FINAL

# OBJECTIVE 4
# OkSockeye: A Simple Life-cycle Model of Okanagan Basin Sockeye Salmon

## Version 2.2
## Design Document

Contribution No. *12* to an *Evaluation of an Experimental Re-introduction of Sockeye Salmon into Skaha Lake: YEAR 3 of 3*

Presented to: Colville Confederated Tribes

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## *Design Document*

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# Summary

The purpose of this model is to support exploration of an adaptive management experiment to introduce sockeye salmon into Skaha Lake, so as to better understand the possible effects of introducing sockeye into Okanagan Lake. The model allows users to explore the biological benefits and risks, and learning value of different candidate strategies for reintroducing sockeye into Skaha Lake. The model operates on an annual time step and provides annual relative abundance estimates of sockeye salmon in Osoyoos and Skaha Lakes, Skaha Lake kokanee, and Skaha and Osoyoos Lake *Mysis* populations. Other fish and mysis populations can be added to the model as required.

The model consists of five submodels (Figure 0.1):

1. Hydrology / Temperature submodel – calculates flows and temperatures in the Okanagan River between Okanagan Lake and the confluence with the Columbia River.
2. Sockeye submodel – calculates survival rates between life stages (Figure 0.2), based on various physical and biological mortality factors.
3. Kokanee submodel – calculates growth, maturation, and survival rates
4. Mysis submodel – calculates annual densities and biomass of mysis in Skaha Lake.
5. Predator submodel – calculates annual production and biomass consumed by lake-resident predators (rainbow trout used as an example predator).

The submodels are connected as shown in Figure 0.1. The hydrology submodel provides flows and temperatures that drive key biological processes in the sockeye, kokanee, and mysis submodels. The sockeye, kokanee, and mysis submodels exchange production information for determining density-dependent growth and survival rates in food-limited rearing habitat in Skaha Lake. The model also includes potential predation on mysis by kokanee. The predator submodel calculates the biomass of sockeye fry and kokanee required to support production of rainbow trout populations.

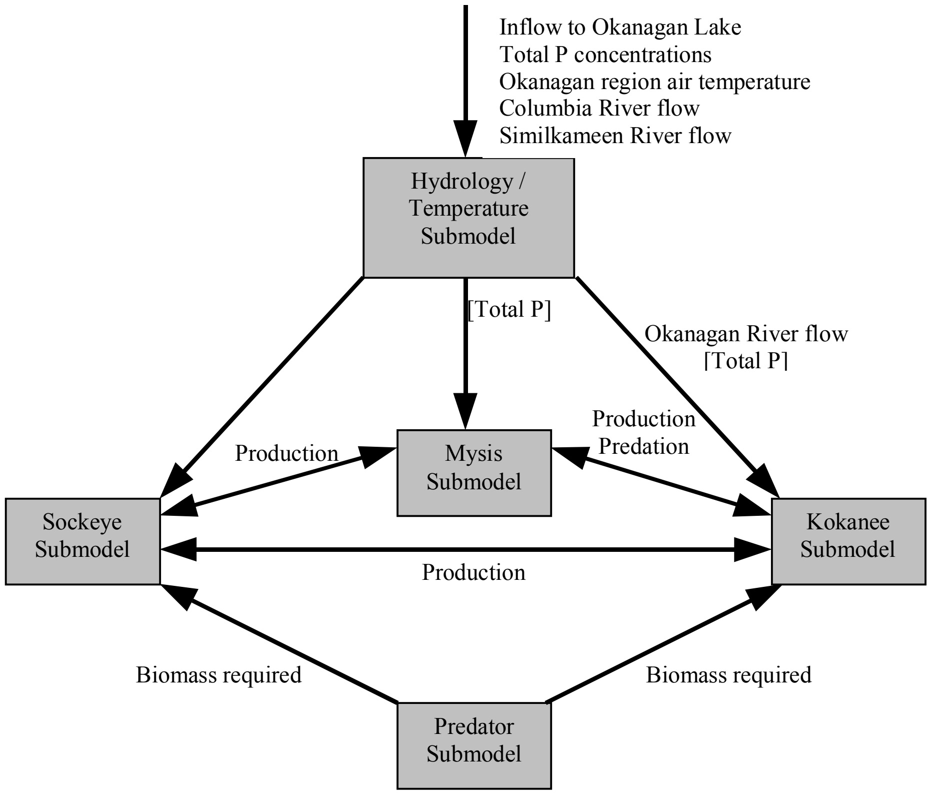



**Figure 0.1.** Overall structure of model showing linkages between submodels.

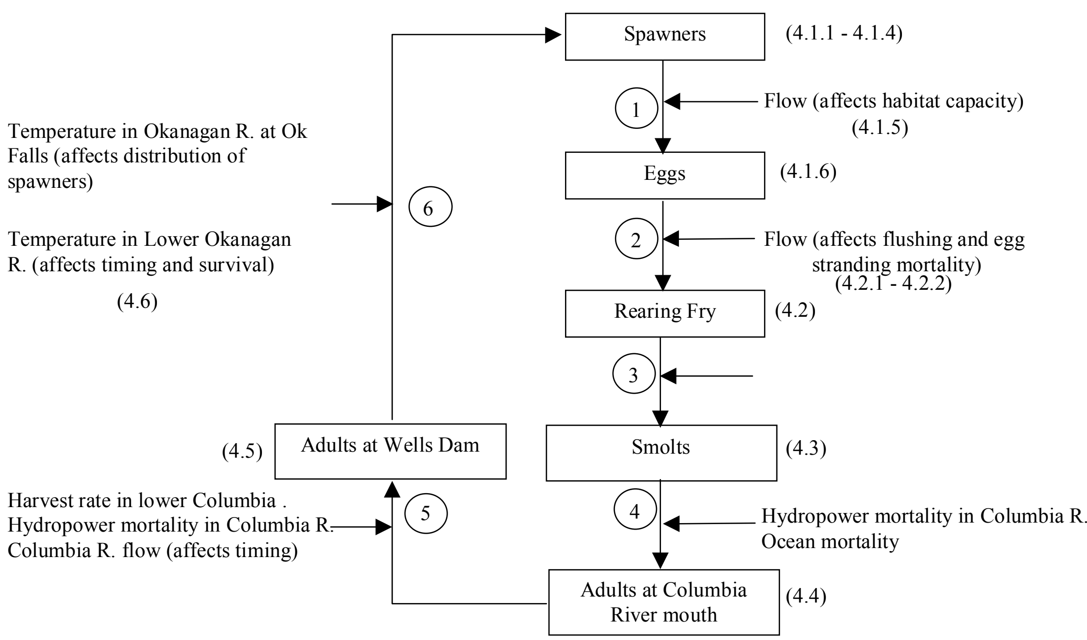



**Figure 0.2.** Schematic of life-cycle of Okanagan sockeye, showing mortality factors included in the model. Numbers in brackets correspond to sections in which each component is described.

# 1.0 Introduction and Project Overview

## 1.1 Background

Historical records indicate that sockeye salmon were once found in most of the lakes in the Okanagan Basin.[1] Currently, the only sockeye population within the Okanagan Basin is found in Osoyoos Lake. Abundance of this stock has declined significantly in the last fifty years. Tribes and First Nations in the U.S. and Canada have proposed re-introducing the species into Okanagan Lake, which has a large rearing capacity. However, assessing the potential benefits and risks associated with a re-introduction of sockeye salmon into Okanagan Lake is difficult because of uncertainties about factors that determine production of Okanagan sockeye,[2] and potential interactions with other species in Okanagan Lake.

A 1997 workshop to discuss these issues recommended that sockeye be re-introduced to Skaha Lake as an experimental management strategy to resolve some of these uncertainties (Peters et al. 1998). In preparation for such an experiment, the Okanagan Nations Fisheries Commission, the Colville Confederated Tribes, and other fisheries agencies have undertaken a research project to identify and assess the risks and benefits of an experimental re-introduction of sockeye salmon into Skaha Lake[3]. Specific risks due to disease transmission and introduction of exotic species are being addressed through ongoing field assessments. Restoration and learning benefits of reintroducing sockeye to Skaha Lake, and potential risks to resident kokanee stocks, will be addressed through the development of a life-cycle model of Skaha Lake sockeye and kokanee populations, together with targeted field work on such topics as disease, exotic species, and habitat inventories.

This document describes the objectives, scope, and design of the life-cycle model of Okanagan sockeye (OkSockeye). The design is based primarily on available data on Okanagan basin sockeye, kokanee, and mysid populations. Development of the OkSockeye model has been an iterative, multi-agency process. The first draft of this design document was reviewed and discussed at a 1-day workshop held in Westbank on February 27, 2002. Comments and suggestions by participants at this workshop have been incorporated into version 1.0 of the document, which was distributed to project participants June 19, 2002. Subsequent to the release of that draft, a model review meeting was held October 15, 2002, followed by a model review and training session on January 15-16, 2003. This version of the model and design document (version 2.2) incorporates comments and improvements coming out of those meetings (major changes from the June 19 2002 (version 1.0) Design Document are noted throughout the text). Appendix B of this document provides a version history of the Okanagan Sockeye model.

1 We use Canadian spelling of Okanagan throughout this document.

2 We refer to all sockeye salmon originating from Okanagan Basin lakes as Okanagan sockeye. Currently the only population of Okanagan sockeye rears in Osoyoos Lake, but populations could also potentially rear in Skaha, Okanagan, and other lakes if passage to those lakes was restored.

3 Funded by contributions of the Bonneville Power Administration to the Northwest Power Planning Council's Fish and Wildlife Program.

## 1.2 Model Objectives

The overall role of the model within the overall Skaha Lake project is to explore the relative benefits and risks of possible reintroduction strategies and alternative monitoring approaches to assess the impacts of reintroduction. Consequently, the key function of the model is to provide a framework for capturing key hypotheses about sockeye and kokanee and the stressors that act on them throughout their entire life-cycles (including interactions among sockeye/kokanee/mysis in Skaha Lake), and produce a range of possible relative outcomes from various management and environmental scenarios.

The life-cycle model has three primary objectives.

1. **Explore stock rebuilding benefits**

   Restoring access to Skaha Lake for the Okanagan sockeye population (which is currently confined to Osoyoos Lake) has potential population-level benefits in terms of providing additional, higher quality rearing habitat for sockeye juveniles. However, increased juvenile output may not translate to increased abundance of returning adult sockeye because of various mortality factors throughout the rest of the life-cycle of the stock. Some of these factors include passage through 9 mainstem dams and many smaller vertical drop structures on the Okanagan and Columbia Rivers, commercial and sport harvests, and numerous physical and thermal barriers during upstream migration.

   The life-cycle model will use historical data and (where necessary) expert judgement to quantify these and other mortality factors and project ranges of future adult population abundance of Okanagan sockeye after reintroduction to Skaha Lake. This will provide a tool for addressing questions such as:

   - What are the overall benefits of reintroduction to Skaha Lake (in terms of numbers of returning adults)?
   - What are some of the potential bottlenecks in overall survival that constrain the benefits of reintroduction to Skaha Lake?
   - How would reducing these bottlenecks through various mitigation measures affect overall production of Okanagan sockeye?

2. **Explore risks to resident kokanee**

   Some agencies have expressed concern over the potential effects of the reintroduction of sockeye salmon on resident kokanee stocks. Potential risks include transmission of disease (which is being assessed through field sampling and assays), and increased competition between kokanee and sockeye juveniles for food resources, particularly in light of an established population of introduced mysid shrimp.

   To assess these risks, the life-cycle model will include a population model of resident kokanee in Skaha Lake, and will model competitive interactions between sockeye, kokanee, and mysis populations. This will allow us to use the model to explore questions such as:

   - What are the possible effects of reintroducing sockeye to Skaha Lake on the abundance of resident kokanee adults?
   - What are potential hypotheses about the mechanism by which kokanee, sockeye, and mysis interact (e.g. effects on lake carrying capacity)?

- What are the implications of these hypotheses in terms of projected effects of sockeye reintroduction on kokanee and sockeye production?
- What are the implications of these results for designing both the re-introduction of sockeye and before / after monitoring?

3. **Explore learning benefits**

   The ultimate purpose of an experimental reintroduction of sockeye into Skaha Lake is to provide a test case for reducing uncertainties surrounding the effects of reintroducing sockeye to Okanagan Lake. The reintroduction of sockeye to Skaha Lake, and the requisite monitoring of key variables both before and after the reintroduction, provides an opportunity to learn something about key uncertainties (e.g. potential impacts of sockeye on resident kokanee populations; mechanisms for sockeye-kokanee-Mysid interactions; shore/river spawning plasticity in sockeye; overall sockeye population responses to increased rearing habitat for juveniles).

## 1.3 Model Complexity

Our general approach to how much detail to include in a simulation model is to *keep it as simple as possible, but not too simple*. Put differently, we feel that the appropriate level of complexity is that which provides a reasonable representation of alternative hypotheses about the links between management actions (in this model, different reintroduction strategies and other mitigative actions) and performance measures (adult abundance of sockeye and kokanee). The mechanisms that we include in the model are thus best viewed as hypotheses that can in theory be tested using empirical data, either now using existing data or in the future if certain data are collected. Data do not necessarily need to be collected for all of the relationships included within the model. Rather it is important that a few critical inputs are provided, and the major model components are monitored as experiments are undertaken. Ultimately, the level of complexity is determined by the objectives of the model and the availability of the data upon which to base alternative hypotheses.

It is important to point out that **we are not attempting to build a model that will make precise predictions of system behaviour or outcomes**. Instead, the model will provide a tool for exploring the relative benefits and risks of possible reintroduction strategies and alternative monitoring approaches. The model should be thought of as a tool to explore the range of possible futures, and the key factors which determine them. The entire process of developing a model is an effort to discover how much detail must be included to adequately describe the behaviour of the system (i.e. to meet the model's objectives).The modelling process should therefore be viewed as iterative, with more components being incorporated only as they are needed and as components previously incorporated are understood (Figure 1.1). The current version of the OkSockeye model is an improvement over earlier versions, but can still be improved by incorporating information gathered through experiments and monitoring.

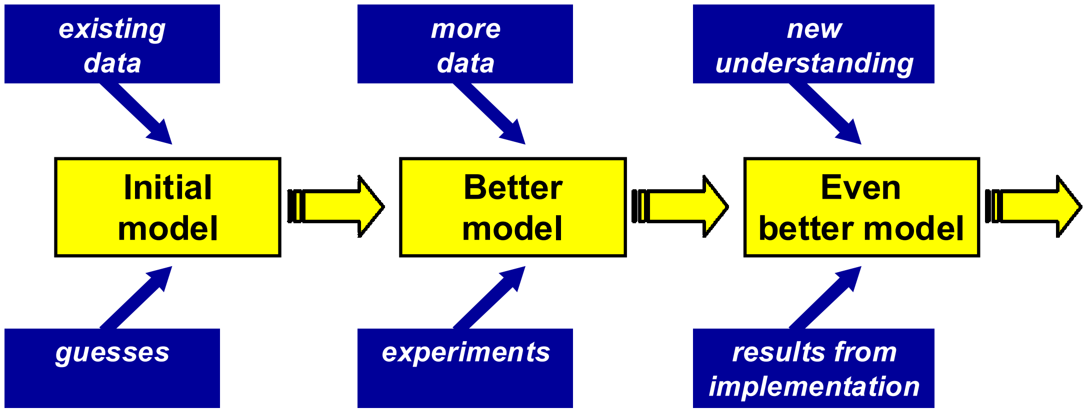



**Figure 1.1.** Iterative approach to model development.

Given the objectives of this model, and the limitations in available data, we have adopted the following simplifying principles in the model design:

1. While in reality there are many potential mortality factors at each life stage, we have chosen to model only the one or two that we perceive to be the most important or the most amenable to management control.
2. Where possible, we rely on simple empirical relationships rather than detailed mechanistic processes. Where more detailed mechanistic approaches are necessary, we have focussed on those mechanisms that appear to be most important in determining survival and growth rates.
3. We have chosen to represent some model components with single input values that may be derived from a more complicated model external to this one (see section 1.4 for an example).
4. We will attempt to make the model design sufficiently flexible to accommodate updates/improvements as more information becomes available or more detailed modules are developed. This modular structure has already proved to be useful in implementing some of the major changes since version 1.0 of the model was released.

We believe that these principles will result in a model that is detailed enough to meet the project objectives, while remaining consistent with the amount of data available.

## 1.4 Relationship to the Fish / Water Management Tool (FWMT)

The Okanagan Basin Technical Working Group, ESSA Technologies Ltd., and Summit Environmental, with funding provided by Douglas Country Public Utility District, have recently developed a Fish / Water Management Tool (FWMT) to explore the effects of flow management at Penticton Dam on downstream sockeye and Okanagan shore-spawning kokanee populations (ESSA Technologies and Summit Environmental 2002). The FWMT model goes into considerably more detail on sockeye early life history stages and its interactions with river flows and temperatures than the OkSockeye model, but considerably less detail on the migrating smolt, ocean residence, and adult return life stages. The two models are therefore complementary, and it will be useful to run the two models simultaneously (i.e., using outputs from FWMT as inputs to OkSockeye and vice-versa) to explore a wider range of suites of management actions (across all life history stages) than can be explored by either of the models on their own.

# 2.0 Model Scope and Overall Structure

## 2.1 Spatial and Temporal Scope

The spatial scope of the model is shown in Figure 2.1. Given the purpose of the model, the model will focus on the following populations:

- sockeye salmon in Osoyoos Lake;
- sockeye salmon in Skaha Lake (this population doesn't currently exist, but could be formed by a northward extension of the Osoyoos Lake population if fish passage around McIntyre Dam is provided);
- kokanee in Skaha Lake; and
- mysis in Skaha Lake.

The model will also include hydrography (flows, air and water temperatures) of Okanagan Lake and the Upper Columbia River to the extent that these physical factors affect downstream fish populations.

