

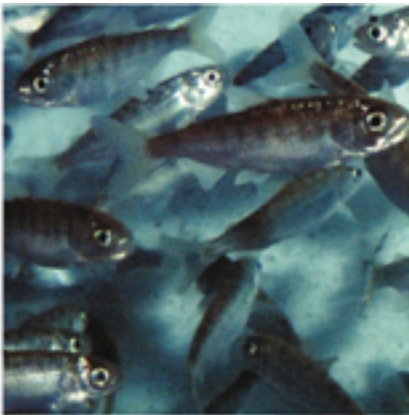
# Yakima/Klickitat Fisheries Project Monitoring and Evaluation

## Initial Review of Models with Potential to Predict Annual Spring Chinook Smolt Production in the Yakima River

Annual Report 2005 - 2006

May 2006

DOE/BP-00022370-8



This Document should be cited as follows:

*Thompson, Brad, Todd Pearsons, "Yakima/Klickitat Fisheries Project Monitoring and Evaluation; Initial Review of Models with Potential to Predict Annual Spring Chinook Smolt Production in the Yakima River", 2005-2006 Annual Report, Project No. 199506325, 21 electronic pages, (BPA Report DOE/BP-00022370-8)*

Bonneville Power Administration  
P.O. Box 3621  
Portland, OR 97208

This report was funded by the Bonneville Power Administration (BPA), U.S. Department of Energy, as part of BPA's program to protect, mitigate, and enhance fish and wildlife affected by the development and operation of hydroelectric facilities on the Columbia River and its tributaries. The views in this report are the author's and do not necessarily represent the views of BPA.

# **Initial Review of Models with Potential to Predict Annual Spring Chinook Smolt Production in the Yakima River**

Yakima/Klickitat Fisheries Project Monitoring and Evaluation

## **Annual Report 2005**

Performance Period: May, 2005 – April, 2006

Prepared by:

Brad E. Thompson

and

Todd N. Pearsons

Washington Department of Fish and Wildlife  
600 Capitol Way North  
Olympia, Washington 98501-1091

Prepared for:

U.S. Department of Energy  
Bonneville Power Administration  
Division of Fish and Wildlife  
P.O. Box 3621  
Portland, Oregon 97283-3621

Project # 1995-063-25  
Contract # 22370

**May 2006**

This report covers one of many topics under the Yakima/Klickitat Fisheries Project's Monitoring and Evaluation Program (YKFPME). The YKFPME is funded under two BPA contracts, one for the Yakama Nation and the other for the Washington Department of Fish and Wildlife (Contract number 22370, Project Number 1995-063-25). A comprehensive summary report for all of the monitoring and evaluation topics will be submitted after all of the topical reports are completed. This approach to reporting enhances the ability of people to get the information they want, enhances timely reporting of results, and provides a condensed synthesis of the whole YKFPME. The current report was prepared by the Washington Department of Fish and Wildlife.

## **Introduction**

The ability to predict the annual number of smolts that are produced within a basin can provide numerous scientific and management benefits. For example, it could provide an early predictor of the number of adults that could be produced, similar to how jacks are used to predict abundances of older fish. This could assist in long-term planning for setting harvest limits. Additionally, evaluation of the competency of hatchery origin fish to reproduce and survive could be accomplished by comparing productivity of hatchery origin fish to modeled predictions of natural origin fish productivities. This would be particularly helpful when control streams are not available, which frequently occurs. Finally, It is well known that annual variation in fish abundance is very high which makes detecting impacts very difficult (Ham and Pearsons 2000). Ability to explain some of the variation in abundance can increase the statistical power to detect impacts substantially and thus decreases the time necessary to evaluate management actions such as supplementation or habitat enhancement (Ham and Pearsons 2000). Finally, carrying capacity is usually expressed as a single number that does not change annually (e.g., 1000 spawners). It is likely that capacity changes annually and therefore influences the number of smolts that are produced. Thus, annual estimates of capacity could be estimated even if the number of spawners is inadequate to fully seed the environment. Understanding the factors that have strong influences on survival and capacity (e.g., model parameters) can also help guide management decisions.

The objective of this work is to determine if a simulation model exists that will annually predict accurate spring Chinook salmon smolt abundance for the Yakima River. This model would preferably use data types previously and currently collected in the Yakima Basin such as water discharge and temperature. We reviewed a variety of models that are currently used in the Pacific Northwest as well as other published models. This report should be viewed as an initial evaluation of these models.

## **Approach**

Based on our own knowledge and consultation with our peers, we identified several simulation models that we believed should be included in this review. Then we gathered and reviewed documentation for each model that is available in both peer-reviewed publications and technical reports. For several of the models, we also contacted the developers in order to answer any lingering questions about a model.

We performed a coarse review of each model that included identifying the input data types, model structure and function, output types, key assumptions, and whether the model has previously been applied for Yakima River spring Chinook. Additionally, we identified whether each model is capable of utilizing annual temperature and flow data in order to make annual predictions of smolt capacity. We classified models as being either statistical, stratified capacity, territory size-based, or mechanistic based on similarity in model structure and data input requirements.

## Results

### Statistical Models

The first suite of models that we reviewed can be broadly classified as statistical models. Hilborn and Mangel (1997) describe statistical models as an attempt to describe a relationship between an independent and dependent variable without any attempt to mechanistically explain why the variables interact in the manner observed. A regression model is the typical representative. The statistical models we reviewed were several regression models that predict annual smolt production as a function of seasonal flow and stock-recruitment models.

