4.3 Model History

The initial model formulation is described in Prager and Mohr (2001). Through the Pacific Fishery Management Council process, the KOHM model has been used extensively for evaluating alternative harvest management scenarios. The KHRM has all of the functionality of the KOHM with some spatial simplifications (Mohr in prep) to allow application to life cycle modeling such as the FPM. The KHRM has only recently been developed out of a need for a simpler version of the KOHM for analyses. The FPM is the first implementation of the simpler KHRM model.

7.4.4 Model Applications Elsewhere

The Pacific Fishery Management Council uses the KOHM to predict fishing impacts on and harvests of Klamath River fall Chinook in the annual assessments that set the regulations on this fishery. The KOHM is used extensively for annual forecasts of harvest among ocean commercial, ocean recreational, tribal and sport fishery harvests (e.g., KRTT 2010).

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