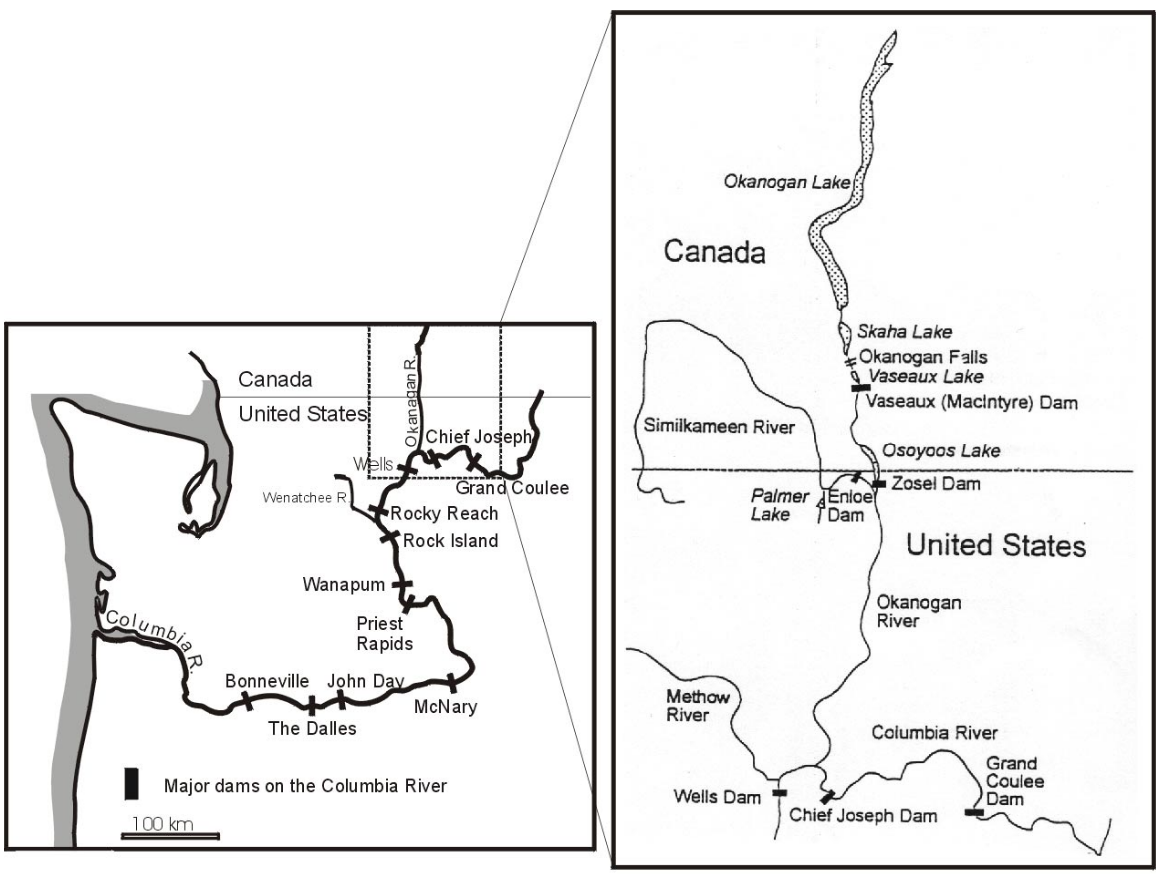



**Figure 2.1.** Map of Columbia and Okanagan Rivers. Inset: Map of Okanagan Basin showing major lakes and dams (inset source: Fryer 1995).

The model will operate at an annual time step, although certain processes will require a finer temporal resolution to capture the dynamics of physical and biological interactions. For example, simulation of sockeye spawning will require a seasonal or monthly time step to account for the effects of seasonal flows on spawning habitat. Similarly, upstream migration of sockeye through the Okanagan River from the confluence with the Columbia River to Osoyoos Lake will be modelled on a daily time step to account for the effects of water temperature on migration timing. Characteristics of fish and mysis populations will be accumulated on an annual basis. Given the pre-dominant 4-year life cycle of Okanagan sockeye, a 20 to 30-year (5–8 generations) time horizon for forward simulations will probably be sufficient.

## 2.2 Management Actions

One of the benefits of models is that it allows users try out different policies and combinations of policies and assess their relative effectiveness. For example, users of the model might wish to explore a scenario that includes harvest of mysis in Skaha Lake, reduction of harvest rates in the lower Columbia River, and flow management to reduce summer water temperatures in the Okanagan River. The model will allow users to implement the management actions shown in Table 2.1. In most cases, management actions are assumed to be constant from year to year.

**Table 2.1.** Management actions implemented in the model, their mechanism (Direct via user-defined parameter value; Indirect via parameterisation of functional relationship), and relevant equation in this report.

| Action | Mechanism | Equation |
|---|---|---|
| **Sockeye** | | |
| Changes in phosphorus concentrations of Osoyoos and Skaha Lakes | Direct | |
| Improvement in habitat quality | Indirect via parameterisation of spawning capacity vs. flow | 4-2 |
| Creation of new habitat | Direct | 4-3 |
| Hatchery fry supplementation | Direct | 4-12 |
| Smolt supplementation | Direct | 4-24 |
| Predator control in Okanagan Lakes (esp. Vaseaux) | Indirect via survival rate from rearing lakes – Wells Dam | 4-25 |
| Operation of mainstem dams | Indirect via mean SAR, upstream survival rate | 4-26, 4-32 |
| Control of northern pikeminnow in Columbia R. reservoirs | Indirect via mean SAR | 4-26 |
| Harvest in the Lower Columbia River. | Direct | 4-30, 4-31 |
| Harvest rate on Okanagan River. | Direct | 4-35 |
| Adult supplementation | Direct | 4-37 |
| **Kokanee** | | |
| Changes in phosphorus concentrations of Osoyoos and Skaha Lakes | Direct | |
| Improvement in habitat quality | Indirect via parameterisation of spawning capacity vs. flow | 4-2 |
| Creation of new habitat | Direct | 5-21 |
| Recreational harvest | Direct | 5-17 |

| Action | Mechanism | Equation |
|---|---|---|
| **Mysis** | | |
| Annual harvest | Direct | 6-9 |
| **Lake Predators** | | |
| Annual harvest | Direct | 7-4 |

## 2.3 Overall Model Structure

The model will consist of five submodels (described in detail in the next sections):

1. Hydrology / Temperature submodel;
2. Sockeye submodel;
3. Kokanee submodel;
4. Mysis submodel; and
5. Lake Predator submodel.

The submodels are connected as shown in Figure 2.2. The hydrology submodel provides flows and temperatures that drive key biological processes in the sockeye, kokanee, and mysis submodels. The sockeye, kokanee, and mysis submodels exchange production information for determining density-dependent growth and survival rates in food-limited rearing habitat in Skaha Lake. The model also includes potential predation on mysis by kokanee. The predator submodel calculates the biomass of sockeye fry and kokanee required to support production of predator populations.

Sections 3–7 describe in detail the proposed design of the submodels. Section 8 summarises the user-defined parameters and preliminary parameter values.

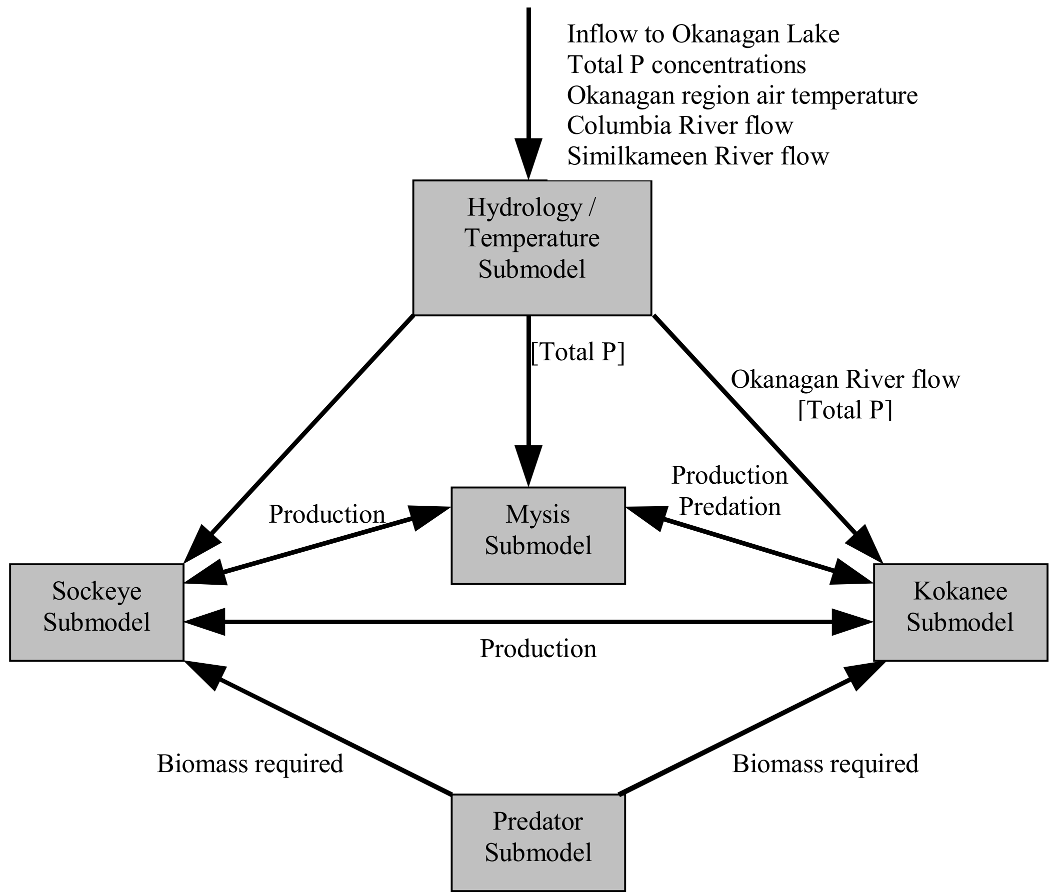



**Figure 2.2.** Overall structure of model showing linkages between submodels.

# 3.0 Hydrology / Temperature Submodel

The Hydrology / Temperature submodel is important for determining sockeye habitat spawning capacity, egg to fry survival and the survival of returning adults (see Figure 4.1).

## 3.1 Selection of Inputs to Hydrology / Temperature Model

Major inputs and outputs of the hydrology / temperature submodel are shown in Figure 2.2. Inputs to the hydrology submodel are assumed to be due to natural precipitation and weather processes (e.g. inflow to Okanagan Lake is governed by precipitation in the Upper Okanagan watershed and/or to management actions that are beyond the scope of this model; Similkameen River flows are determined by precipitation in the Upper Similkameen watershed and by management of Enloe Dam). To capture the variation in these inputs, the hydrology submodel will simply select a series of sequential water years from historical datasets to represent future flow and temperature scenarios (Table 3.1). It is preferable to select from a long a time series as possible to capture a broad range of environmental conditions.

For example, a 20-year simulation may use the daily flow and temperature data from years 1956-1975 to drive the model. Daily flow and temperature data will be aggregated up to annual, monthly, or seasonal values (averages, maxima, minima) as needed to fit the temporal requirements of the sockeye, kokanee, and mysis submodels. Starting water years can be selected randomly (to represent uncertainty in future climate conditions), or one could specify a particularly wet or dry series of water years to represent alternative hypotheses about future climate regimes.

**Table 3.1.** Hydrologic data sets.

| Data | Years Available | Source |
|---|---|---|
| Okanagan Lake inflows | 1922 to 1997 | Bull 1999, citing Ward and Associates 1998 |
| Okanagan River flow (at Oliver) | 1944-1999 | Stockwell et al. 2001 |
| Similkameen River flow (at Nighthawk) | 1928 to 2001 | WA Dept of Ecology (www.ecy.wa.gov/programs/ewp) |
| Okanagan Region air temperature (at Oliver) | 1939 to 1999 | Environment Canada; Stockwell et al. 2001 |
| Phosphorus concentrations in Skaha and Osoyoos Lakes | 1968 to 2001 | Geri Huggins, WLAP (email dated March 25 2002) |

Historical flow and temperatures will be used to calculate various physical attributes in the Upper Okanagan River (between Okanagan Lake and Osoyoos Lake) and Lower Okanagan River (from Osoyoos Lake to the confluence with the Columbia River). Phosphorus concentrations are used to determine the productive capacity and Secchi Depths of rearing lakes. The following sections provide more details on how physical attributes are used in the other submodels to drive biological processes, the spatial and temporal elements of these attributes, and the proposed approaches for calculating them.

## 3.2 Flow in the Okanagan River (above Osoyoos Lake)

Flows in the Okanagan River (between Okanagan Lake and Osoyoos Lake) during spawning (September-October) will be used to determine the capacity of spawning habitat for Skaha Lake and Osoyoos Lake sockeye spawners. Flows during incubation (November–February) will be used to determine the flushing and stranding mortality of emergent sockeye fry. Daily flows during the summer (June – September )are used to determine daily temperatures, which determine the spatial distribution of sockeye spawners in the Okanagan River.

Flows out of Okanagan Lake are regulated to balance biological requirements of downstream sockeye, and regulation of lake levels for recreation, flood control, and biological requirements of shore-spawning kokanee. A detailed management model of Okanagan River flow management is beyond the scope of this project and is currently a task in an Okanagan Basin Technical Working Group project funded by the Douglas County PUD. The earlier draft of the design document proposed a simple approach to capture possible management effects on Okanagan River flows, but participants at the February 27th workshop suggested that the proposed approach was too simplistic and that it was too difficult to model this complex management situation in a simple way.

Therefore, in this model we assume that management of Okanagan River flows will continue into the future as they have since the Canada-BC Okanagan Basin Implementation Agreement was developed in the early 1970s. This agreement prescribes minimum and maximum flows during spawning, incubation, and upstream migration periods. Flows are managed to remain within these bounds, within the constraints imposed by drought and high flow conditions. This approach will produce flows within the prescribed minima and maxima in average water years, but will also produce flows outside of the prescribed constraints during the relatively rare water years when flows are excessively high or low.

This approach will be implemented in the model by using actual spawning, incubation, and upstream migration flows (as measured at Oliver, B.C.) for water years 1974 through 1999 (i.e., the years in which the current set of management rules have been implemented). Water years prior to 1974 will be “mapped” to post-1974 years according to the similarity of net inflows to Okanagan Lake (an indicator of natural runoff conditions). For example, comparison of net Okanagan Lake inflows for 1944 to net inflows for the 1974–1999 (current management years) suggests that runoff conditions in 1944 were most similar to those in 1985 (Figure 3.1). Therefore, if water year 1944 is selected for a given simulation year, then actual Oliver flows from the year 1985 will be used to drive physical and biological processes in the model. The result of this mapping approach is a simulated time series of spawning, incubation, and upstream migration flows from 1944–1999 (Figure 3.2). Simulated flows from 1944–1973 approximate what managed flows would have been in those years, given the post-1973 management regime and the natural runoff conditions in those years. In general, simulated flows during the 1944–1973 period are less variable than the actual flows.

Future development of a more detailed management model of Okanagan River flow control can feed into this model by providing revised historical time series of spawning, incubation, and upstream migration flows for sets of alternative management regimes.

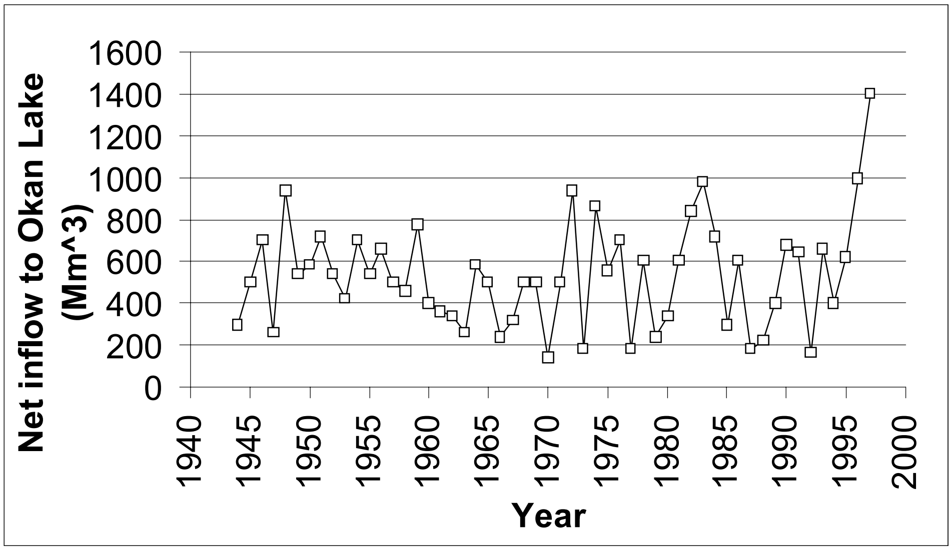
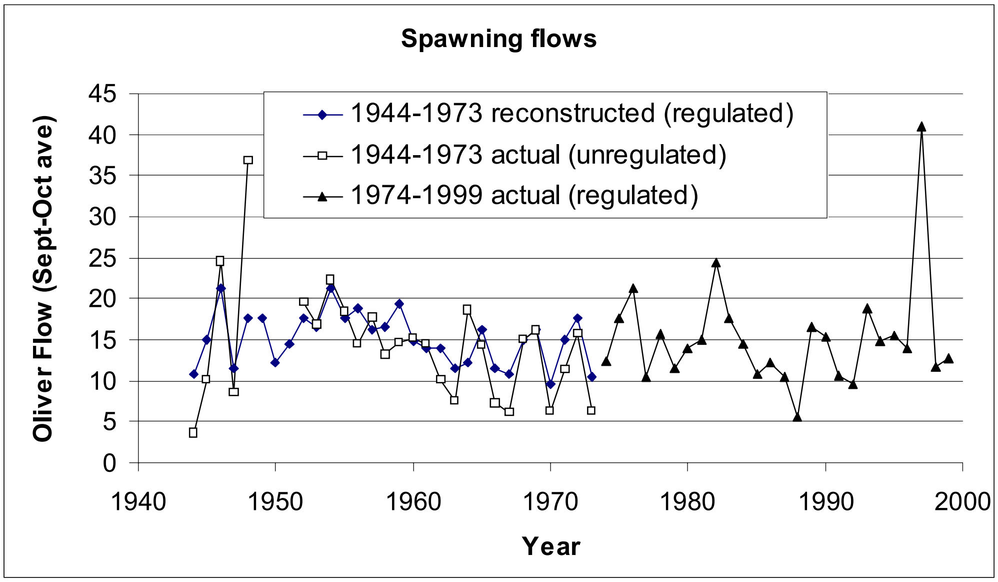



**Figure 3.1.** Net inflows to Okanagan Lake, 1944-1997.



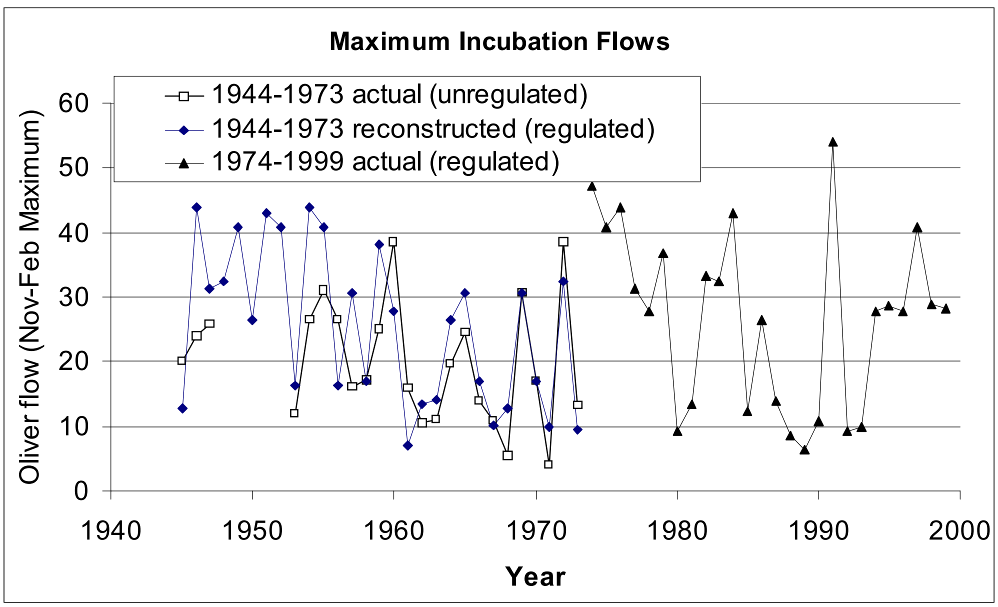




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**Figure 3.2.** Reconstructed spawning, incubation, and upstream migration flows at Oliver for years 1944-1974 based on mapping to post-1973 years.