#### *WDFW Flow-Smolt Regressions*

Annual WDFW wild salmon production and survival monitoring studies (Seiler et al. 2004a) have provided the time series data necessary for regressing estimates of total smolts against measurements and indices of river discharge (i.e., flow). Examples include the negative linear regression for Clearwater River coho salmon smolt production and peak incubation flow (Seiler et al. 2004b), positive linear regression for Chehalis River coho salmon smolt production and minimum spawning flow (Seiler et al. 2004b), positive linear relationship between Bingham Creek coho salmon smolt production and an index summer low flow for Puget Sound watersheds (Seiler et al. 2004b), and negative linear relationship between wild age-0+ Skagit River Chinook salmon egg-to-migrant survival and peak incubation flow (Seiler et al. 2003). The statistical measure of goodness-of-fit reported for these relationships is commonly quite high,  $r^2 > 0.70$  (Seiler et al. 2004b). Inter-annual process error is not incorporated in these WDFW models to explain the annual deviations from the regression lines.

Despite available Yakima time series smolt and flow data, application of the WDFW Western Washington coho and Chinook regression models as a stand-alone tool for our Yakima River spring Chinook modeling project may be problematic. First, out-of-basin transfer of any statistical model may not provide capacity predictions with adequate accuracy for the new watershed if the two watersheds are not similar in size or habitat quality. Secondly, the independent variables in the WDFW regression models may not be accurate predictors of Yakima spring Chinook smolt production because Yakima spring Chinook experience different environmental conditions related to climate and water management and rear in freshwater longer (i.e., yearling) than in Western Washington Chinook populations (sub-yearling) monitored by Seiler et al. (2004b).

Recommendation: Do not apply existing WDFW regression models for estimating Yakima spring Chinook smolt capacity. However, investigate and develop regression models for Yakima spring Chinook using Yakima data with similar independent variables as used in the WDFW regression models (Seiler et al. 2004b). These new regression models may be suitable as sub-components of mechanistic models discussed below.

#### *Stock-Recruit Models*

Fisheries managers and scientists frequently predict the future number of returning adult salmon based on the number of adults that spawned them several years previously. The future adult salmon are commonly referred to as recruits while their

parents are called the stock. Time series of these data are typically plotted with stock size on the x-axis and number of recruits along the y-axis. A Beverton-Holt or Ricker or other regression function is often fitted to the time series data in order to obtain the equation and associated parameter estimates that can best be used to predict future salmon run size (Hilborn and Walters 1992). A similar procedure can be performed to predict total smolts based on previous escapement for populations where both escapement and out migrants are monitored. The key assumption common to all stock-recruit models is that recruitment (i.e., adult or smolts) is only explained by the stock size. Annual deviations from the regression prediction are often large and always unexplainable using these models. Therefore, stock-recruit models alone do not increase our understanding of the factors that lead to observed variation in smolt output at a given stock size.

Recommendation: We already have a stock-recruit model for Yakima spring Chinook. This model does not explain the large annual recruitment variation we observe when escapement is greater than about 760 redds. Identify if additional variables can be used to explain this annual recruitment variation.

### **Stratified Capacity Models**

We characterize the second suite of models included in our review as stratified capacity models. The general approach is to assign all of the channel area to several habitat strata that support a gradient of fish densities. Potential smolt production for a stratum is commonly estimated by multiplying the total surface area assigned to the stratum by the fish density (i.e., number/area) associated with that stratum. Summing these stratum-specific products results in the estimate of total smolt production for the watershed. The two stratified capacity models that we reviewed are the Unit Characteristic Method for steelhead (Cramer and Ackerman in review) and a GIS based approach for estimating potential Chinook salmon spawning capacity in Puget Sound watersheds (Sanderson et al. in prep).

#### *Unit Characteristic Method (UCM)*

The general approach of the Unit Characteristic Method (UCM) is to multiply summer wetted stream surface area by unit-type (e.g., pool, riffle, etc.) fish densities and several unit-specific and reach-specific scalars and then sum the product over the entire watershed. "The UCM estimates steelhead summer parr capacity for a stream based on the availability of different channel morphological units [e.g., pool, riffle, glide] identified through stream surveys. The surface area of each unit is multiplied by capacity [unit-specific densities from ODFW 1985-1992 data] of these types of units to rear steelhead parr. The capacity estimate for each unit is subsequently adjusted by increments and decrements based on depth and cover. Unit capacities are then summed across a reach where further adjustments are made for riffle availability, turbidity, alkalinity, and presence of fines in the substrate. Finally, reaches are summed together to estimate parr capacity of each stream. A final adjustment is made to reflect a relative decrease in capacity when availability of over-winter habitat drops below that needed to support parr that survived through the summer. To estimate smolt output, the parr capacity is multiplied by an over-winter survival ( $S_{ow}$ ) (Cramer and Ackerman in review).

Key assumptions of the steelhead UCM are that 1) availability of summer parr rearing habitat primarily limits total smolt production; 2) Over-winter parr survival is secondarily limiting total smolt production; 3) Egg incubation and water temperature are NOT limiting; 4) the watershed is fully seeded; and 5) inter-specific competition is not incorporated. The UCM model produces deterministic output and therefore it is not currently possible to incorporate or explain inter-annual process error.

#### *Puget Sound Chinook Salmon Potential Spawner Capacity*

The Sanderson et al. (in prep.) approach for estimating potential Chinook spawning capacity in Puget Sound watersheds starts by stratifying all potential freshwater habitat for spawning quality according to a spawning habitat suitability index (Davies et al. in press) that incorporates GIS derived channel gradient (grad), bankfull width (bfw), and riparian seral stage data layers. A fish passage barrier GIS layer (SSHIAP) is overlaid to estimate potential spawning area currently excluded from fish use. The result is set of contiguous reaches with reach breaks defined according to changes in gradient (< 1%, 1-4%, > 4%), bankfull width (< 5 m, 5-25 m, and > 25 m), riparian seral stage (non-forested, early-, mid-, and late-seral), and barrier proximity (downstream or upstream of a barrier). Then the potential spawner capacity for each reach is estimated according to one of three equations. For reaches with bfw >25m and grad < 4%, potential spawning capacity = [stream area (km<sup>2</sup>) \* % spawnable area (6.2%) \* adults/redd (1.9)] / area of each redd (14.1 m<sup>2</sup>). For reaches with bfw 5-25 m and grad < 1%, potential spawning capacity = stream length (m) \* adults/redd \* redds/km. For reaches with bfw 5-25 m and grad 1-4%, potential spawning capacity = stream length (m) \* (% forced pool-riffle/100) \* adults/redd \* redds/km, where % forced pool-riffle is a function of seral stage (i.e., 100% for late seral, 78% for mid seral, 74% for early seral, and 35% non-forest) (Bartz et al in press Table 6). Total potential spawning capacity for the entire watershed is estimated by summing all the reach capacity estimates.