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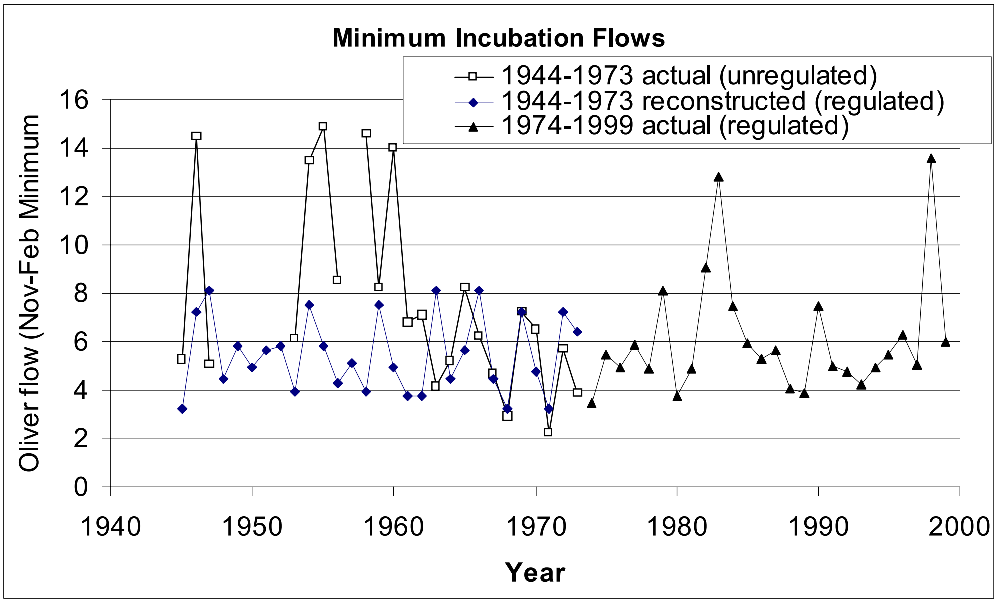


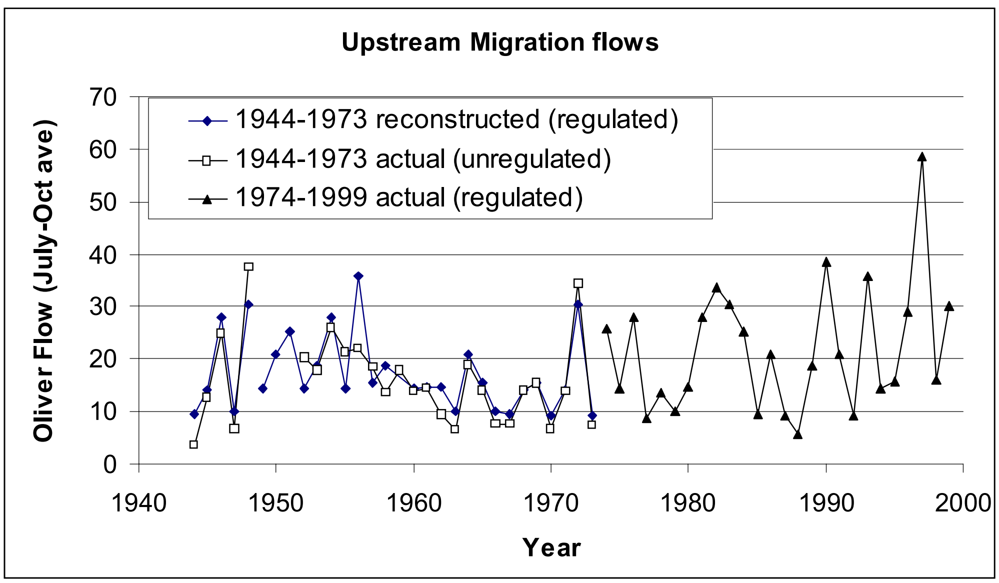


**Figure 3.2.** Reconstructed spawning, incubation, and upstream migration flows at Oliver for years 1944-1974 based on mapping to post-1973 years.

## 3.3 Temperature in the Okanagan River (at Okanagan Falls)

*Note: The empirical relationship between water temperatures and 5-day average air temperatures developed for version 1.0 of the model has been replaced with the seasonal relationships developed by Hyatt and Stockwell (2002) for the FWMT project.*

Water temperatures between Osoyoos and Skaha Lakes during the adult migration period (June–October) are required to determine the distribution of returning sockeye spawners between the two lakes. Lower temperatures in the Okanagan River will permit sockeye spawners to migrate further up the river (see section 4.6.3). Water temperatures are derived from a relationship between water temperatures and air temperatures developed by Hyatt and Stockwell (2002). The relationship is:

$$WaterTemp_{OkFalls} = Slope_{OkFallsTemp} (AirTemp_{Oliver,10\text{-}dayAve}) + Int_{OkFallsTemp} \quad \text{[eq. 3-1]}$$

where: $AirTemp_{Oliver,10\text{-}dayAve}$ = air temperature measured at Oliver, average of 10 days preceding day on which water temperature recorded

Slope and $Int_{OkFallsTemp}$ = user-defined parameters, based on empirical relationship

We will use this relationship to construct a daily time series of water temperatures for water years 1944-1999. The time series used in a particular simulation year will be selected according to water year as discussed above.

## 3.4 Flow and Temperature in the Okanagan River (below Osoyoos Lake)

*Note: The empirical relationship between water temperatures and 5-day average air temperatures developed for version 1.0 of the model has been replaced with the seasonal relationships developed by Hyatt and Stockwell (2002) for the FWMT project.*

Daily flow and water temperatures in the Okanagan River below Osoyoos Lake are used (in conjunction with flows and temperatures in the Similkameen River, which joins the Okanagan River south of Osoyoos Lake) to determine water temperatures in the Lower Okanagan River (at the confluence with the Columbia River) between June and September. Summer temperatures in the lower river are used in the sockeye submodel to determine when returning adults enter the Okanagan River (see Section 4.6). This timing affects both the distribution and survival of returning adult spawners.

Flows below Osoyoos Lake will be selected according to water year using the same mapping approach described above for flows at Oliver. Only post-1973 actual flows will be used, to represent the assumption that future management rules will be the same as those in place since 1974. The reconstructed time series of average upstream migration flows is shown in Figure 3.3.

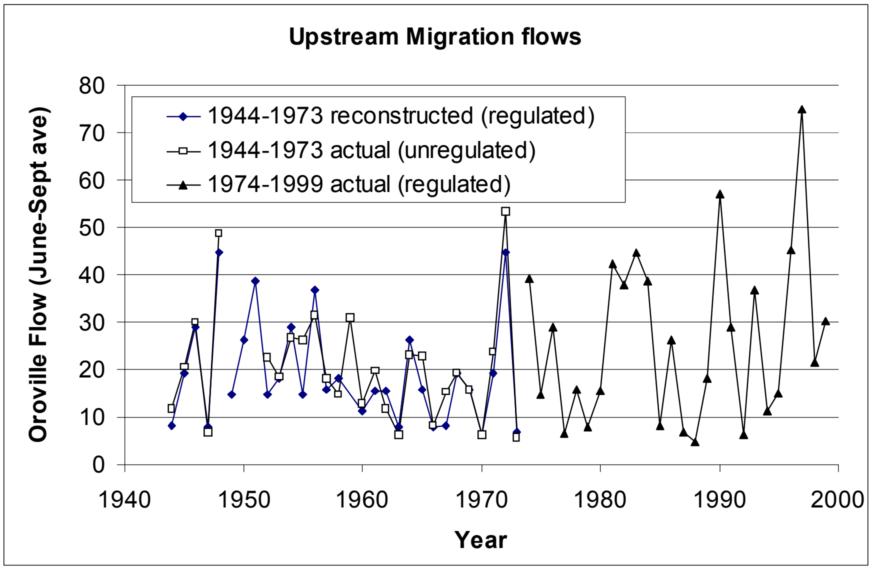


**Figure 3.3.** Reconstructed upstream migration below Osoyoos Lake for years 1944-1974 based on mapping to post-1973 years.

Because water temperature data in the Okanagan River are intermittent, we reconstructed a continuous time series of daily water temperatures based on an empirical relationship between water temperature at Zosel Dam (Oroville, WA) and air temperatures at Oliver (Hyatt and Stockwell 2002).

$$WaterTemp_{Oroville} = Slope_{OrovilleTemp} (AirTemp_{Oliver,10\text{-}dayAve}) + Int_{OrovilleTemp} \quad \text{[eq. 3-2]}$$

where: $AirTemp_{Oliver,5\text{-}dayAve}$ = air temperature measured at Oliver, average of 10 days preceding day on which water temperature recorded

Slope and Int = user-defined parameters, based on empirical relationship

## 3.5 Flow and Temperature in the Similkameen River

Daily flows and temperatures in the Similkameen River, the largest tributary to the Okanagan River south of Osoyoos Lake, are needed to calculate temperatures in the lower Okanagan River. Flow data from the Similkameen River (measured at Nighthawk, located about 8 miles from the confluence with the Okanagan River) is available from 1928, and will be selected according to water year as described in section 3.1. Water temperature data for the Similkameen River is also intermittent, so we developed a relationship between summer (June-September) water temperatures, air temperatures (measured at Oliver) and Similkameen River (at Nighthawk) flows ($p<<0.001$; R-squared = 0.85):

$$WaterTemp_{Sim} = Const_{SimTemp} + TempCoef_{SimTemp} * AirTemp_{Oliver} + FlowCoef_{SimTemp} * Flow_{Sim} \quad \text{[eq. 3-3]}$$

where: $WaterTemp_{Sim}$ = daily water temperature in Similkameen River;

$Const_{SimTemp}$, $TempCoef_{SimTemp}$, $FlowCoef_{SimTemp}$ = user-defined parameters, based on empirical relationship between water temperature, air temperature, and flow (parameter values are 6.22692, 0.58611, and –0.0005, respectively)

$AirTemp_{Oliver}$ = daily air temperatures, selected according to water year

$Flow_{Sim}$ = daily flow of Similkameen River at Nighthawk, selected according to water year

## 3.6 Temperature in the lower Okanagan River (at confluence with Columbia River)

Summer daily water temperatures (June-September) in the lower Okanagan River are important in determining the migration timing of returning adults. Water temperatures greater than 21 degrees constitute a thermal block to upstream migration, and fish will hold in the Columbia River until water temperatures in the Okanagan River fall to below that threshold. Delays in migration may be associated with lower prespawning survival and egg viability (Alexander et al. 1998).

There is no long-term continuous record of daily water temperatures in the lower Okanagan River. Therefore, in the model, daily temperatures in the lower Okanagan River will be approximated as the flow-weighted average of water temperatures in the Okanagan River at Zosel Dam and in the Similkameen River:

$$WaterTemp_{OkLower} = \frac{Flow_{Oroville,Summer} * WaterTemp_{Oroville} + Flow_{Sim} * WaterTemp_{Sim}}{AdjFlow_{Oroville} + Flow_{Sim}} \quad \text{[eq. 3-4]}$$

where: $Flow_{OkOroville}$ = selected according to water year (see Figure 3.3)
$WaterTemp_{OkOroville}$ = derived from equation 3-2
$Flow_{Sim}$ = daily flow of Similkameen River at Nighthawk, selected according to water year
$WaterTemp_{Sim}$ = derived from equation 3-3

The weighted average as calculated in equation 3-4 closely approximates the limited observations of water temperatures at Malott, WA about 11 miles from the confluence with the Columbia River (Figure 3.5; correl. coeff. = 0.96).

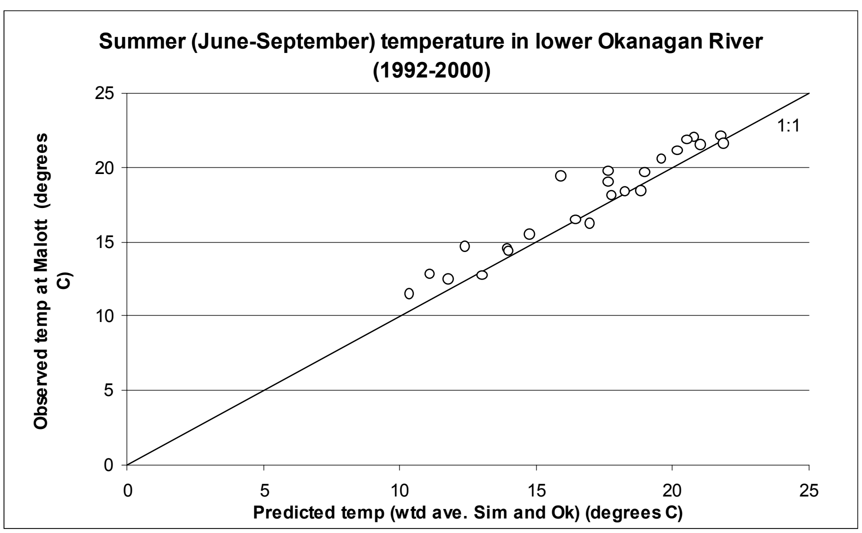


**Figure 3.5.** Predicted vs. observed water temperature in lower Okanagan River. Observed water temperatures from Stockwell et al. 2001.

## 3.7 Phosphorus concentration in Osoyoos and Skaha Lake

Total phosphorus concentrations have been found to be a reasonable predictor of a lake's ability to produce fish biomass (Hyatt and Rankin 1999). Total phosphorus concentrations for Osoyoos and Skaha Lakes are shown in Figure 3.6 (top panel). P concentrations have declined since the earliest records around 1970, likely as a result of installation of more efficient sewage treatment plants in the 1970s and 1980s. We assume that post-1985 values represent current conditions, and use these values to reconstruct a continuous time series of P concentrations from 1944 to 1984 (Figure 3.6, bottom panel). Reconstruction of the pre-1985 years is based on similarity in the maximum flows in the Okanagan River at Oliver (see Figure 3.2). The reconstructed time series thus represents an approximation of the P concentrations that might have been observed in years prior to 1985, given the current efficiency of Okanagan waste treatment plants and the hydrological conditions that existed in the earlier years.

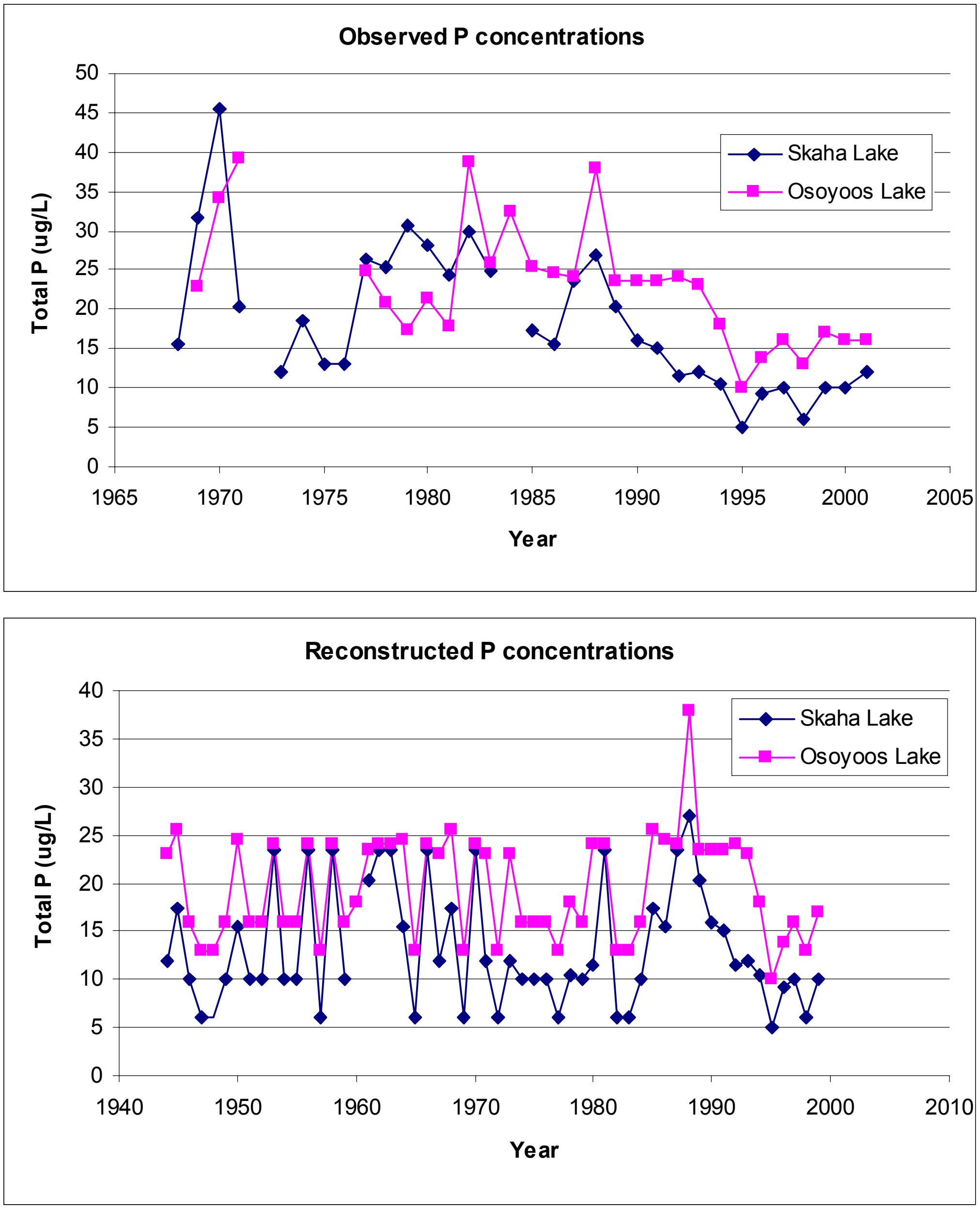


**Figure 3.6.** Observed (top) and reconstructed (bottom) Phosphorus concentrations in Skaha and Osoyoos Lakes. Reconstruction was based on maximum flows in the Okanagan River at Oliver.

## 3.8 Secchi Depths in Osoyoos and Skaha Lake

Lake Secchi Depths are required by the Kokanee submodel for determining growth rates of adult fish. We calculate Secchi Depths (in meters) based on Total Phosphorus concentrations using Phosphorus and Secchi Depth data from Okanagan Lake (1997–2000; Andrusak et al. 2001). The relationship is:

$$\log(SecchiDepth) = Int_{SecchiDepth} + Slope_{SecchiDepth} * \log(TotalPhosphorus) \qquad \text{[eq. 3-5]}$$

where: $Int_{SecchiDepth}$ = user-defined parameter
$Slope_{SecchiDepth}$ = user-defined parameter
TotalPhosphorus = total P concentration (ug/L); reconstructed as shown in Figure 3.6.

# 4.0 Sockeye Submodel

The sockeye submodel is based on survival from one life-stage to the next. Figure 4.1 shows a general schematic of these life stages and the mortality factors included in the model. Each of the linkages is described in the following sections. Participants at the February 27th workshop suggested a simpler approach in which the number of emerging fry is a density-dependent function of spawner abundance. This function would represent the aggregated response of fry production to changes in spawning and incubation flows, assumptions about the capacity of spawning habitat, and other biological parameters such as fecundity and survival rates, and optimal female densities. The function would change from year to year in response to variation in spawning and incubation flows.

We have chosen to retain the less aggregated approach (in which spawner-egg and egg-fry life stages are modelled separately) for two reasons. First, this approach allows more direct control over the capacity of spawning habitat, which workshop participants indicated was a potentially important management action. Second, the less aggregated approach requires assumptions about potentially important biological parameters (e.g. optimal female densities) to be explicit, and allows users to explore the implications of these parameters for model results.

Note that one can reconstruct spawner-fry production relationships using the outputs of the model's aggregated approach, then compare the implied relationships across a set of flow conditions to determine the effects of flows on the shape of the production curves. Some of these comparisons are shown in Section 4.2 below for illustration.

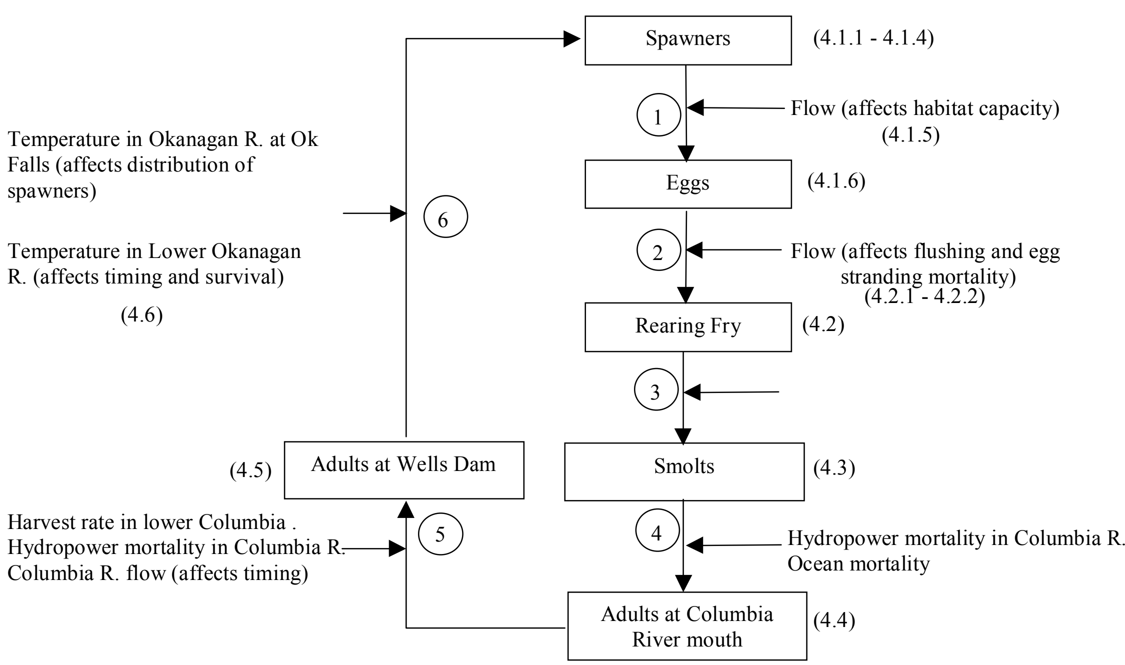


**Figure 4.1.** Schematic of life-cycle of Okanagan sockeye, showing mortality factors included in the model. Numbers in brackets correspond to sections in which each component is described.

## 4.1 Spawner - Egg

Egg production is a function of maturity schedule, age-specific fecundity, sex ratio, optimal female density, and spawner capacity of the spawning grounds.

### 4.1.1 Maturity Schedule

*Note: Maturity schedules have been updated using the Core Numbers and Traits (CNAT) estimates from Hyatt et al. (2002), adjusted for fish of unknown age.*

Hyatt et al. (2002) estimated the age composition of Okanagan sockeye for 1988-1992 and 2000-2001. Because the vast majority of Okanagan sockeye spend only 1 winter in freshwater (average 96% over the seven years of CNAT estimates), the model assumes that all Okanagan sockeye are age 1.x. The simplified maturation schedule is shown in Table 4.1. The proportions of ages 1.1, 1.2, and 1.3 in Table 4.1 are based on Hyatt et al.'s estimated age composition.

While the maturation schedule is likely a result of interactions between genetic and environmental factors, such complexity is beyond the scope of this model. Instead, we propose to simply select randomly from these seven maturity schedules (and other years if such data are available) for each brood year of sockeye.

**Table 4.1.** Age composition estimates from Hyatt et al. (2002). Age notation indicates # of winters spent in freshwater. # of winters spent in ocean.

| | Age (%) | | |
|---|---|---|---|
| Return Year | 1.1 | 1.2 | 1.3 |
| 1988 | 0.2 | 98.0 | 1.8 |
| 1989 | 4.4 | 92.1 | 3.5 |
| 1990 | 62.0 | 26.8 | 11.2 |
| 1991 | 13.9 | 84.7 | 1.4 |
| 1992 | 2.2 | 97.8 | 0.0 |
| 2000 | 8.9 | 90.3 | 0.8 |
| 2001 | 3.3 | 94.4 | 2.3 |

### 4.1.2 Age-specific Fecundity

Fryer (1995) reports age-specific fecundity rates (eggs per female) estimated from spawning ground surveys (Table 4.2).

**Table 4.2.** Age-specific fecundities (Major and Craddock 1965, as reported by Fryer 1995).

| Age | Fecundity (eggs per female) |
|---|---|
| 1.1 | 2014 |
| 1.2 | 2879 |
| 1.3 | 3609 |

The age-weighted average fecundity in a given brood year is:

$$AveFecundity = \Sigma_t (\#Spawners_t * Fec_a) / \Sigma_a \#Spawners_a \quad [eq. 4-1]$$

where: $\#Spawners_a$ = # of spawners of age a
$Fec_a$ = fecundity at age a (from Table 4.2)

### 4.1.3 Female Proportion

*Note: Sex composition has been updated using the Core Numbers and Traits (CNAT) estimates from Hyatt et al. (2002).*

Hyatt et al. (2002) estimate an average female proportion of 0.52 from 21 years of data between 1971 to 2001. For the Osoyoos population. this value is adjusted to account for removal of females for broodstock for hatchery fry supplementation into Skaha Lake (see section 4.2.6).

### 4.1.4 Optimal female density

Hyatt and Rankin (1999) report optimal female densities for a number of sockeye stocks. These range from 0.56 to 2.0 females/$m^2$ (mean 1.48).

### 4.1.5 Spawner capacity

Existing spawning habitat for Osoyoos Lake sockeye is in the Okanagan River between McIntyre Dam and Osoyoos Lake, with the majority of spawning taking place in the 2.4 km index section immediately downstream of McIntyre Dam (Hyatt and Rankin 1999). Surveys conducted in the early seventies generated estimates of the amount of "good" spawning habitat in this section at various flows (Figure 4.2; Fisheries Service Environment Canada 1973). Potential spawning habitat for Skaha Lake sockeye is available in the channelled portion of the Okanagan River between Okanagan Lake and Skaha Lake. A recent survey of spawning habitat conducted as part of the overall Skaha Lake project estimated that there was 63 $m^2$ of high quality habitat and 6,955 $m^2$ of medium quality spawning habitat in this reach (ONFC 2002). Workshop participants noted that this area was not likely to be flow-dependent because the reach is channelled with uniform geometry. Based on this information, we can develop a relationship between flows and spawning habitat to reflect the estimated capacity of both high and medium quality spawning habitat (Figure 4.3; note different scales from Figure 4.2). Note that the relationships shown in Figure 4.3 can be reparameterised to represent potential improvement of existing medium quality spawning habitat to good quality habitat.

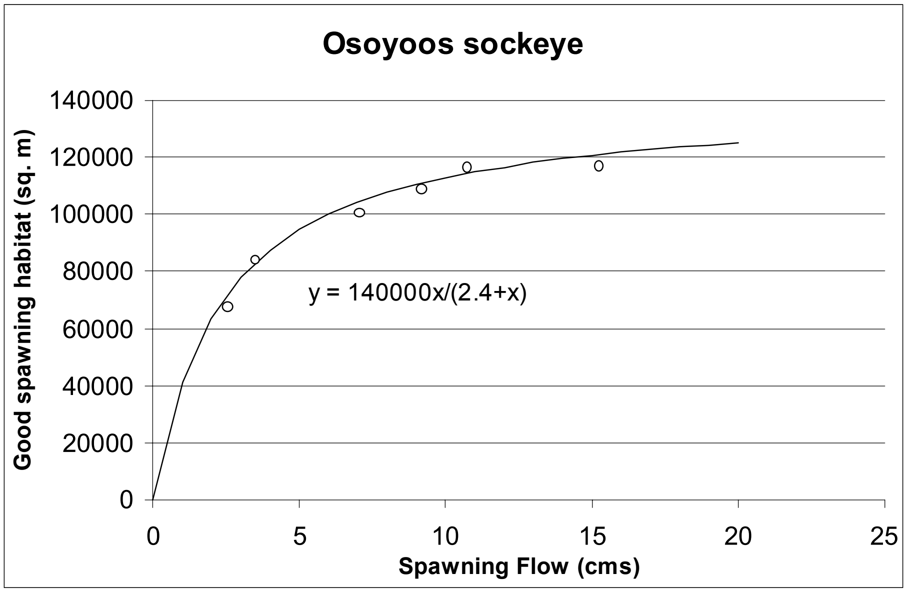


**Figure 4.2.** Area of good habitat in Osoyoos spawning index reach at various flows.

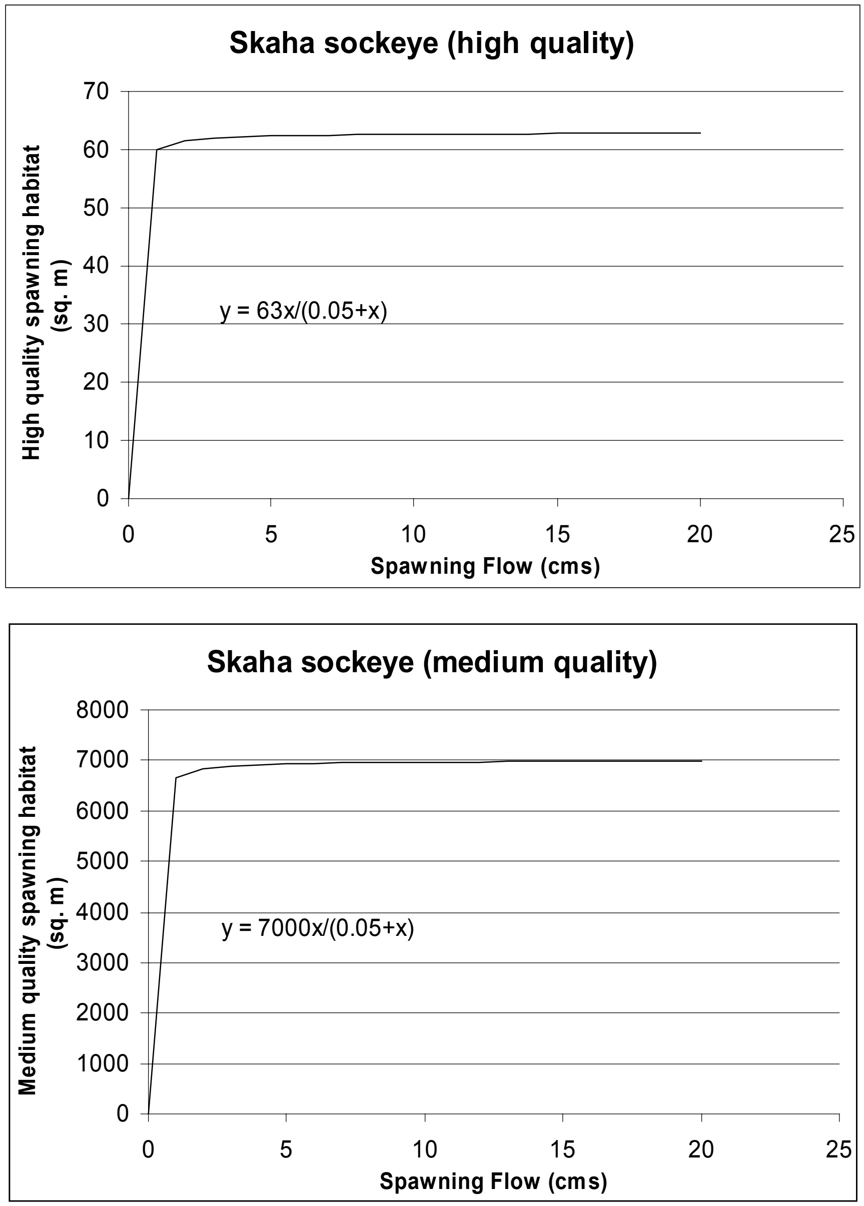


**Figure 4.3.** Area of high (top) and medium (bottom) quality spawning habitat for Skaha sockeye.

The relationship between spawning habitat and average spawning flows for both Osoyoos and Skaha spawning populations is:

$SpawnHab_{Current} = MaxHabitat * Flow_{Oliver,AveSpawn} / (FHalfMaxHabitat + Flow_{Oliver,AveSpawn})$ [eq. 4-2]

where: MaxHabitat = the maximum amount of habitat at high flows (user-defined population-specific parameter; $m^2$)

$Flow_{Oliver,AveSpawn}$ = average spawning flow (equation 3-1; cms)

FHalfMaxHabitat = flow producing half of MaxHabitat (user-defined population-specific parameter)

Workshop participants suggested that the model should allow the user to increase the habitat area by a fixed, flow-invariant amount. For Osoyoos sockeye, this could represent potential spawning habitat in the channelled portion of the Okanagan River immediately upstream from Osoyoos Lake. Although most spawning currently takes place in the natural river portion, the channelled portion could become important if spawning densities increase dramatically. The inclusion of a fixed additional habitat area could also be used to represent additional spawning habitat for Osoyoos sockeye between Vaseaux and Skaha Lakes (which would become accessible to Osoyoos spawners if passage around McIntyre and Okanagan Falls dams were restored), or restoration of spawning habitat for Skaha spawners between Skaha and Okanagan Lakes.

Total spawning habitat is therefore given by:

$$SpawnHab_{Total} = SpawnHab_{Current} + SpawnHab_{New} \quad \text{[eq. 4-3]}$$

where: $SpawnHab_{Current}$ = the current amount of habitat derived from equation 4-2 ($m^2$)
$SpawnHab_{New}$ = additional spawning habitat created or restored (user-defined population-specific parameter; $m^2$)

An additional complication in determining spawning capacity for Skaha sockeye spawners is the degree of overlap (competition for spawning habitat) with kokanee spawners. Overlap arises because of similarities in the timing, location, and habitat preferences of spawning kokanee and sockeye. Workshop participants suggested that the overlap was likely to occur mainly in the "medium quality" spawning areas, because substrate size in those areas were closer to the range utilised by kokanee (gravel size in the high quality areas is generally larger than the range preferred by kokanee).

To model these interactions, the model will include a user-defined overlap parameter ranging from 0 to 1. This parameter represents the fraction of the total medium-quality spawning habitat (as determined from equation 4-3) that is shared by sockeye and kokanee. A value of 0 indicates that there is no spatial or temporal overlap between the two populations; all spawning habitat is equally available to both populations at the time that they spawn. This represents an hypothesis where the two spawning populations are distinct in time and space. A value of 1 indicates that the two populations overlap completely in time and space; all of the available spawning habitat is competed for by the two populations. Since there is some spatial and temporal overlap between the two spawning populations, one would expect the overlap parameter to have a value close to 1, and a value of 0 for the overlap parameter is probably not justified.