Key assumptions of the Sanderson et al. (in prep) approach are that 1) spawning habitat quality is a function of geomorphology and riparian vegetation status; 2) bankfull width, gradient, and seral stage can be accurately characterized using remotely sensed data (Davies et al. in press), 3) percent spawnable area, adults/redd, and redd size are constants based on unpublished data collected in the Stillaguamish and Skagit Rivers; 4) the difference between current and historic spawning capacity is due to anthropogenic barriers, the difference between current and historic riparian seral stage, and temporal differences between percent spawning area and percent forced pool-riffle habitat; and 5) the model does not consider specific factors affecting habitat quality (e.g., wood, temperature, fines, etc.) .

Uncertainty in potential spawning capacity estimates provided by this model can be accounted for by bootstrap sampling redds/km time series data from the North Fork Stillaguamish River. However, the three input data layers (i.e., gradient, bankfull width, and riparian seral stage) are constant from year to year. Therefore, it is not currently possible to incorporate or explain inter-annual process error using this GIS based stratified capacity model.

Application of these two models for annually estimating Yakima spring Chinook smolt capacity as a function of habitat capacity and quality is problematic for several reasons. First, Yakima River juvenile spring Chinook have been observed in pods of

individuals that stack both vertically as well as laterally within the water column (Pearsons et al. 2005 – past YKFP reports). Therefore, the ideal Yakima spring Chinook habitat-based smolt capacity model needs to quantify habitat in three dimensions (i.e., volume). However, both models quantify habitat space in only two dimensions (i.e., surface area). Additionally, neither of these stratified capacity models is currently capable of predicting stochastic smolt capacity output and therefore are unable to explain inter-annual smolt capacity variation associated with process error. Some of the UCM assumptions may be violated if the UCM is applied in the Yakima for spring Chinook. Most notable is that spring Chinook escapement may not be great enough in certain years to fully seed the watershed (Pearsons et al. 2004 Figure 9). A current drawback for transferring the Sanderson et al. (in prep.) approach to the Yakima for spring Chinook is that the model currently does not predict smolt capacity, but instead only predicts spawner capacity.

Recommendation: Do not apply the UCM or Sanderson et al. (in prep.) models as a single tool for estimating Yakima spring Chinook smolt capacity. However, investigate the ease of developing a Sanderson et al. (in prep.) type of potential spawner capacity estimate for Yakima spring Chinook that could be a sub-component of a mechanistic life-cycle model that will predict smolt capacity as a function of habitat quality and quantity. Further investigate the spring Chinook UCM model developed by S.P. Cramer for an Oregon spring Chinook stock.

### **Territory Size-Based Models**

For at least 40 years, fisheries scientists have contended that food and space act as regulators on drift feeding salmonid populations in freshwater systems (Chapman 1966; Allen 1969; Titus 1990). The basic concept is that each individual fish requires a minimum area that it defends from others in order to capture enough food to meet metabolic needs and grow rapidly enough to survive and eventually reproduce. Dividing the entire stream area by territory size could theoretically provide a capacity estimate if you assume that the entire stream is suitable habitat and territory size is equal for all individuals. In reality, these assumptions are usually untrue because not all habitat is usable and where it is territory size varies with many factors including fish size (Keeley and Grant 1995). In an effort to account for difference in territory size associated with body size variation, Grant and Kramer (1990) advanced the concept of percent habitat saturation (PHS) to calculate habitat fullness. PHS is expressed on a scale of 0% to 100% where density dependent processes and thus capacity have been shown to likely occur when  $PHS > 27\%$  (Grant and Kramer 1990). Grant et al. (1998) contend that PHS as an improvement over density for measuring salmonid population abundance and illustrate their contention with an Atlantic salmon population example.

The key assumptions for territory size-based models are that 1) the population is regulated by density-dependent processes, 2) the density-dependent process is expressed as competition for space and can be quantified as a territory size, and 3) attributes within the function that calculates territory size are influential and parameterized accurately.

Incorporating inter-annual variation in territory-sized based models for Yakima spring Chinook smolt production seems unlikely unless inter-annual flow variation explains variation in annual smolt production, flow can be monitored annually, and we

can accurately quantify how total number of spring Chinook territories fluctuates with flow levels.

Application of territory size-based models for our Yakima spring Chinook study may be limited due to several factors including the conflicting requirement of quantifying territory size as part of a relatively small-scale approach versus our need to make this measurement over the entire Yakima basin. Second, similar to the stratified capacity models discussed above, the PHS approach discussed in Grant et al. (1998) defines territory size in only two dimensions rather than the three dimensions necessary to define spring Chinook territory size as a volume. Finally, PHS does not express abundance or capacity in units of fish, the desired unit of measure for our modeling effort. Rather, PHS is reported as a percentage.

**Recommendation:** Do not apply the territory size-based modeling approach for estimating Yakima spring Chinook smolt capacity for the several reasons listed above, most notably that existing territory size models do not express territory size in units of volume. Investigate the feasibility of developing a territory size-based model as a sub-component of a mechanistic life-cycle model for predicting smolt capacity as a function of habitat quality and quantity.

### **Mechanistic Models**

Unlike statistical models, mechanistic models attempt to explain why the independent variable predicts the dependent variable. Mechanistic models can be qualitative or quantitative in how they describe the magnitude and direction of the dependent variable's response to variation in the independent variable. As an example, a bioenergetics model is a quantitative mechanistic model often used to predict fish growth as a function of the difference between consumption and the sum of egestion, excretion, specific dynamic action, and respiration (Jager et al. 1997). In this example, the mechanistic model is quantitative because it provides a numerical estimate of how much mass remains available for fish growth after metabolic needs are satisfied. Although qualitative models can be especially useful for hypothesizing which variables should be considered in quantitative mechanistic models, we did not include any qualitative models in this review. Instead, we reviewed a diverse suite of quantitative mechanistic models. We have further categorized each of these mechanistic models as either expert-based or individual-based and provide a more detailed discussion of some representatives from each category in the sections below.

#### ***Expert-Based Mechanistic Models***

For the purposes of this review, we define expert-based mechanistic models as those that allow the user to utilize a combination of expert opinion and empirical data as values for independent variables in the model's functional relationships. Additionally, some these models also rely on a combination of expert opinion and empirical data to derive the parameter values of the model's functional relationships. Examples of expert-based mechanistic models included in our review are Ecosystem Diagnosis and Treatment (EDT) and Bayesian models.

### *Ecosystem Diagnosis and Treatment (EDT)*

The EDT model has been widely applied in Columbia River sub-basin planning (BPA website) and regional salmon recovery planning efforts (Thompson et al. in review) to diagnose which river reaches and which habitat components within a basin limit salmon population capacity, productivity, and life-history diversity.

Model inputs include a minimum of two extensive habitat characterizations, each representing different time periods (e.g., current and pre-settlement conditions). Empirical, expert opinion, and hypothetical data types can be referenced by the user in order to assign a habitat rating to each of the 46 freshwater habitat attributes (Lestelle 2004) that collectively define the environmental condition of each spatial unit (e.g., river reach). Additional user defined EDT inputs include the temporal and spatial spawning distribution, composition of life history patterns (Mobrand Biometrics Inc. 2005) expressed by the population, and exploitation rate the population experiences in the marine environment.

The general EDT model structure is a multiple stage Beverton-Holt stock production function (Moussalli and Hilborn 1986; Beverton and Holt 1957) that has been disaggregated for multiple life-stages (Mobrand Biometrics Inc. 2005 for a detailed description). Fish are represented in the model as probes (i.e., fish movement patterns) that are subjected to incremental mortality associated with the environmental conditions of the spatial units they encounter throughout the entire life-history. More specifically, the model contains a large set of life-stage specific quantitative relationships (i.e., survival rules) that decrement benchmark productivities and capacities as functions of the 46 habitat ratings specified for each reach the probe encounters.

Model outputs include a Beverton-Holt production function defined by the productivity and capacity parameter (Beverton and Holt 1957) estimates associated with each temporal habitat characterization. Parameter estimates, including capacity, are expressed in both adult and smolt units. Other EDT outputs include a diagnosis of which river reaches most limit restoration of the population and which reaches should be protected from further degradation in order prevent additional decline. Finally, more diagnostic output is provided to indicate which habitat attributes in each reach are most limiting the population.

Assumptions of the EDT model are numerous because of its complex structure. Notable assumptions include: 1) the Beverton-Holt function accurately describes any density-dependent process; 2) life history patterns represented as probes in the model are accurate in their reflection of how individuals utilize the basin in space and time; 3) benchmark densities, productivities, and capacities are applicable to the watershed of interest; 4) the numerous functional relationships are accurately parameterized and represent the key process regulating population dynamics; 5) the entire range of freshwater habitats utilized by all life-stages are represented in the EDT habitat characterizations; and 6) habitat attribute ratings provided by the user accurately describe the average conditional state for each temporal habitat characterization.

The EDT model currently exists for Yakima spring Chinook. However, EDT provides deterministic output. The model was not designed or intended to provide annual smolt capacity estimates. Furthermore, use of the model for this purpose would be difficult because of the enormous number of model inputs (46 attributes X total number of river reaches) that would need to be updated in order to create a habitat

characterization for each year. Furthermore, we believe annually changing the ratings for only a subset of the model attributes is ill advised until a formal sensitivity analysis of the EDT model is completed. Preliminary EDT sensitivity analysis indicate that model output is fairly insensitive to large rating changes for attributes that describe flow conditions (Paul McElhany, NOAA Fisheries Northwest Fisheries Science Center, personal communication).

Recommendation: Do not utilize the EDT model as a tool to annually predict Yakima River spring Chinook smolt production. EDT was designed for a different purpose.

### *Bayesian Models*

Probabilistic networks can be used to formalize beliefs of various outcomes occurring. Probabilistic networks are sometimes called Bayes networks because they use Bayes Theorem, a basic rule of probability, which calculates the probability of an event given changed conditions of the factors that affect it. The benefits of using probabilistic networks to assist in decision making include, 1) transparency of assumptions used, valuation of probabilities, and relationships; 2) mathematically sound; 3) documentation and support for decisions; 4) consistency of output; and 5) output is easy to understand.

Probabilistic networks (Bayesian viability assessment procedure, BayVAM) have been used to assess population viability of salmonids and is particularly useful when scientific uncertainty is high (Lee and Rieman 1997). This model could be reparameterized and modified to predict smolt abundance. As of this writing, we have not adequately reviewed this model. Currently, a Delphi process is being used in the Yakima to evaluate effects of different flows. This process has not been completed yet and therefore cannot be evaluated yet.

Recommendation: When a report becomes available, evaluate the Delphi analysis that is being sponsored by the Bureau of Reclamation. Investigate the utility of the BayVAM model.

### *Individual-Based Mechanistic Models*

We define an individual-based model (IBM) as a model that track the survival of individuals through time and mechanistic models as described above. Several IBMs models have been developed for resident salmonids (Railsback and Harvey 2001; Van Winkle et al. 1998; Clark and Rose 1997) and Chinook salmon (Scheuerell et al. In press; Jager et al. 1997) in the past ten years. Given our project objective, we limited our in-depth review to the two salmon IBMs.