Partitioning of shared habitat is based on the relative abundance of spawners.

The spawning overlap parameter is used to calculate the fraction of medium quality spawning habitat available to sockeye using equation 4-4:

$$SpawnHabFrac_{sockeye} = \#Spawners_{sockeye} / (\#Spawners_{sockeye} + \#Spawners_{kokanee}) * (SpawnOverlap) + (1 - SpawnOverlap) \quad \text{[eq. 4-4]}$$

where: $\#Spawners_{sockeye}$ = obtained from equation 4-37
$\#Spawners_{kokanee}$ = obtained from the kokanee submodel

SpawnOverlap = fraction of habitat competed over by kokanee and sockeye (user-defined parameter)

The total habitat available for use by Skaha Lake sockeye is calculated using equation 4-5):

$$SpawnHab_{Total} = SpawnHab_{Total,Medium} * SpawnHabFrac_{sockeye} + SpawnHab_{Total,High} \quad \text{[eq. 4-5]}$$

where: $SpawnHab_{Total,Medium}$ = amount of medium quality habitat, obtained from equation 4-3 and parameter values given in Figure 4.3 (bottom panel).
$SpawnHabFrac_{sockeye}$ = obtained from equation 4-4
$SpawnHab_{Total,High}$ = amount of high quality habitat, obtained from equation 4-3 and parameter values given in Figure 4.3 (top panel).

Calculated values of spawning habitat for Osoyoos (equation 4-3) and Skaha (equation 4-5) are used to estimate the spawning capacity (maximum number of female spawners on the spawning grounds) based on an optimal female density of 1.48 females / $m^2$ (mean of other sockeye stocks; Hyatt and Rankin 1999). The equation is:

$$SpawnCapacity = SpawnHab_{Total} * FemaleDensity \quad \text{[eq. 4-6]}$$

where: $SpawnHab_{Total}$ = obtained from equation 4-3 or equation 4-5
FemaleDensity = # of females per sq. m of spawning habitat (user-defined parameter)

### 4.1.6 Annual egg abundance

The number of eggs laid in a brood year is a Beverton-Holt type of function based on the number of spawners. This function produces a density-dependent relationship between spawner abundance and egg abundance (Figure 4.4). The function is mediated by spawning flow through its effect on the capacity of spawning habitat (equation 4-2).

$$\#Eggs = \frac{\#Spawners_{total} * FemaleProp * AveFecundity}{[1+(AveFecundity/EggCap * (\#Spawners_{total} * FemaleProp)]} \quad \text{[eq. 4-7]}$$

where: #Eggs = total number of eggs deposited
$\#Spawners_{total}$ = number of spawners from equation 4-36 and 4-37
AveFecundity = age-weighted average fecundity (from equation 4-1)
EggCap = egg capacity of spawning habitat
= SpawnCapacity (equation 4-3) * AveFecundity (equation 4-1)
FemaleProp = average proportion of the population that are female (user-defined parameter)

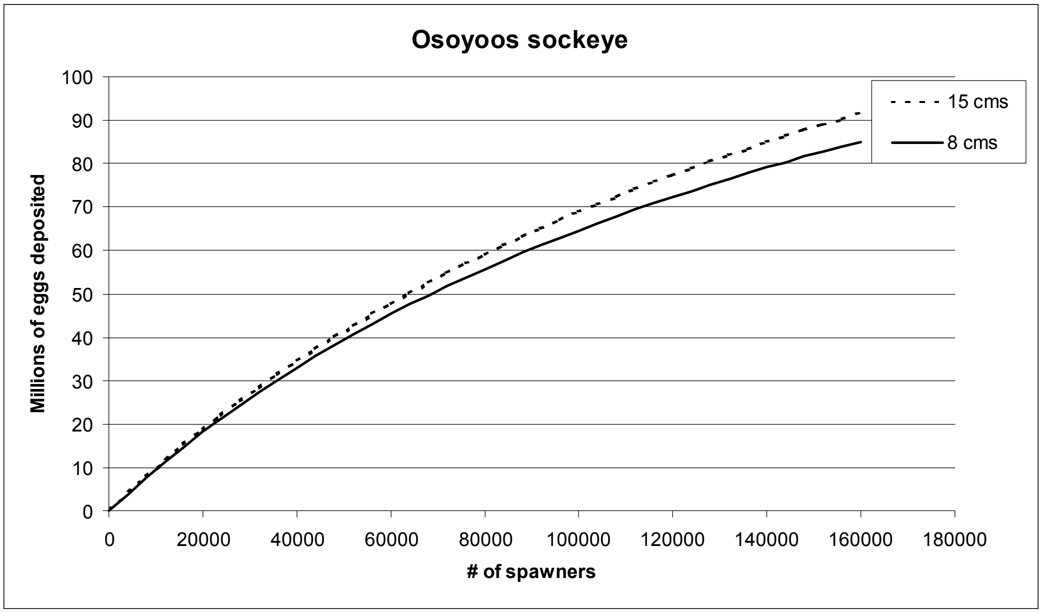


**Figure 4.4.** Relationship between number of eggs deposited and numbers of spawners at various flows.

## 4.2 Egg – Fry

Fry production for a given number of eggs is determined by three factors:

1. Egg stranding if incubation flows are too low.
2. Mortality associated with premature flushing of pre-emergent fry by excessive incubation flows.
3. Natural survival rate of eggs (survival in the absence of egg stranding or premature flushing of pre-emergent fry).

### 4.2.1 Egg Stranding

High flows during spawning followed by low flows during incubation can lead to stranding and desiccation or freezing of redds in the upper margin of the wetted spawning area. In the Okanagan River, minimum incubation flows have ranged from 27 to 69% of average spawning flows since 1981 (Figure 4.5).

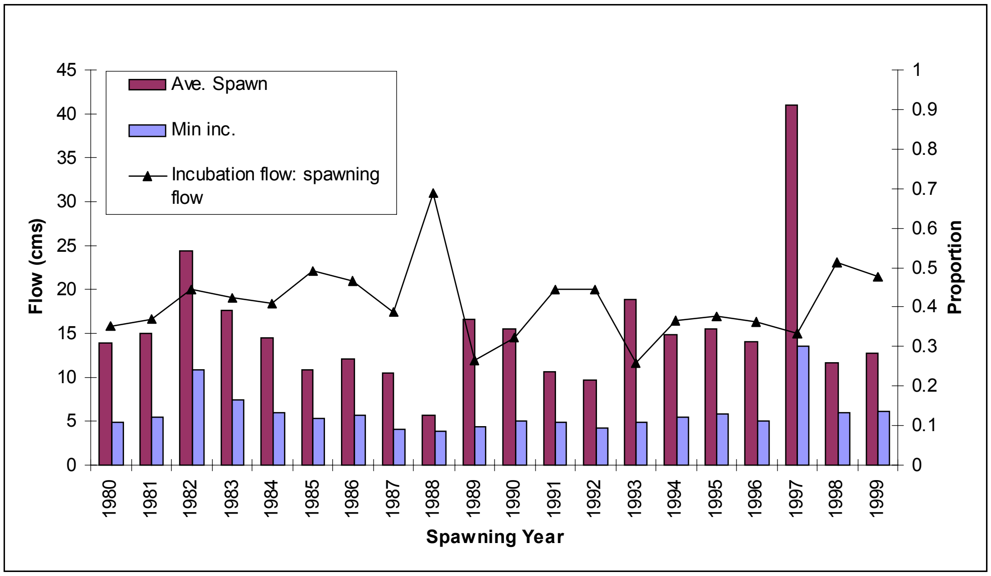


**Figure 4.5.** Average spawning flows, minimum incubation flows, and the ratio of these flows in the Okanagan River, 1980-1999. Data source: Stockwell et al. 2001.

Presumably, higher stranding mortality is associated with lower incubation flow: spawning flow ratios. Workshop participants indicated that there is no data on stranding mortality, and that eggs will continue to incubate as long as they are wet. We propose to include a simple approach based on the amount of stranding on the change in spawning habitat between spawning and incubation periods, using Figure 4.2 and 4.3:

$$EggSurvRate_{Strand} = 1 - \frac{StrandAdj * (SpawnHab_{AveSpawnFlow} - SpawnHab_{MinIncFlow})}{SpawnHab_{AveSpawnFlow}} \quad \text{[eq. 4-8]}$$

where: spawning habitats are estimated from equation 4-3 and 4-5; and
StrandAdj = adjustment to modify the strength of the stranding effect (user-defined parameter)

The StrandAdj factor reflects the combined effects of channel shape and sockeye depth spawning preferences. Setting StrandAdj >1 would increase stranding mortality; setting StrandAdj <1 would decrease it. Setting StrandAdj = 0 would represent the hypothesis that stranding is not a significant mortality factor for eggs.

### 4.2.2 Flushing mortality

*Note: The scour relationship developed for version 1.0 of the model has been replaced with the scour-mortality relationships developed by Summit Environmental for the FWMT project (Summit 2002).*

High incubation flows can lead to flushing of fry out of the gravel prematurely (prior to emergence). Data to characterise this relationship comes from the empirical and modelling work done by Summit Environmental in 2002, where they developed a series of equations to describe redd scour at various flow levels (Figure 4.6). Based on their work, we developed a single equation to compute egg mortality due to scour as a function of flows during incubation:

$EggSurvRate_{Flush} = 1 - [Flow_{Oliver,MaxInc}{}^{FlushShape} / (FHalfFlush^{FlushShape} + Flow_{Oliver,MaxInc}{}^{FlushShape})]$ [eq. 4-9]

where: $Flow_{MaxInc}$ = maximum daily flow Nov-Feb in Okanagan River, selected according to water year
FlushShape = shape parameter (user-defined parameter)
Fhalf = Flow that generates 50% survival rate (user-defined parameter)

This equation closely approximates the series of equations developed by Summit (2002).

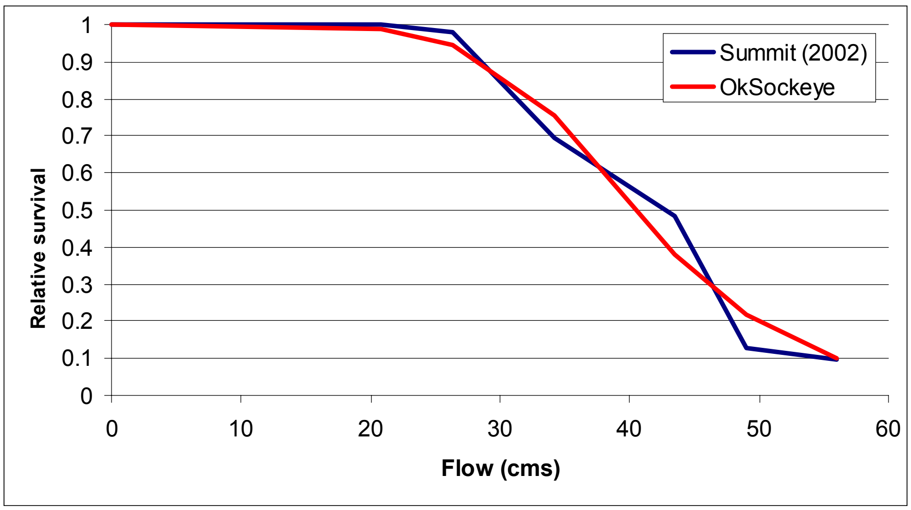


**Figure 4.6.** Relationship between # of pre-emergent flushed and maximum incubation (Nov-Feb) flow. Data source: Summit (2002).

### 4.2.3 Natural Survival Rate

Natural egg-fry survival rates in sockeye stocks range from 7 to 50% (17 to 20% in flow-controlled streams) (Bradford 1995). The biostandard for British Columbia is 15% (Shepherd and Inkster 1995). Because these rates can be highly variable, we propose to draw from a log-normal distribution of survival rates with mean and standard deviation set by the user:

$\ln(EggSurvRate_{Nat}) = N(EggFrySurvMean, EggFrySurvStDev)$ [eq. 4-10]

where: EggFrySurvMean = mean of the $\log_e$-transformed distribution of survival rates (user-defined parameter)
EggFrySurvStDev = standard deviation of the $\log_e$-transformed distribution of survival rates (user-defined parameter)

We could also use a smaller amount of natural variation in the egg survival rate, and apply the relationship in Equation 4-8 to reflect year to year changes in stranding mortality.

The model will allow different natural egg-fry survival rates (means and standard deviations) for Skaha sockeye eggs laid in medium and high quality spawning habitat to reflect alternative hypotheses about the effects of habitat quality on egg survival (see section 4.1.5). Survival rates may be reduced in medium quality gravel, for example, because of greater amounts of fine sediments and corresponding reductions in oxygen concentrations in redds.

### 4.2.4 Annual Fry Abundance

The number of fry produced in a year is:

$$\#Fry_{wild} = \#Eggs * EggSurvRate_{Strand} * EggSurvRate_{Flush} * EggSurvRate_{Nat} \qquad \text{[eq. 4-11]}$$

where: #Eggs = derived from equation 4-7
$EggSurvRateS_{trand}$ = derived from equation 4-8
$EggSurvRate_{Flush}$ = derived from equation 4-9
$EggSurvRate_{Nat}$ = derived from equation 4-10

### 4.2.5 Effect of flow on spawner-fry production functions

The spawner-egg and egg-fry survival relationships described in the preceding sections can be combined to develop implied spawner-fry production relationships. Spawner-fry relationships, while not used explicitly in the model, are useful for assessing the implied effects of flows on overall production of fry. We have developed implied relationships for Osoyoos Lake sockeye in four fry emergence years: 1973, 1974, 1997, and 1998 (brood years 1972, 1973, 1996, and 1997; Figure 4.7). These years were used because fry densities were estimated for those years (Hyatt and Rankin 1999), and because they represent a range of spawning and incubation flows.

For example, 1998 and 1973 both have average or above average spawning flows, and incubation flows that are within the range recommended in the Canada-B.C. Okanagan Basin Agreement. Fry production is highest in those years (the two curves are virtually indistinguishable) because spawning habitat is not flow-limited (Figure 4.2) and incubation flows are not high enough to cause significant flushing mortality (Figure 4.6). 1997 had average spawning flows but excessive incubation flows, leading to higher incidence of flushing mortality and a lower fry production curve. Lowest fry production is seen in 1974, which had both high incubation flows and low spawning flows. Fry production in that year was limited by flow-related reductions in both spawning capacity and in egg-fry survival rates.

The figure also shows the observed spawner and fry abundances for those years. Deviations between predicted and observed values reflect differences between actual natural egg-fry survival rates in those years and the constant natural egg-fry survival rate used to derive the implied relationships (which was around 9%, based on average sockeye values reported by Bradford 1995). For example, the deviation of the observed fry abundance in 1973 from the fry abundance predicted by the implied production function suggests that the natural egg-fry survival rate in that year was considerably lower than 9%.

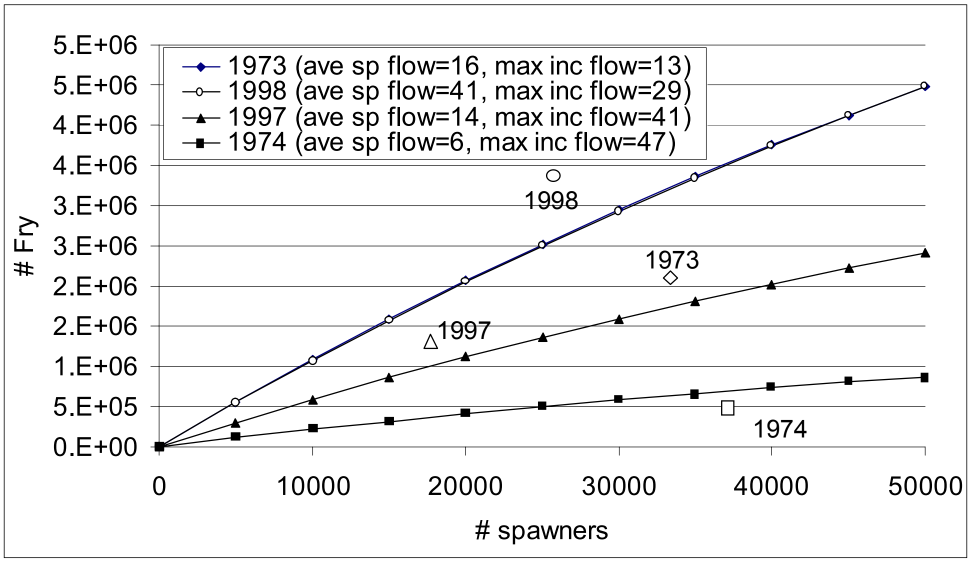


**Figure 4.7.** Implied fry production curves for 1973, 1974, 1997, and 1998.

### 4.2.6 Fry Supplementation

*Note: This component is new to Version 2.2 of the model, added after the October 2002 review meeting to represent a potential mode of reintroduction to Skaha Lake.*

A potential strategy for reintroducing sockeye to Skaha Lake is to extract eggs from female broodstock from the Osoyoos population, raise those eggs to fry stage in a hatchery, then release the fry into Skaha Lake. The OkSockeye model allows users to model this process by selecting a target number of fry to supplement into Skaha Lake for a given year, then computing how many Osoyoos females would have to be from the spawning population in the previous year to produce that number of fry given assumptions about average fecundity and egg-fry survival rates in hatcheries. The equation to compute the number of females required is:

$$\#FemaleBroodstock_{Os,t-1} = FrySupp_{Sk,t} / (AveFecundity * HatcheryEggFrySurv) \quad \text{[eq. 4-12]}$$

where: $FrySupp_{Sk,t}$ = the target number of fry to release into Skaha Lake in year t (user-defined parameter)

AveFecundity = the age-weighted average fecundity, derived from equation 4-1 (assumes that the age proportions in the group of females extracted for broodstock is the same as in the population).

HatcheryEggFrySurv = survival rate of eggs to fry in hatcheries (user-defined parameter)

To address potential damage to the Osoyoos population by removing too many females, the model includes a hard minimum level of Osoyoos females that must be maintained ($MinFemale_{Os}$). If the number of females required (as computed in equation 4-12) would cause the female abundance of the Osoyoos stock to go below this level, then the model will extract as many females as possible given the minimum constraint and use equation 4-12 to compute the number of fry that can be produced by those females. This means that in years with low returns of Osoyoos sockeye, the target number of fry supplements into Skaha Lake may not be reached. In years when the Osoyoos female population is below the minimum level, no females are extracted.

### 4.2.7 Fry Production

The total production from sockeye fry (kg/ha) in year t is needed to a) partition lake carrying capacity for survival of sockeye fry, kokanee fry; and immature mysis; and b) compute growth rates of adult kokanee. Fry production values specific to each of these applications are computed by adjusting basic production rates by population and age-specific equivalence factors (described below).

Basic production is calculated from the biomass using Production:Biomass ratios specific to each species and age. Production rate (kg/ha) is calculated as:

$$P{:}B_{SxFry} = FeedingRate_{SxFry} * ConvEff_s \qquad \text{[eq. 4-13]}$$

where: $ConvEff_s$ = conversion efficiency of sockeye fry (kg/ha production per kg/ha consumed; assume same size-dependent function as kokanee; see equation 5-3)
$FeedingRate_{SxFry}$ = feeding rate of sockeye fry (kg/ha consumed per kg/ha biomass; user-defined parameter)

Production from sockeye fry is:

$$SxFryProd_{SxFry} = [\#Fry * (Weight_{SxFry}/1000)] / LakeArea * P{:}B_{SxFry} * SxEquiv \qquad \text{[eq. 4-14]}$$

where: #Fry = computed from equation 4-11 (plus any supplemented fry from equation 4-12)
$Weight_{SxFry}$ = user-defined parameter (g)
LakeArea = area of rearing lake (ha)
$P{:}B_{SxFry}$ = Production:Biomass ratio of sockeye fry (see equation 4-13)
SxEquiv = sockeye equivalence factor (user-defined parameter; depends on species)

The SxEquiv factor for determining the effects of sockeye fry on sockeye smolt capacity is obviously 1. However, for determining the effects of sockeye fry on kokanee and mysid survival and growth the equivalence factors represent differences in competitive ability and ecological niches beyond the differences represented by differences in P:B ratios. Examples of such differences that can be represented by the equivalence factors include differences in diet, spatial or temporal overlap, or the ability of populations to physically exclude other populations from food or space. Two equivalence factors are needed:

1. The equivalence factor $SxEquiv_{JuvSurv}$ is needed for partitioning lake carrying capacity for survival of kokanee and mysis juveniles. This equivalence factor, and the analogous equivalence factor for mysis, is expressed in terms of kokanee juveniles (i.e. $SxEquiv_{JuvSurv}$ =2 implies that sockeye fry are twice as successful as kokanee fry in utilising lake capacity). The use of kokanee juveniles as a "common currency" simplifies the definition of equivalence factors while still allowing for complex interactions among sockeye, kokanee, and mysis juveniles. For example, setting the sockeye equivalence factor to 1 and the mysis equivalence factor to 0.5 would imply that mysis are half as competitive as both sockeye and kokanee juveniles. Setting the sockeye equivalence factor to 5 and the mysis equivalence factor to 0.5 would imply that mysis are half as competitive as kokanee juveniles but are 1

tenth as competitive as sockeye fry. As a preliminary assumption, we assume that sockeye fry and kokanee fry are direct ecological analogs (i.e., $SxEquiv_{K,Fry} = 1$).

2. The equivalence factor $SxEquiv_{AdGrowth}$ is needed to account for the effects of sockeye production on growth rates of adult kokanee. As a preliminary assumption, we assume that sockeye fry are out-competed by kokanee adults and thus do not affect adult growth of kokanee (i.e., $SxEquiv_{K,Ad} = 0$).

## 4.3 Fry - Smolt

Fry rearing in Skaha and Osoyoos Lakes experience different rearing conditions and mortality factors. In Skaha Lake, kokanee and mysis potentially compete with juvenile sockeye for food resources. In Osoyoos Lake, epilimnial water temperature and hypolimnial oxygen concentrations are thought to be the major limiting factors on juvenile production. The proposed modelling approach is the same for both lakes, but different parameterisations can represent different rearing conditions. For example, density of mysis and kokanee can be set to low values in Osoyoos Lake to reflect reduced competition, but the lake area of Osoyoos Lake can be set to the area of the North Basin only to represent oxygen and temperature constraints on rearing habitat in the south basin.

### 4.3.1 Predation

The predator submodel (see section 7) calculates the maximum biomass of sockeye that was required during the previous year to produce the biomass at each predator age class in the current year. Unlike kokanee, only one age-class (fry) of sockeye is available to lake predators. The predation effects included in the model therefore include predation at the time of migration into the lake and predation throughout the year while fry are maturing into smolts. This section describes the process to compute the sockeye losses due to consumption that occurred between year t-1 (fry) and year t (smolts).

The maximum biomass required by the predator population is based solely on its consumptive requirements, and must be adjusted to account for the density of sockeye fry available and for size-dependent relative vulnerability of sockeye fry to predator age classes.

**a) Density adjustment**

At low prey densities, predators will presumably shift to an alternate prey source and realised predation rates will decline. This relationship is illustrated in Figure 4.8.

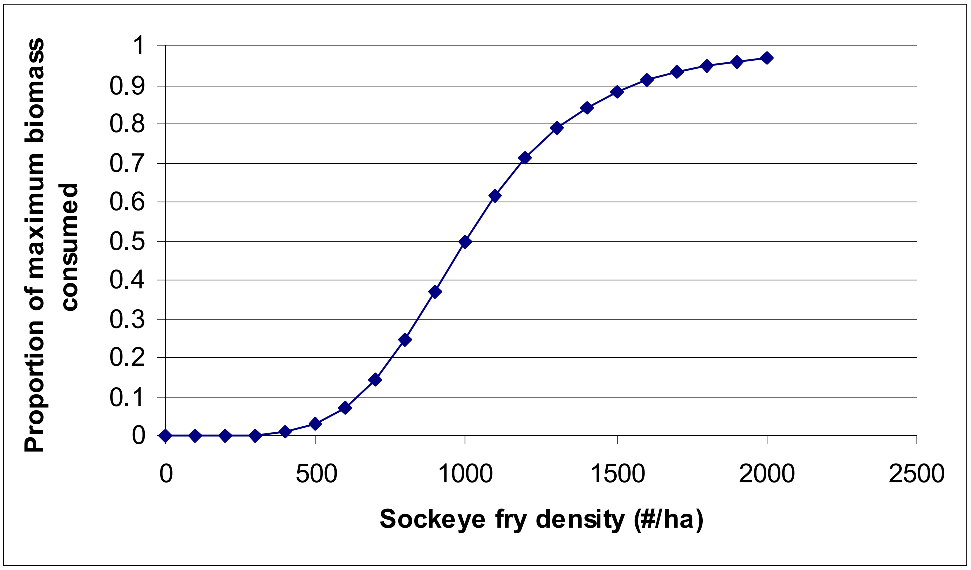


**Figure 4.8.** Density-dependent adjustment of biomass consumed by predators.

The relationship in Figure 4.8 (a Type III functional response) determines the actual proportion of sockeye fry biomass consumed during year t by a predator age class p and has the equation:

$$PropCons_{p,t} = SoxDensity_{t-1}^{SoxConsShape} / (SoxConsHalf^{SoxConsShape} + SoxDensity_{t-1}^{SoxConsShape}) \quad \text{[eq. 4-15]}$$

where: SoxConsShape = shape parameter (user-defined parameter)

SoxConsHalf = sockeye density where proportion consumed = 0.5 (user-defined parameter)

$SoxDensity_{t-1}$ = sockeye fry density in previous year (#/ha)

= $\Sigma \#Fry_{t-1}$ / LakeArea

**b) Relative vulnerability adjustment**

Relative vulnerability of sockeye fry to predation is assumed to be a function of the ratio of relative prey/predator fork lengths, which will vary among predator age classes (sockeye fry fork lengths are assumed to be constant). We assume that the relationship between relative vulnerability of sockeye fry and prey:predator fork length is the same as that derived for kokanee predation from rainbow trout stomach content data Korman et al. 1993). This relationship is shown in Figure 5.7 and described in equation 5-12.

The actual biomass of sockeye fry consumed by each predator age class during year t is determined from the biomass required by predators, the density-dependent proportion of the required biomass that is consumed, and the length-dependent relative vulnerability of sockeye fry to the predator age class:

$BiomassCons_{Sxfry,p,t} = PropCons_{p,t} * SoxBioCons_{p,t} * RelVuln_{Sxfry,p}$ [eq. 4-16]

where: $PropCons_{p,t}$ = proportion of biomass consumed (from equation 4-15)
$SoxBioCons_{p,t}$ = sockeye biomass required by predators (from equation 7-8)
$RelVuln_{Sxfry,p}$ = relative vulnerability of sockeye fry to predation, based on relative prey:predator fork lengths (see equation 5-12)

The total biomass of sockeye consumed is obtained by summing equation 4-16 over all predator age classes:

$BiomassCons_{Sxfry,t} = \Sigma_p BiomassCons_{Sxfry,p,t}$ [eq. 4-17]

where: $BiomassCons_{Sxfry,p,t}$ = biomass of sockeye fry consumed by age p predators (from equation 4-16)

Finally, the fraction of sockeye fry consumed by predators is calculated as:

$FractionCons_{Sxfry,t} = (BiomassCons_{Sxfry,t} / Weight_{Sxfry,t-1}) / \#Fry_{,t-1}$ [eq. 4-18]

where: $BiomassCons_{Sxfry,t}$ = biomass of sockeye fry consumed during year t (from equation 4-17)
$Weight_{Sxfry,t-1}$ = weight of sockeye fry in year t-1 (user-defined parameter)
$\#Fry_{t-1}$ = # of sockeye fry in year t-1 (from equation 4-11)

### 4.3.2 Smolt capacity

The total fish capacity (kg/ha) is a function of total phosphorus concentrations in many northern temperate lakes, including Osoyoos Lake (North Basin, where most rearing occurs) (Hyatt and Rankin 1999). Re-creation of a historical time series of Phosphorus concentrations in Osoyoos and Skaha Lakes was discussed in section 3.7 above. We will use the relationship between total P concentrations and productive capacity of lakes (described in Hyatt and Rankin 1999) to compute the rearing capacity of each lake (kg/ha) in each simulation year:

$\log(TotalCap) = Int_{TotalCap} + Slope_{TotalCap} * \log(TP)$ [eq. 4-19]

where: $Int_{TotalCap}$ = user-defined parameter
$Slope_{TotalCap}$ = user-defined parameter
TP = Total Phosphorus concentration (ug/L), recreated as in Figure 3.6.

Computation of smolt production in rearing lakes is complicated by competitive interactions with kokanee and mysis. In reality, such interactions are complex, and involve spatial/temporal differences in distributions, as well as possibly differences in zooplankton prey preferences. In this model, we propose to model these interactions by simply partitioning the capacity of each lake according to the relative production from the sockeye, kokanee and mysis biomass in the previous year. Because smolts migrate in the spring, we assume that their survival from fry in year t-1 to smolt in year t is a function of lake capacity during year t-1 (i.e., the year in which most of their survival and growth occurs). The capacity of the lake to produce sockeye smolts in year t is therefore given by:

$$TotalCap_{s,t-1} = \frac{SxFryProd_{t-1} * TotalCap_{t-1}}{(SxFryProd_{t-1}+KokFryProd_{t-1}+KokAdProd_{t-1}+ImmMysProd_{t-1}+MatMysProd_{t-1}} \quad \text{[eq. 4-20]}$$

where:
- $TotalCap_{t-1}$ = derived from equation 4-19 (kg/ha)
- $SxFryProd_{t-1}$ = sockeye fry production (kg/ha) in the previous year from equation 4-14, (SxEquiv = 1)
- $KokFryProd_{t-1}$ = production (kg/ha) of kokanee fry biomass in year t-1 from kokanee submodel equation 5-27 using the equivalence factor $KokFryEquiv_{JuvSurv}$ (which by definition = 1)
- $KokAdProd_{t-1}$ = production (kg/ha) of kokanee adult biomass in year t-1 from kokanee submodel equation 5-31 using the equivalence factor $KokAdEquiv_{JuvSurv}$
- $ImmMysProd_{t-1}$ = production (kg/ha) of immature mysis biomass in year t-1 from mysis submodel equation 6-11b using the equivalence factor $ImmMysEquiv_{JuvSurv}$
- $ImmMysProd_{t-1}$ = production (kg/ha) of mature mysis biomass in year t-1 from mysis submodel equation 6-11a using the equivalence factor $MatMysEquiv_{JuvSurv}$

We assume that the production from kokanee and mysis biomass in the fall of year t-1 provides a reasonable approximation of the average level of competition encountered by sockeye fry from the time they emerge in the spring of year t-1 to the time they emigrate as smolts in year t.

Equation 4-20 computes the portion of the total capacity of the lake (in kg/ha) to produce sockeye smolts. Converting this to fish numbers requires an assumption about body size of smolts; larger body sizes means that fewer fish are required to utilise capacity, while smaller body sizes require more fish to utilise capacity. An additional complication is that juvenile body sizes are also related to fry density. Hyatt and Rankin (1999) developed a power relationship between smolt size (in grams) and fry density in Osoyoos Lake (Figure 4.9). This relationship is applicable to the fry densities commonly observed in Osoyoos Lake, but may not be applicable at lower fry densities (the power function predicts smolt sizes in excess of 700g at low fry densities). A linear relationship, which is applied to Skaha Lake sockeye, provides a similar fit to the Osoyoos Lake data but predicts much lower smolt sizes at low fry densities (Figure 4.9). For the linear relationship, we assume that the minimum size achieved by smolts at very high densities (>4800 fry/ha) is 5 g.

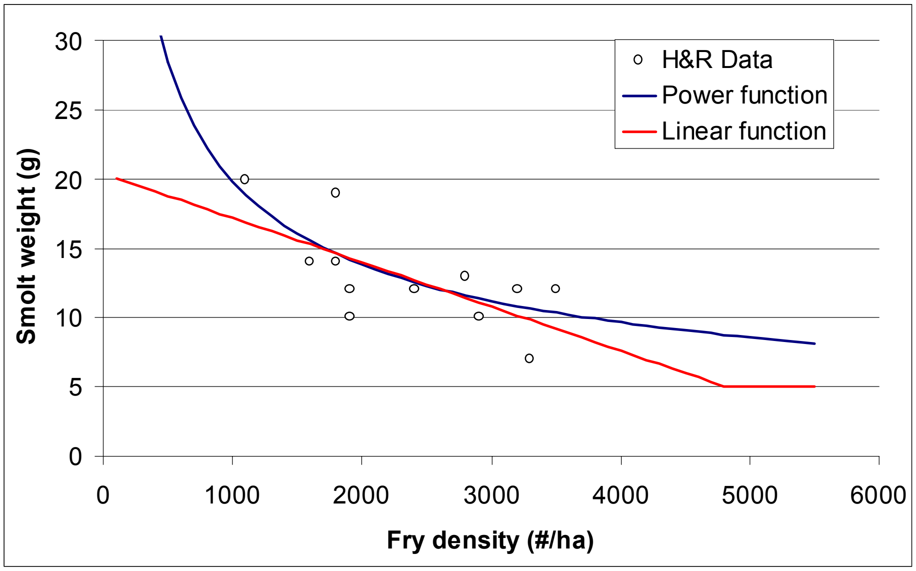


**Figure 4.9.** Relationship between sockeye smolt body weight and fry density. Based on Hyatt and Rankin 1999.

The model includes a generic smolt weight vs. fry density function that can be parameterised to represent either the power or linear relationship shown in Figure 4.9. The equation is:

$$SmoltSize_t = SmoltSizeInt + SmoltSizeSlope * (\#Fry_{t-1}/LakeArea)^{SmoltSizeShape} \quad \text{[eq. 4-21]}$$

where:
- SmoltSizeInt = hypothetical smolt weight at zero fry density; user-defined parameter
- SmoltSizeSlope = coefficient relating smolt size to fry density; user-defined parameter
- $\#Fry_{t-1}$ = number of fry in year t-1(from equation 4-11)
- LakeArea = area of the rearing lake (ha)
- SmoltSizeShape = rate of decline in smolt weight; user-defined parameter

A power relationship (used to represent Osoyoos sockeye) is represented by setting SmoltSizeInt = 0, SmoltSizeSlope = some large positive number, and SmoltSizeShape < 0. A linear relationship (used for Skaha sockeye) is represented by setting SmoltSizeInt > 0, SmoltSizeSlop < 0, and SmoltSizeShape = 1.

Given the total capacity of the lake to produce sockeye smolts in year t from fry in year t-1 ($TotalCap_{s,t-1}$) and the size of smolts produced ($SmoltSize_t$), the model will calculate the capacity of the lake for sockeye smolts from equation 4-22:

$$SmoltCap_t = TotalCap_{s,t-1} * LakeArea / (SmoltSize_t /1000) \quad \text{[eq. 4-22]}$$

where:
- $TotalCap_{s,t-1}$ = capacity of lake for sockeye smolts (kg/ha); derived from equation 4-20
- LakeArea = area of the rearing lake (ha)
- SmoltSize = derived from equation 4-21 (g)

### 4.3.3 Smolt Production

The smolt capacity and fraction of fry consumed by predators are then used to compute the number of smolts produced from the number of fry according to a density-dependent function (similar to Figure 4.4)

$$\#Smolts_{wild,t} = \frac{\#Fry_{t-1} * (1 - FractionCons_{Sxfry,t}) * MaxFrySurv}{[1 + (MaxFrySurv / SmoltCap_t) * \#Fry_{t-1} * (1 - FractionCons_{Sxfry,t})]} \qquad \text{[eq. 4-23]}$$

where:

- $\#Smolts_{wild,t}$ = number of smolts in year t (assumes that all fry spend only one winter in freshwater)
- $\#Fry_{t-1}$ = number of fry in year t-1 (from equation 4-11)
- $FractionCons_{Sxfry,t}$ = fraction of fry consumed by predators (from equation 4-18)
- MaxFrySurv = fry-smolt survival rate at very low fry densities (user-defined parameter)
- $SmoltCap_t$ = smolt capacity in year t (from equation 4-22)

The combination of density-dependent predator effects and density-dependent capacity effects results in a fry to smolt relationship like the one shown in Figure 4.10. At low fry densities, predation is minimal (due to the relationship shown in Figure 4.8) and the production curve increases at a rate equal to the maximum fry-smolt survival. As fry abundance increases, the fraction consumed increases non-linearly until 100% of the biomass required by predators is consumed (see Figure 4.8). At this point, the # of fry consumed represents a significant fraction of the total number of smolts, resulting in a decline in the production curve. Beyond this point, predators are saturated and the number of fry consumed makes up an increasingly smaller fraction of the total number of fry. At high fry abundances, the slope of the production curve declines as the fry abundance approaches the carrying capacity.