### *SHIRAZ*

The first IBM we reviewed is a salmon life cycle model named SHIRAZ (Scheuerell et al. In press; Bartz et al. In press). Model inputs include 1) user-defined stock(s) and associated life-history trajectories; 2) a network of user-defined spatial units (e.g. reaches or sub-watersheds); 3) the initial and final time step (i.e., year) for the simulation; 4) a set of habitat indicators represented in functional relationships that affect fish survival; 5) the initial number of individuals alive at each life stage for each stock and the proportion of each life stage occupying each spatial unit; 6) a matrix of

movement probabilities to realistically represent downstream migration patterns (the SHIRAZ model structure allows the user to specify these constants or rely on ideal free distribution theory); 7) stray rates to non-natal reaches/sub-watersheds; 8) age-specific maturation rates; 9) and a harvest strategy that can be either a constant escapement goal or constant exploitation rate (Scheuerell et al. In press).

Similar to EDT, the basic structure of SHIRAZ is a multi-stage Beverton-Holt production function (Moussalli and Hilborn 1986). Both SHIRAZ and EDT are structured to simulate fish movement among spatial units over their entire life history and simulate survival rates that are a function of the condition of each encountered spatial unit. However, one of the main structural differences between the two models is the manner in which fish are represented. Unlike probes that represent multiple individuals in EDT, SHIRAZ tracks the number of fish for a particular life-stage by stock by sub-area over time. Thus, we included SHIRAZ in the IBM model group. Population productivity and capacity estimates are calculated for various life stages using the multi-stage Beverton-Holt production function (Moussalli and Hilborn 1986). Another structural difference between SHIRAZ and EDT is the smaller set of functional relationships in SHIRAZ for decrementing productivity and capacity based on habitat condition. For example, the Snohomish River Chinook salmon version of SHIRAZ contains only four functional relationships for decrementing productivity as a function of survival. Pre-spawning in-river survival is a function of water temperature while incubation survival is a function of water temperature, normalized mean flow, and percent fines in the spawning gravel (Scheuerell et al. In press). Egg capacity is estimated by multiplying a constant for fecundity times an adult capacity estimate generated using the Sanderson et al. (In prep.) stratified capacity model (see above for a description of the Sanderson et al. model). Fry capacity is estimated via another stratified capacity model (Bartz et al. in press) that multiplies a GIS derived rearing area estimate times habitat-specific densities. Finally, maturation rate and fecundity are age-specific.

The SHIRAZ model provides several outputs including abundance estimates for different life-stages (e.g., smolts, ocean ages, spawners) in each spatial unit. These estimates can be summed across sub-areas by stock. Mark Scheuerell (NOAA Fisheries Northwest Fisheries Science Center, personal communication) indicated that Snohomish version of the model needs to be run for approximately 20 annual time steps before abundance output stabilizes. However, time to equilibrium will likely change if SHIRAZ is parameterized for other watersheds and stocks with different numbers of life-stages, stocks, habitat areas, hatchery practices, etc. Second, SHIRAZ estimates stock-specific Beverton-Holt capacity and productivity parameters values (see figure 3 in Scheuerell et al. In press for an example) that are calculated based on the abundance output. Finally, the life-stage specific abundance estimates for each spatial unit can be displayed as densities in a map in order to visually assess the freshwater spatial distribution of spawners or other lifestages.

Implicit assumptions of the SHIRAZ modeling framework are that 1) all spatial units are identical in size with respect to fish movement and 2) the Beverton-Holt function accurately describes any density-dependent process regulating the population being modeled. Additional explicit assumptions for the Snohomish version of SHIRAZ are that 1) temperature, flow and sediment are actually the key environmental factors driving productivity and 2) the recruitment bottleneck occurs in freshwater.

The SHIRAZ user can incorporate stochasticity by selecting a statistical distribution (i.e., uniform, normal, log-normal) from which to draw variates that can replace constant parameter values in functional relationships or static estimates of habitat condition used in functional relationships (Scheuerell et al. In press). This procedure can be applied in two ways: 1) draw one random variate for each major spatial unit per time step (year) and tie survival rates to this variate over all years or 2) use a Monte Carlo approach to estimate the overall effect of the stochastic variable by creating probabilistic output. Theoretically, annual flow, temperature, and fines data can be used to deterministically re-run the functional relationships for annually estimating the year-specific smolt and adult abundances. For each annual data update, SHIRAZ would need to run for about 20 annual time steps with the new environmental data held constant among years while the output stabilizes (Mark Scheuerell, NOAA Fisheries Northwest Fisheries Science Center, personal communication). Mark Scheuerell has not attempted this yet, but theoretically it should provide representative annual predictions of smolt and adult abundance that differ based on inter-annual environmental variation.

Application of SHIRAZ for our Yakima spring Chinook study is possible but may require revisiting and potentially modifying some of the functional relationships to account for additional freshwater rearing time exhibited by stream type Chinook in the Yakima versus ocean type Puget Sound Chinook. It may be necessary to add functions in order to represent the effect of summer freshwater environmental conditions on juvenile Yakima spring Chinook productivity and capacity. Additionally, another model or new set of functional relationships may need to be developed in order to estimate juvenile capacity densities as fish per volume rather than per wetted surface area.

Recommendation: Formally test whether the Snohomish SHIRAZ model can produce representative annual predictors of smolt and adult abundance using annual Snohomish River temperature and flow data. Explore development of a Yakima spring Chinook SHIRAZ version. Assemble the required model inputs for this exercise and then run the model using the functional relationships used in the Snohomish version. Compare the predicted smolt capacity to Yakima smolt trap data. Develop new functional relationships if the original estimates do not closely match the smolt trap estimate.

#### *Oak Ridge Chinook salmon Model (ORCM)*

The second IBM we reviewed is the Oak Ridge Chinook salmon model (ORCM) that was developed to predict the instream flow effects on fall Chinook salmon in the Toulumne River, California. The ORCM is a spatially explicit life cycle model that predicts the development, growth, and survival of individuals on a daily time step as a result of freshwater habitat quality and quantity (Jager et al. 1997).