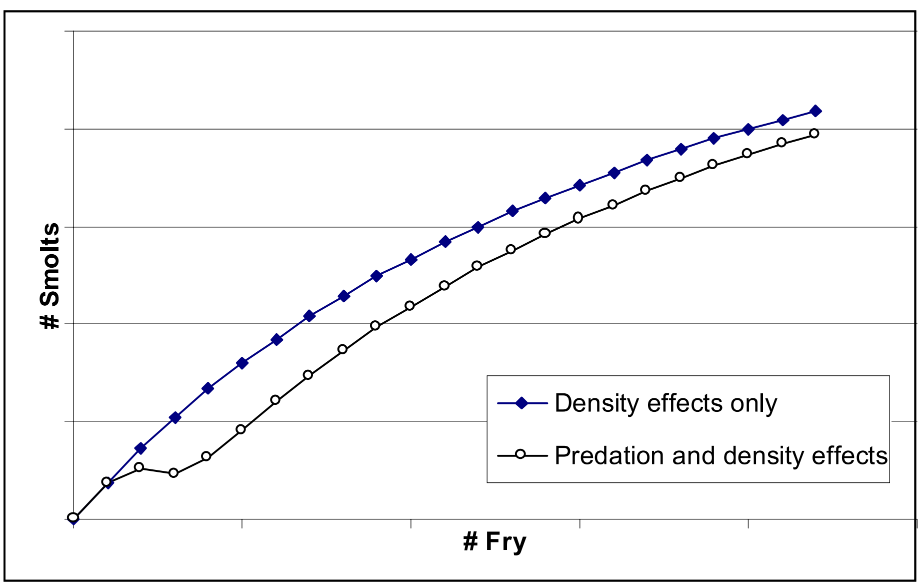


**Figure 4.10.** Smolt production curves with density effects (diamonds) and both predation and density effects (circles). The shape of this curve will depend on the density of predators.

### 4.3.4 Smolt Supplementation

The Colville Confederated Tribes have operated a supplementation program for Okanagan sockeye since 1995 (average 82,000 smolts released; Table 4.3).

**Table 4.3.** Okanagan sockeye supplementation. Source: FPC Annual Reports 1996-2001.

| Year of Release | Number released | Location / time of release |
|---|---|---|
| 1995 | 40963 | Osoyoos stock reared at Cassimir Bar hatchery, then taken to net pens in Osoyoos Lake for acclimation |
| 1996 | 150000 | Osoyoos stock reared at Cassimir Bar hatchery, then taken to net pens in Osoyoos Lake for acclimation |
| 1997 | 188350 | Osoyoos stock reared at Cassimir Bar hatchery, then taken to net pens in Osoyoos Lake for acclimation |
| 1998 | 80585 | released near mouth of Okanagan River in April |
| 1999 | 13396 | released near mouth of Okanagan River in April |
| 1999 | 21557 | released into Osoyoos Lake in October |

Supplementation of smolts into Skaha Lake is therefore a possible mechanism for establishing a Skaha Lake population. However, funding for the Cassimir Bar Hatchery facility by the Douglas Count Public Utility District has been discontinued. Smolt supplementation is therefore likely to be nil in the foreseeable future until an alternative facility is found. To allow for potential future supplementation of smolts, the model will allow the user to specify a constant number of smolts to be released in each year for each lake. The total number of smolts produced in a given outmigration year is:

$$\#Smolts_{total} = \#Smolts_{wild} + \#Smolts_{supp} \quad \text{[eq. 4-24]}$$

where: $\#Smolts_{wild}$ = number of wild smolts produced (from equation 4-23)
$\#Smolts_{supp}$ = number of supplemented smolts (user-defined parameter)

## 4.4 Smolt – Adult

### 4.4.1 Rearing lakes – Wells Dam

Osoyoos lake sockeye smolts migrate through Osoyoos Lake and the lower Okanagan River before encountering Wells Dam. Skaha lake smolts must migrate through the Okanagan River between Skaha and Vaseaux lakes, Vaseaux Lake, the Okanagan River between Vaseaux and Osoyoos lakes, Osoyoos Lake, and the lower Okanagan River on their way to Wells Dam. Mortality factors through this portion of the downstream migration route include warm temperatures, passage over numerous vertical drop structures, and predation in lakes and rivers. Workshop participants were particularly concerned with predation on smolts migrating through Vaseaux Lake, which is a small and shallow lake with a high density of predaceous fish.

Modelling each of these mortality factors individually is beyond the scope of this model. A simpler approach is to allow the user to specify a survival rate for each sockeye population from their rearing lake to Wells Dam. This survival rate would implicitly account for effects of predation and vertical drop structures, and would likely be higher for Skaha sockeye than Osoyoos sockeye.

$\#Smolts_{Wells} = \#Smolts_{Total} * SmoltSurvWells$ [eq. 4-25]

where: $\#Smolts_{Total}$ =# of smolts produced (from equation 4-24)
SmoltSurvWells = survival rate of smolts from their rearing lake (Skaha or Osoyoos) to Wells Dam

### 4.4.2 Smolts at Wells Dam – Adults at Wells Dam

*Note: This version of OkSockeye has been revised to include annual variations in smolt-adult survival rates (SARs), using year effects developed from variations in SARs of other salmon stocks.*

Mortality in this portion of the smolt-adult life stage is thought by many reviewers to be the primary cause of recent stock declines (e.g. Fryer 1995, 1996 Okanagan Sockeye Workshop). Passage through or around ten major mainstem dams during both upstream and downstream migration represents a significant source of mortality. Ocean conditions also vary significantly from year to year. Unfortunately, data to quantify smolt-adult survival rates are few, primarily because migrating smolts have not been systematically enumerated. Fish Passage Indices are monitored at several Columbia River dams, but expressing these indices in terms of absolute abundances is problematic because the efficiency with which smolts are bypassed into the counting systems is unknown and varies dramatically from year to year (Fryer 1995). A detailed model of sockeye passage through the mainstem Columbia River dams is beyond the scope of this model.

There are at least two potential approaches for modelling survival rates in this life stage. Each is discussed below along with their pros and cons.

1. **Fryer's SARs**

   Fryer (1995) estimated SARs from Priest Rapids Dam (PRD) to the mouth of the Columbia River. Smolt abundance at PRD was estimated using mark-recapture studies from 1984-1988; adult abundance was estimated from counts at Bonneville Dam and lower Columbia River harvest data. SARs ranged from 0.1 to 1.9% over the 5 years of the study (mean=1.1%, st.dev = 0.7%). The life-cycle model could simply draw from these estimates (or a distribution described by the mean and standard deviation of the estimates) in forward simulations.

   A problem with this approach is that the limited number of years encompasses a limited number of years of ocean conditions and river flow conditions. Fryer (1995) reports a significant relationship between absolute smolt abundance estimates at PRD and the smolt index estimated at McNary Dam (MCN). Theoretically, one could use this relationship to derive a longer time series of PRD absolute smolt estimates from the time series of MCN smolt indices. However, this would require a sequence of assumptions about stock and age composition of smolts and returning adults. Another problem is that the SAR estimates cover only 5 of the 9 dams of the Columbia River hydropower system. Some assumption would have to be made about survival rates through the four dams between the Okanagan River and PRD. Finally, dam counts and smolt estimates are problematic because of changes in sampling methods between years, changes in dam operations that affect sampling precision and accuracy, limitations of the counting systems, and other factors.

## 2. 1998-2000 Reach Survival Estimates

The Fish Passage Center (FPC) has estimated survival rates of PIT-tagged sockeye through three dams, from Rock Island Dam (RIS) to McNary Dam (MCN) since 1998 (FPC 1999, 2000, 2001). These survival rates have ranged from 46 to 68% (mean = 59%) over the three years of estimates. Extrapolating these results on a per-project basis to passage through all nine dams of the hydropower system leads to estimates of hydropower system survival rates of 10 to 31% (mean = 21%). One would then need to assume some magnitude (or distribution) of ocean survival rate to derive a true SAR (from Wells Dam to return to Columbia River mouth).

Problems with this approach include a lack of data on marine survival rates and the limited number of years in which reach survival rates were estimated. Bradford (1995) reviews SARs of other sockeye stocks but these rates include mortality during the freshwater portion of smolt migration as well as marine mortality.. An additional problem is that the reach survival estimates may not apply outside of the reach they were estimated over. For example, survival rates at Wells Dam may be higher than what is suggested by the RIS-MCN reach survival estimate because the Wells bypass system is more efficient.

Hyatt (pers. comm.) has indicated that a more reliable set of SAR estimates may be forthcoming based on improved estimates of smolt densities in Osoyoos Lake. In the meantime, we propose to combine Fryer's SARs with survival rates through the four dams upstream from Priest Rapids Dam (derived from per-project expansion of the 1998–2000 reach survival estimates) to yield overall Wells – Columbia River mouth SARs (Table 4.4).

**Table 4.4.** Preliminary set of SARs (Wells Dam to return to mouth of Columbia). Source: Fryer (1995); FPC Annual Reports 1998–2000. SARs represent averages over all age classes. See Table notes for explanation of how each column was calculated.

| (1) Year | (2) Fryer's SAR PRD-Columbia at mouth | (3) Ave. RIS-MCN survival rate 1998-2000 (%) (3 projects) | (4) Ave. per-project RIS-MCN survival rate 1998-2000 (%) | (5) WEL-PRD survival rate | (6) Overall SAR Wells-Columbia at Mouth | (7) ln(Overall SAR) |
|---|---|---|---|---|---|---|
| 1984 | 0.010 | 0.59 | 0.84 | 0.49 | 0.0050 | -5.30 |
| 1985 | 0.017 | 0.59 | 0.84 | 0.49 | 0.0085 | -4.77 |
| 1986 | 0.007 | 0.59 | 0.84 | 0.49 | 0.0035 | -5.65 |
| 1987 | 0.001 | 0.59 | 0.84 | 0.49 | 0.0005 | -7.60 |
| 1988 | 0.019 | 0.59 | 0.84 | 0.49 | 0.0095 | -4.66 |

Table Notes:

Column2: From Fryer 1995
Column3: From FPC Annual Reports
Column4 = Column3$^{(1/3)}$
Column5 = Column4$^{4}$
Column6 = Column2 * Column5
Column7 = ln(Column6)

The mean of the ln(SARs) from Table 4.4 is –5.6. Based on suggestions by workshop participants, the model incorporates a time series of annual variations from the mean value (or year-effects) based on SAR data from Robertson Creek coho (Figure 4.11). Variations in marine survival of Barkley Sound coho appear to be correlated with deviations in adult returns of Barkley Sound sockeye (Hyatt et al. 2000). Barkley Sound sockeye have a minimal riverine migration period and thus variations in SAR represent variations in marine survival rates. Year-effects will be selected according to water year to reflect the effects of large-scale climatic effects on marine survival rates. This approach assumes that Columbia River sockeye and Barkley Sound sockeye experience similar ocean conditions, an assumption that workshop participants felt was reasonable.

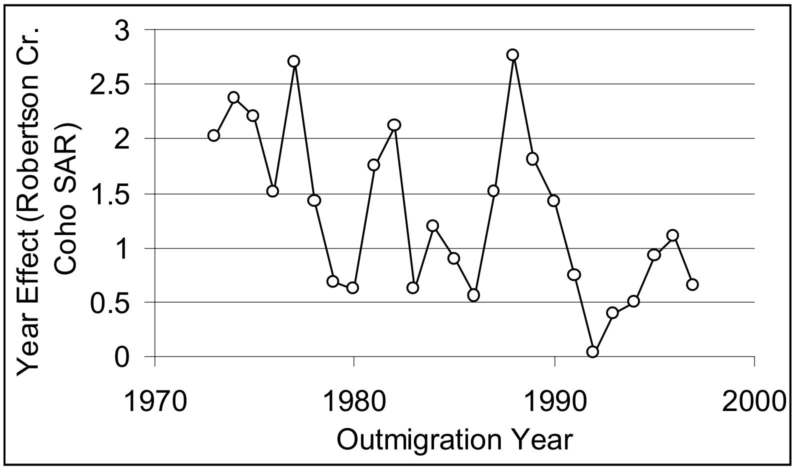


**Figure 4.11.** Year effects applied to average Okanagan sockeye SARs. Developed from SAR data for Robertson Creek coho (Hyatt et al. 2000).

Using this approach, the SAR for smolts entering the ocean in year t is:

$SAR_t = e^{SARMean} * SARYearEffect$ [eq. 4-26]

where: SARMean = mean of the $\log_e$-transformed distribution of survival rates (user-defined parameter; use mean from Table 4.4 as preliminary value until better estimates are available)

SARYearEffect = variation in SAR from mean in year t, derived from SAR data for Barkley Sound coho

One could adjust the mean of this distribution to reflect potential future improvements in passage conditions and/or changes in ocean climate regimes. For example, the mean SAR could be increased to reflect potential reductions in reservoir mortality in lower Columbia dams from the northern pikeminnow control program. This program pays a bounty to fishermen who catch this predator of salmonid smolts. This program was initiated in the early 1990's and thus are not reflected in Fryer's SAR estimates.

SARs and maturity schedule (see Table 4.1) will be applied to a particular smolt migration to determine the number of Okanagan sockeye adults returning to the mouth of the Columbia River in a particular return year t:

$$\#AdultsColMouth_{Ok,t} = \#Smolts_{Wells,t-1} * PropAge_{1.1,t-1} * SAR_{t-1} + \#Smolts_{Wells,t-2} * PropAge_{1.2,t-2} * SAR_{t-2} + \#Smolts_{Wells,t-3} * PropAge_{1.3,t-3} * SAR_{t-3}$$ [eq. 4-27]

where: $\#Smolts_{Wells}$ = obtained from equation 4-25
$PropAge_{1.x}$ = selected from Table 4.1
SAR = selected from Table 4.4

## 4.5 Returning Adults (Columbia River mouth to Wells Dam)

The number of adults returning to the Columbia River mouth in a particular return year is obtained from equation 4-27. Major processes affecting the survival of these fish to Wells Dam include Lower River harvest (between Columbia River mouth and The Dalles Dam), losses during upstream migration, and arrival timing at Wells Dam. We assume that none of these processes are age-selective (i.e., the age distribution of fish surviving to the spawning grounds is the same as the age distribution of fish arriving at the mouth of the Columbia River).

### 4.5.1 Lower River harvest

*Note: In version 2.2, total sockeye returns to the mouth of the Columbia River (Okanagan + Wenatchee) is computed using Wenatchee abundance, rather than an estimate of Okanagan:Wenatchee proportion. In addition, parameters for equation 4-29 have been updated using adult return data from CNAT v. 1.0 (Hyatt et al. 2002).*

The 2001–2003 Interim Management Agreement is based on a combined (Okanagan and Wenatchee) sockeye escapement of 75,000 fish at Bonneville Dam (ODFW and WDFW 2002). Below this level, only small Treaty ceremonial and subsistence (C&S) fisheries (which occur in Zone 6, between Bonneville and McNary Dams; most fishing occurs in Bonneville Reservoir ODFW and WDFW 2002) are permitted. For run sizes above the target, commercial fisheries above and below Bonneville Dam (Zones 1-5) are allowed on a sliding scale (Table 4.5).

**Table 4.5.** Sockeye harvest schedule as proposed by the 2001-2003 Interim Management Agreement. Source: ODFW and WDFW 2002.

| Projected Run Size at Bonneville Dam | Non-Treaty Commercial Harvest (Zones 1-5) | Treaty C&S Harvest | Treaty Commercial Harvest (Zone 6, Bonneville reservoir) |
|---|---|---|---|
| < 50,000 | 0 | 5% | 0 |
| 50,000 – 75,000 | 0 | 7% | 0 |
| > 75,000 | surplus (negotiated) | > 7% (negotiated) | surplus (negotiated) |

Several assumptions are required to model lower river harvest. First, we assume that the fisheries are not stock-selective (i.e., the fraction of Okanagan sockeye in the fisheries is the same as the fraction at the mouth of the Columbia River). Data to support this assumption are limited. Fryer (1995) found that lower river fisheries were significantly selective for Wenatchee fish in only one of the three years examined. More stock composition data is needed to test this assumption.

Second, because escapement targets are set for combined Wenatchee and Okanagan sockeye stocks, we must make some assumptions about the contribution of Wenatchee fish to the number of adult returns to the mouth of the Columbia. The relative escapement of Wenatchee and Okanagan sockeye is highly variable over time and shows no apparent temporal trend (Figure 4.12).

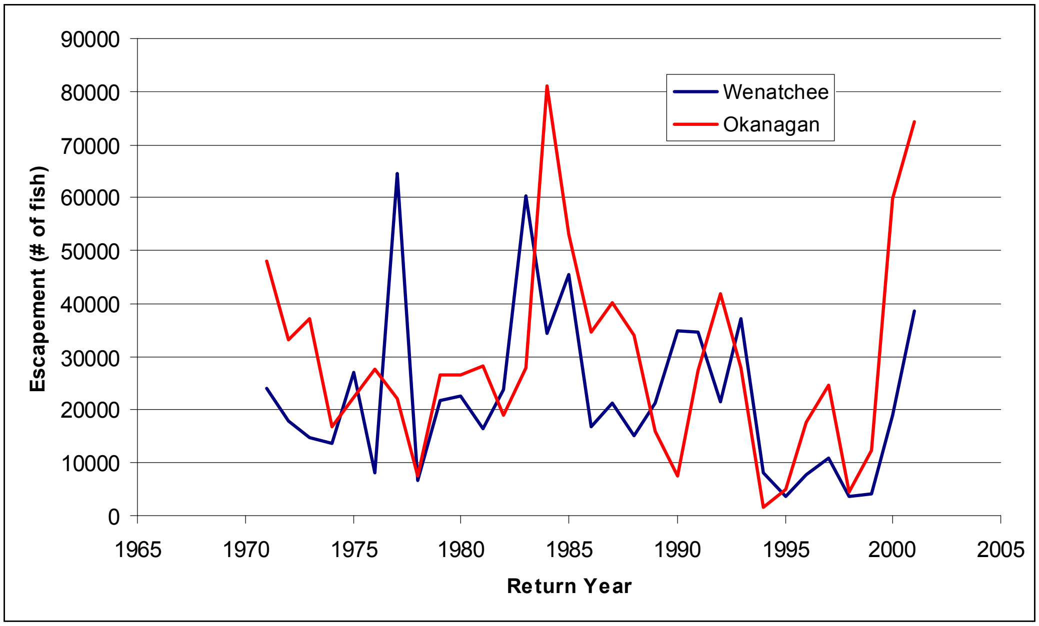


**Figure 4.12.** Okanagan and Wenatchee escapement (CNAT data from Hyatt et a. 2002). Okanagan escapement based on adult counts at Wells Dam; Wenatchee escapement based on adult counts at Rock Island and Rocky Reach dams.