The spatial scale of the model is limited to the portion of the freshwater river network utilized by Chinook salmon during the spawning to smolt lifestages (Jager et al. 1997). Spatial units are user specified river segments that differ from one another according to spawner preference, riffle:pool:run ratio, quantity of weighted usable area (WUA)(Bovee et al. 1998 for detailed methods and calculation), water temperature, abundance of conspecific competitors, and predator density (Jager et al. 1997). Data inputs include 1) daily streamflow, 2) minimum flows ranges of dates throughout the year, 3) daily temperature, 4) WUA curves at different flows, and 5) escapement. The

structure of the ORCM is complex, yet conceptually simple because it is hierarchical, drawing upon other models for some of its subcomponents. As an example, the growth during juvenile lifestages in the ORCM is predicted using the Wisconsin bioenergetics model (Stewart et al. 1983). Redd distribution and capacity are a function of flow, riffle area, and a constant for redd area. Incubation and egg development is a function of temperature and tracked as degree days. Incubation survival is a function of temperature, redd superimposition, and flow. Life-stage specific juvenile Chinook habitat capacities are expressed as number of juveniles per surface area in each segment and are a function of riffle:pool:run ratio and flow. Individual fry growth and development is a function of temperature, flow, and competition with other fry in the segment. Growth is estimated with the Wisconsin bioenergetics model. Proportion of maximum daily intake is a function of body size with larger individuals occupying feeding stations with the highest growth potential. The number of feeding sites is derived via the Grant and Kramer (1990) territory size model. Juvenile survival is a function of water temperature and predator density. Fry move in search of unoccupied habitat with a high enough tradeoff between growth potential and predation risk. Direction of fry movement can be upstream or downstream and also dependent upon water temperature to avoid lethal thermal conditions. Smolts move downstream each day as function of flow and eventually outmigrate to the ocean. Model outputs include predictions of the total smolt abundance and size distribution. Additional outputs include the temporal and spatial distribution of intermediates of earlier lifestages and redds (Jager et al. 1997).

Some of the key assumptions of the ORCM are that 1) juvenile capacity is function of area and not of volume; 2) the only density independent factors influencing lifestage survival and capacity are water temperature, flow, pool:riffle:run ratios, and predation; 3) WUA is a sound approach for accurately identifying the potential range of inriver habitat for the lifestages included in the ORCM; 4) curves relating WUA to flow for each lifestage and habitat are accurate; 5) fixed parameter values for the bioenergetics model are transferable from the Great Lakes study (Stewart et al. 1983) to the Toulumne River, California to provide accurate growth rate predictions; 6) predator densities can be accurately estimated at the spatial scale required by the model; and 7) Chinook smolts are ocean-type and thus outmigrate as sub-yearlings. The ORCM is capable of predicting a smolt capacity for each year that flow and temperature data are available if WUA estimates have been independently estimated throughout the observed range of flows.

Application of the ORCM model for Yakima spring Chinook may be problematic for several reasons. First, the ORCM was designed for estimating smolt capacity for Chinook salmon that smolt as subyearlings. Yakima spring Chinook smolt as yearlings and therefore the ORCM does not include survival and capacity functions for some of the Yakima spring Chinook juvenile freshwater lifestages (late summer, fall, and winter). Additional functional relationships would need to be defined and developed for these Yakima spring Chinook lifestages. Second, the ORCM model structure shares one of the same design limitations as described for the stratified capacity models and territory size-based models. Each of these models defines available habitat in only two-dimensions but Yakima spring Chinook have commonly been observed distributed throughout the water column in pods that are vertically and horizontally oriented. Therefore the ORCM would potentially underestimate spring Chinook capacity in the Yakima River. Finally, application of the ORCM would require WUA area estimates for a range of Yakima

River flows. We are currently unaware if such estimates are available and if so, recent enough to still be accurate.

Recommendation: Do not attempt to utilize the ORCM as a stand-alone tool for annually predicting Yakima spring Chinook smolt production. However, investigate the possibility of modifying the capacity equations to redefine habitat space as a volume. Determine whether existing Yakima WUA estimates are adequate for future application of a modified ORCM model that contains additional functional relationships for all spring Chinook juvenile lifestages.

## **Discussion**

All of the models that we reviewed are not currently ready for us to immediately apply in order to annually predict the natural capacity of the Yakima River to produce spring Chinook smolts. Two of the models do not predict capacity for the smolt lifestage (Table 1). The EDT model predicts smolt capacity and has already been applied in the Yakima River for salmon recovery planning, but the EDT model is not designed to predict annual changes in smolt capacity associated with environmental variation. All of the remaining models, except for the stock-recruitment models, can theoretically be structurally modified to predict Yakima spring Chinook smolt capacity. However, for most there is at least one limitation to quick and inexpensive implementation of the model (Table 1). As an example, both of the stratified capacity models and the territory size-based model calculate territory size as an area unit, which is not commensurate with the observation that spring Chinook in the Yakima defend territories that are both vertically and horizontally aligned with one another. Therefore, the desirable model should calculate territory size as a volume. As time permits, we will also review models that we weren't aware of, models that we didn't have time to evaluate (e.g., Bayesian), and models we were aware of but are lacking sufficient documentation for our review (All-H-Analyzer). The SHIRAZ model is the single model that we believe we can slightly modify to meet our project needs. However, the current SHIRAZ model is not structured for spring Chinook.

Therefore, we propose a two-pronged approach for developing a habitat-based simulation model capable of predicting annual spring Chinook smolt capacity for the Yakima basin. First, we will attempt to create a Yakima spring Chinook version of the SHIRAZ model by modifying the Snohomish Fall Chinook version. This approach will require us to both acquire and assemble all the necessary input data and likely modify and add some functional relationships to the current model structure in order to account for the longer freshwater residency of spring Chinook compared to Puget Sound Fall Chinook stocks and customize the functional relationships for eastern Washington sub-basins. Additionally, we propose to start development of a new model. Desirable components and attributes of the new model include 1) a three-dimensional expression of juvenile territory size, 2) ability to utilize long-term environmental monitoring data including flow and temperature as inputs for functional relationships, and 3) the ability to annually estimate basin smolt capacity as a function of habitat quality and quantity.

We intend to evaluate candidate models by comparing predicted smolt abundance and actual smolt abundance as well as the cost to collect annual data. As part of this

evaluation, we propose to develop statistical decision criteria for evaluating whether the similarity between predicted and observed smolt abundance is great enough to accept a model as adequate for management needs discussed earlier. Additionally, we propose to rigorously compare the tradeoff of decreasing model complexity and model fit (e.g., AIC theory) in order to compare the utility of models exhibiting varying structural complexity.

**Table 1. -- Summary of whether the reviewed models annually predict smolt capacity, are adaptable for Yakima Spring Chinook, potential limitations for Yakima Spring Chinook application, and recommendations for whether and how the model can be applied in the future to annually predict Yakima River spring Chinook annual smolt capacity.**

Model Type	Model	Does model annually predict smolt capacity?	Adaptable for Yakima Spring Chinook?	Application Limitations	Recommendation
Statistical	WDFW Regressions	Yes	Yes	<ul style="list-style-type: none"> <li>• Yakima data mining required</li> </ul>	<ul style="list-style-type: none"> <li>• Create with Yakima fish &amp; flow data</li> </ul>
	Stock-Recruit	Yes	Exists	<ul style="list-style-type: none"> <li>• Design does not meet project need</li> </ul>	<ul style="list-style-type: none"> <li>• Do not apply as a single model</li> <li>• Consider including as a sub-component to a new mechanistic life-cycle model</li> </ul>
Stratified Capacity	UCM	Yes	Yes	<ul style="list-style-type: none"> <li>• Proprietary</li> <li>• Area vs. Volume</li> </ul>	<ul style="list-style-type: none"> <li>• Review spring Chinook version</li> <li>• Identify cost to apply in Yakima</li> </ul>
	PS Chinook Potential Spawner Capacity	No	Yes	<ul style="list-style-type: none"> <li>• Does not estimate smolt capacity</li> <li>• Area vs. Volume</li> <li>• GIS data creation \$</li> </ul>	<ul style="list-style-type: none"> <li>• Do not apply as a single model</li> <li>• Consider including as a sub-component to a new mechanistic life-cycle model</li> </ul>
Territory Size	PHS	Yes	Yes	<ul style="list-style-type: none"> <li>• Area vs. Volume</li> </ul>	<ul style="list-style-type: none"> <li>• Do not apply as a single model</li> <li>• Consider including as a sub-component to a new mechanistic life-cycle model</li> </ul>
Expert-Based Mechanistic	EDT	No	Exists	<ul style="list-style-type: none"> <li>• Not designed to meet our objective</li> </ul>	<ul style="list-style-type: none"> <li>• Do not use for this project</li> </ul>
	Bayesian	No	Yes	<ul style="list-style-type: none"> <li>• Not designed to meet our objective</li> </ul>	<ul style="list-style-type: none"> <li>• Investigate for use in Yakima</li> </ul>
Individual-Based Mechanistic	SHIRAZ	Yes	Yes	<ul style="list-style-type: none"> <li>• Fall Chinook only</li> </ul>	<ul style="list-style-type: none"> <li>• Test with Yakima data</li> <li>• Modify for spring Chinook</li> </ul>
	ORCM	Yes	Yes	<ul style="list-style-type: none"> <li>• Fall Chinook only</li> <li>• Area vs. Volume</li> <li>• Yakima WUA</li> <li>• Computer Capacity?</li> </ul>	<ul style="list-style-type: none"> <li>• Modify for spring Chinook</li> <li>• Determine if Yakima WUA data avail.</li> </ul>

## References

- Allen, K.R. 1969. Limitations on production in salmonid populations in streams. In Symposium on salmon and trout in streams. Edited by T.G. Northcote. University of British Columbia, Vancouver, B.C. pp. 3-18.
- Bartz, K.K., Lagueux, K.M., Scheuerell, M.D., Beechie, T., Haas, A.D., and M.H. Ruckelshaus. In press. Translating restoration scenarios into habitat conditions: an initial step in evaluating recovery strategies for Chinook salmon (*Oncorhynchus tshawytscha*). Can. J. Fish. Aquat. Sci.
- Beverton, R.J.H. and S.J. Holt. 1957. On the dynamics of exploited fish populations. Chapman & Hall, London.
- Bovee, K.D., B.L., Lamb, J.M. Bartholow, C.B. Stalnaker, J. Taylor and J. Henriksen. 1998. Stream habitat analysis using the instream flow incremental methodology. U.S. Geological Survey, Biological Resources Division Information and Technology Report USGS/BRD-1998-0004. viii + 131 pp.
- Chapman, D.W. 1966. Food and space as regulators of salmonid populations in streams. The American Naturalist. 100(913):345-357.
- Clark, M.E. and K.A. Rose. 1997. Individual-based model of stream-resident rainbow trout and brook char: model description, corroboration, and effects of sympatry and spawning season duration. Ecological Modelling. 94:157-175.
- Cramer, S.P. and N.K. Ackerman. In review. Use of stream habitat surveys to predict rearing capacity for juvenile steelhead (*Oncorhynchus mykiss*), In Pacific Salmon Environment and Life History Models: Advancing Science for Sustainable Salmon in the Future. Edited by E. Knudsen, J. Michael, and C. Steward. American Fisheries Society, Bethesda, Maryland.
- Davies, J., K. Lagueux, B. Sanderson, T. Beechie. In Press. Modeling stream channel characteristics from drainage enforced DEMs in the Pacific Northwest. J. Am. Water Resour. Assoc.
- Grant, J.W.A. and D.L. Kramer. 1990. Territory size as a predictor of the upper limit to population density of juvenile salmonids in streams. Can. J. Fish. Aquat. Sci. 47: 1724-1737.
- Grant, J.W.A., Steingrimsson, S.O., Keeley, E.R., and R.A. Cunjak 1998. Implications of territory size for the measurement and prediction of salmonid abundance in streams. Can. J. Fish. Aquat. Sci. 55(Suppl. 1): 181-190.

- Ham, K.D. and T.N. Pearsons. 2000. Can reduced salmonid population abundance be detected in time to limit management impacts? *Can. J. Fish. Aquat. Sci.* 57:17-24.
- Hilborn, R., and M. Mangel. 1997. *The ecological detective: confronting models with data.* Princeton University Press, Princeton, New Jersey.
- Hilborn, R., and C.R. Walters. 1992. *Quantitative fisheries stock assessment: choice, dynamics & uncertainty.* Chapman and Hall, New York.
- Jager, H.I., Cardwell, H.E., Sale, M.J., Bevelhimer, M.S., Coutant, C.C., and W. Van Winkle. 1997. Modelling the linkages between flow management and salmon recruitment in rivers. *Ecological Modelling* 103:171-191.
- Keeley, E.R., and Grant, J.W.A. 1995. Allometric and environmental correlates of territory size in juvenile Atlantic salmon (*Salmo salar*). *Can. J. Fish. Aquat. Sci.* 52:186-196.
- Lee, D. C., and B. E. Rieman 1997. Population viability assessment of salmonids by using probabilistic networks. *North American Journal of Fisheries Management* 17: 1144-1157.
- Lestelle, L.C. 2004. Guidelines for rating Level 2 Environmental Attributes in Ecosystem Diagnosis and Treatment. Report prepared for Northwest Power Planning Council. Mobrand Biometrics, Inc. Vashon, WA. 143 p. Available at <http://www.mobrand.com/MBI/library.html>
- Mobrand Biometrics Inc. 2005. Documentation of the mathematical algorithms within EDT. Mobrand Biometrics Inc. 27 p. <http://www.mobrand.com/MBI/library.html>
- Moussalli, E. and R. Hilborn. 1986. Optimal stock size and harvest rate in multistage life history models. *Can. J. Fish. Aquat. Sci.* 43(1): 135-141.
- Pearsons, T. N., C. L. Johnson, B. B. James, and G. M. Temple. 2004. Spring Chinook salmon interactions indices and residual/precocial monitoring in the Upper Yakima Basin. Annual Report FY 2003 submitted to Bonneville Power Administration, Portland, Oregon. DOE/BP-00013756-5.
- Pearsons, T. N., C. L. Johnson, B. B. James, and G. M. Temple. 2005. Spring Chinook salmon interactions indices and residual/precocious male monitoring in the Upper Yakima Basin. Annual Report FY 2004 submitted to Bonneville Power Administration, Portland, Oregon. [DOE/BP 00017478-5](http://www.doe.gov/DOE/BP/00017478-5).
- Railsback, S.F., and B.C. Harvey. 2001. Individual-based model formulation for cutthroat trout, Little Jones Creek, California. General Technical Report PSW-GTR-182, Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture, Albany, California.

- Sanderson, B.L., J. Davies, K. Lagueux, T. Beechie and M. Ruckelshaus. In prep. Does sufficient habitat remain to support viable Chinook salmon populations in the Pacific Northwest of the United States? A spatially explicit assessment of spawning habitat in Puget Sound.
- Scheuerell, M.D., Hilborn, R., Ruckelshaus, M.H., Bartz, K.K., Lagueux, K.M., Haas, A.D., and K. Rawson. In press. The SHIRAZ model: a tool for incorporating anthropogenic effects and fish-habitat relationships in conservation planning. *Can. J. Fish. Aquat. Sci.*
- Seiler, D., S. Neuhauser, and L. Kishimoto. 2003. 2002 Skagit river Wild 0+ Chinook Production Evaluation Annual Report. July 2003. Washington Department of Fish and Wildlife. 52 p.
- Seiler, D., P. Hanratty, S. Neuhauser, P. Topping, M. Ackley, L.E. Kishimoto, L. Peterson, M. Hino, and G. Volkhardt. 2004a. Wild Salmon Production and Survival Evaluation Annual Report October 1998 – September 1999. Washington Department of Fish and Wildlife. December 2004. 174 p.
- Seiler, D., G. Volkhardt, S. Neuhauser, P. Hanratty, L. Kishimoto, P. Topping, M. Ackley, L. Peterson, and L. Fleischer. 2004b. 2004 Wild Coho Forecasts for Puget Sound & Washington Coastal Systems. Washington Department of Fish and Wildlife. 22 p.
- Stewart, D.J., Weininger, D.D., Rottiers, V., Edsal, T.A., 1983. An energetics model for lake trout, *Salvelinus namaycush*: application to the Lake Michigan population. *Can. J. Fish. Aquat. Sci.* 40, 681-698.
- Thompson, B.E., Lestelle, L.C., Blair, G.R., Mobernd, L.E., and J.B. Scott. In review. EDT application in salmon recovery planning: Diagnosing habitat limitations and modeling restoration action effectiveness in Pacific Salmon Environment and Life History Models: Advancing Science for Sustainable Salmon in the Future. *Edited by E. Knudsen, J. Michael, and C. Steward.* American Fisheries Society, Bethesda, Maryland.
- Titus, R.G. 1990. Territorial behavior and its role in population regulation of young brown trout (*Salmo trutta*); new perspectives. *Ann. Zool. Fennici*, 27:119-130.
- Van Winkle, W., Jager, H.I., Railsback, S.F., Holcomb, B.D., Studley, T.K., and J.E. Baldrige. 1998. Individual-based model of sympatric populations of brown and rainbow trout for instream flow assessment: model description and calibration. *Ecological Modelling* 110:175-207.