We use Wenatchee escapement and CNAT data on lower Columbia River catch to compute the number of Wenatchee fish at the mouth of the Columbia for each water year for which there is data (1971-2001), then add this number to the number of returning Okanagan fish to obtain the total number of adult sockeye at Columbia River mouth (equation 4-28). For water years prior to 1971, we select a Wenatchee abundance randomly from 1971-2001 estimates.

$$\#AdultsColMouth_{Total} = \#AdultsColMouth_{Ok} + \#AdultsColMouth_{Wen} \quad \text{[eq. 4-28]}$$

where: $\#AdultsColMouth_{Ok}$ = obtained from equation 4-27.
$\#AdultsColMouth_{Wen}$ = computed from Wenatchee escapement + Wenatchee contribution to lower Columbia River harvest.

Finally, the model must make some assumptions about the ability of the fisheries to catch their allowable limits. For Treaty C&S fisheries, harvest rates are relatively small and we will assume that the full allocation is caught in each year. Treaty and non-Treaty commercial fisheries are less efficient in catching available surpluses because commercial harvests are opened only sporadically, and because pre-season predictions of run sizes are imperfect. A comparison of maximum possible harvest and actual total (commercial and C&S) harvest since 1981 suggests that the fraction of the potential harvest that is actually harvested is usually small in the first year or two that a commercial fishery is allowed (this fraction is close to the C&S harvest rate), but increases with the number of consecutive years a commercial fishery is opened as commercial fishermen become accustomed to fishing (Figure 4.13).

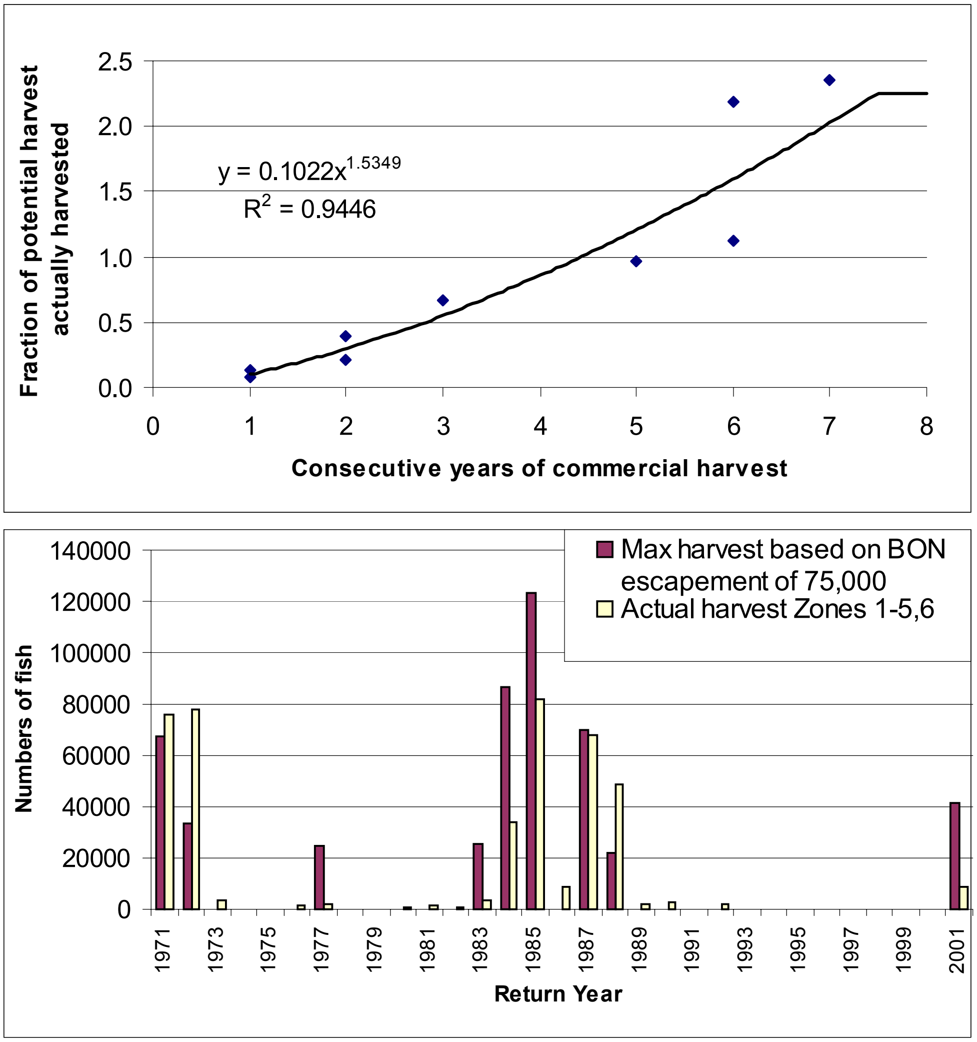


**Figure 4.13.** Top: Potential and actual harvest 1971–2001. Bottom: Fraction of potential harvest actually harvested as function of the number of consecutive years in which a commercial harvest was opened. Data sources: Hyatt et al. (2002).

We will use the relationship in the bottom pane of Figure 4.13 as a simplified representation of the dynamics of the commercial fishery in response to sporadic openings and the imprecision of run forecasts upon which openings are planned. The equation is:

$$\text{FractionCaught} = \text{Minimum}(\text{HarvRateFirstYear} * \#\text{ConsYear}^{\text{HarvShape}}, \text{MaxFraction}) \qquad \text{[eq. 4-29]}$$

where:

| | |
|---|---|
| HarvRateFirstYear | = fraction of potential harvest actually caught in the first year of a commercial fishery (user-defined parameter) |
| Shape | = parameter that determines how quickly the efficiency increases in consecutive years (user-defined parameter) |
| MaxFraction | = upper limit on the efficiency of the commercial fishery (user-defined parameter; represents some maximum at which managers are likely to shut down a commercial fishery) |

The number of Okanagan sockeye caught when the total run size exceeds the escapement target at Bonneville Dam is:

$$\#FishCaught_{Okanagan} = (\#AdultsColMouth_{Total}) - EscTarget_{Bon} * FractionCaught * (\#AdultsColMouth_{Ok}/\#AdultsColMouth_{Total}) * FracSurplusAvail \quad \text{[eq. 4-30]}$$

where: $\#AdultsColMouth_{Total}$ = derived from equation 4-28
$EscTarget_{Bon}$ = sockeye escapement target at Bonneville Dam (user-defined parameter)
FractionCaught = derived from equation 4-29
FracSurplusAvail = fraction of surplus available to lower River fisheries (user-defined parameter); this proportion is currently 1.0, but could conceivably be negotiated to allow larger harvests upriver.
$\#AdultsColMouth_{Ok}$ = obtained from equation 4-27

The number of Okanagan sockeye caught in years where the total run size does not exceed the escapement target is:

$$\#FishCaught_{Okanagan} = \#AdultsColMouth_{Ok} * TreatyC\&SHarvestRate \quad \text{[eq. 4-31]}$$

where: $\#AdultsColMouth_{Ok}$ = derived from equation 4-27
TreatyC&SHarvestRate = Treaty C&S harvest rate (user-defined parameter based on Table 4.5)

### 4.5.2 Survival rate during upstream migration (Mouth of Columbia to Wells Dam)

Past attempts to quantify upstream migration mortality have relied on adult dam counts (Fryer 1995). There are many problems with these data (e.g. changes in methods between dams and years) and survival estimates based on them are widely variable and are often unreliable (survival rate > 1) when one looks at the full data set from 1980-2001[4]. However, notwithstanding the significant problems with adult dam counts these data provide a convenient means of quantifying upstream survival rates and will be used in this model.

Fryer (1995) estimated an average survival rate of 0.76 from the Zone 6 fishery (Bonneville reservoir) to Wells Dam from 1985-1992. An alternative approach is to look at all relevant dam counts and calculate per-project survival estimates.[5] Relevant dam count comparisons include:

- The Dalles – John Day (JDA) (1 project)
- The Dalles – McNary (2 projects)
- The Dalles – Priest Rapids (3 projects)
- The Dalles – Rock Island (5 projects)
- Rocky Reach – Wells (1 project)

Not all comparisons produced useable estimates in all years (because the survival rates were > 1).

[4] Post-1979 conditions are though to be most representative of current hydrosystem operations.

[5] Relevant comparisons are those that do not include harvest in Bonneville reservoir (i.e. the lowest dam should be The Dalles or above), and do not compare Okanagan sockeye counts to mixed Okanagan/Wenatchee counts (i.e., counts from dams below the Wenatchee River should not be compared to counts from above the Wenatchee River).

Per-project survival rates from these dam count comparisons are shown in Figure 4.14. Average across dams varies from 0.81 to 1.0. The average is negatively correlated with Columbia River flows (measured at Wells Dam; $R^2 = -0.64$), suggesting that using Columbia River flows is a reasonable explanation for the observed variability. Therefore, our approach to modelling hydrosystem-related survival rates through this life-stage will be to select annual per-project survival rates according to the water year (selection of water years is discussed in section 3.1 above). Historical water years will have to be "mapped" to years where upstream survival data exist (i.e., historical water years without upstream survival data will be matched with a year with upstream survival data based on the similarity of the Columbia River flows). Such an approach reflects the association between Columbia River flows and per-project upstream survival rates. Therefore, the number of adult fish at Wells Dam is given by:

$$\#AdultsWells = (\#AdultsColMouth_{Ok} - \#FishCaught_{Okanagan}) * PerProjSurv^{9} \qquad [eq. 4\text{-}32]$$

where: $\#AdultsColMouth_{Ok}$ = derived from equation 4-27
$\#FishCaught_{Okanagan}$ = derived from equation 4-30 or 4-31
PerProjSurv = per-project upstream survival rate, selected according to water year

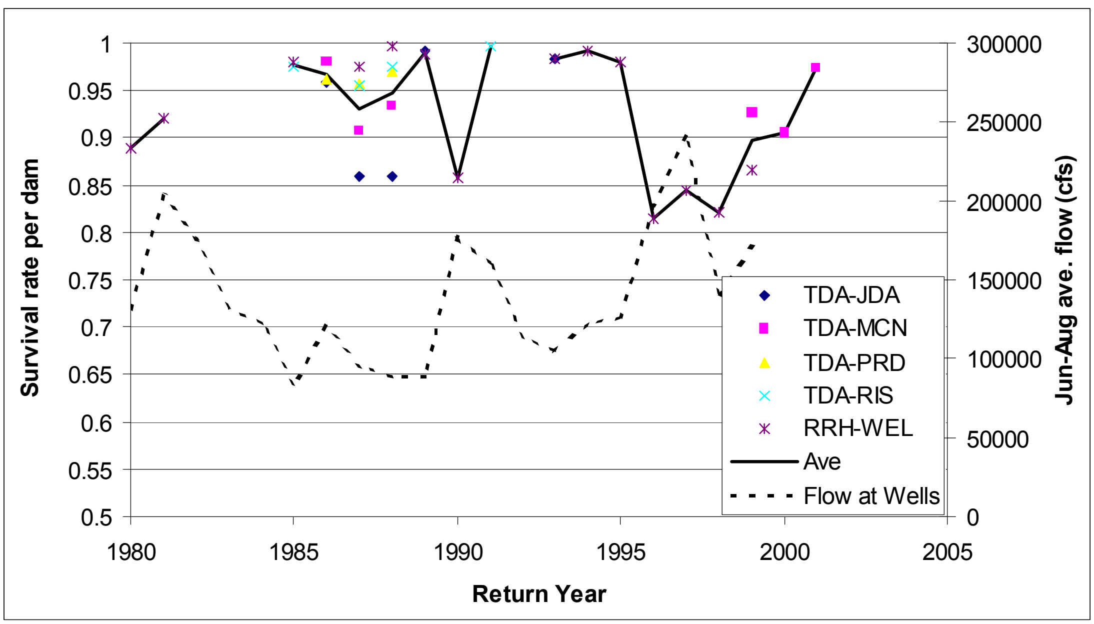


**Figure 4.14.** Survival rate per dam 1980-2001, based on comparison of dam counts. Average June-August flow at Wells Dam also shown. Dam count data from Fish Passage Center; flow data from Stockwell et al. 2001.

### 4.5.3 Run Timing at Wells Dam

We use daily adult dam counts at Wells Dam from 1977-2001 to model run timing of Okanagan sockeye (Figure 4.15). Quinn et al. (1997) found a statistically significant relationship ($p<0.001$) between sockeye arrival time at Rock Island Dam and Columbia River flows. The relationship between arrival time at Wells Dam and Columbia River flows is weaker but still significant ($p<0.05$). To represent this association, we will select a historical run time curve from those shown in Figure 4.15 according to the water year. The number of fish arriving at Wells Dam on a particular day d is:

$$\#ArriveWells_d = \#AdultsWells * ProportionArrivingWells_d \qquad \text{[eq. 4-33]}$$

where: #AdultsWells = computed using equation 4-32
$ProportionArrivingWells_d$ = derived from run timing curve selected according to water year

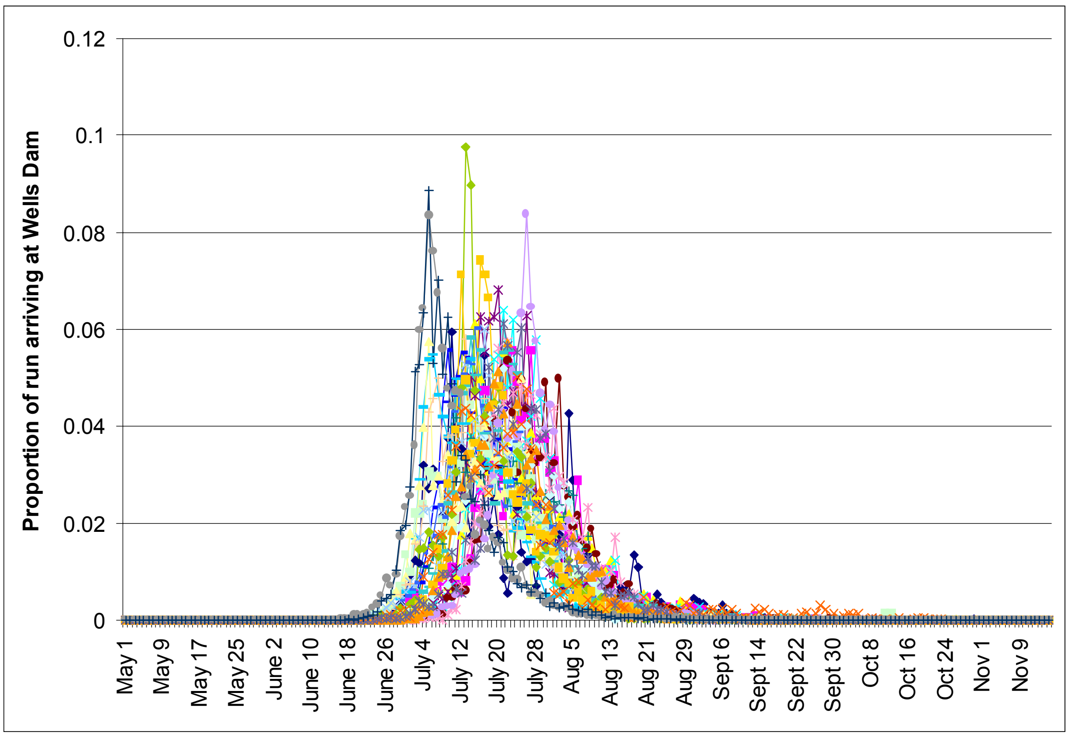


**Figure 4.15.** Proportion of sockeye arriving at Wells Dam, based on daily adult dam counts. Source: Fish Passage Center.

## 4.6 Prespawning Survival and Distribution (Wells Dam to Spawning Grounds)

This component of the model includes timing of migration up the Okanagan River, pre-spawning survival rate, supplementation, and distribution of spawners between Skaha spawning areas and Osoyoos spawning areas.

### 4.6.1 Migration up the Okanagan River

Returning sockeye frequently encounter a thermal barrier to upstream migration in the Okanagan River at its confluence with the Columbia (Fryer 1995, Hyatt and Rankin 1999, Alexander et al. 1998). Sockeye appear to hold in the Columbia River when water temperatures exceed 21°C, and migrate up the Okanagan River when temperatures fall below this threshold. The movement of fish up the Okanagan River is thus a function of arrival timing at Wells Dam (which was discussed in section 4.5.3) and water temperatures in the Okanagan River (discussed in section 3.5).

Overlapping the arrival timing distribution with water temperatures will determine how many fish migrate up the river each day ($\#MigrateOkan_d$). In each day during the summer migration period, the model will calculate the water temperature in the lower Okanagan River (equation 3-4). If the temperature is below 21 degrees, all of the fish arriving at Wells Dam in that day will enter the Okanagan River. If the daily temperature is above 21 degrees, the fish arriving at Wells Dam in that day will hold in the Columbia River. Fish will continue to hold until temperatures fall below 21 degrees, at which time all of the fish that are holding in the Columbia River will proceed up the Okanagan River. An example of this approach is shown in Figure 4.16 (assumes 30,000 fish arriving at Wells Dam and 1992 water temperatures and return timing). From July 6 – July 11, the water temperature is below 21 degrees and the number of fish entering the Okanagan River is equal to the number of fish arriving at Wells Dam. From July 12 to July 15, the temperature exceeds 21 degrees and fish do not enter the Okanagan River but accumulate in the Columbia. On July 16$^{th}$, the temperature drops to below 21 degrees and all of the fish that have been accumulating in the Columbia since July 12, as well as the fish that arrive at Wells on the 16$^{th}$, enter the Okanagan River. This explains the large peak of fish entering the Okanagan River on July 16$^{th}$ in the lower pane of Figure 4.15.

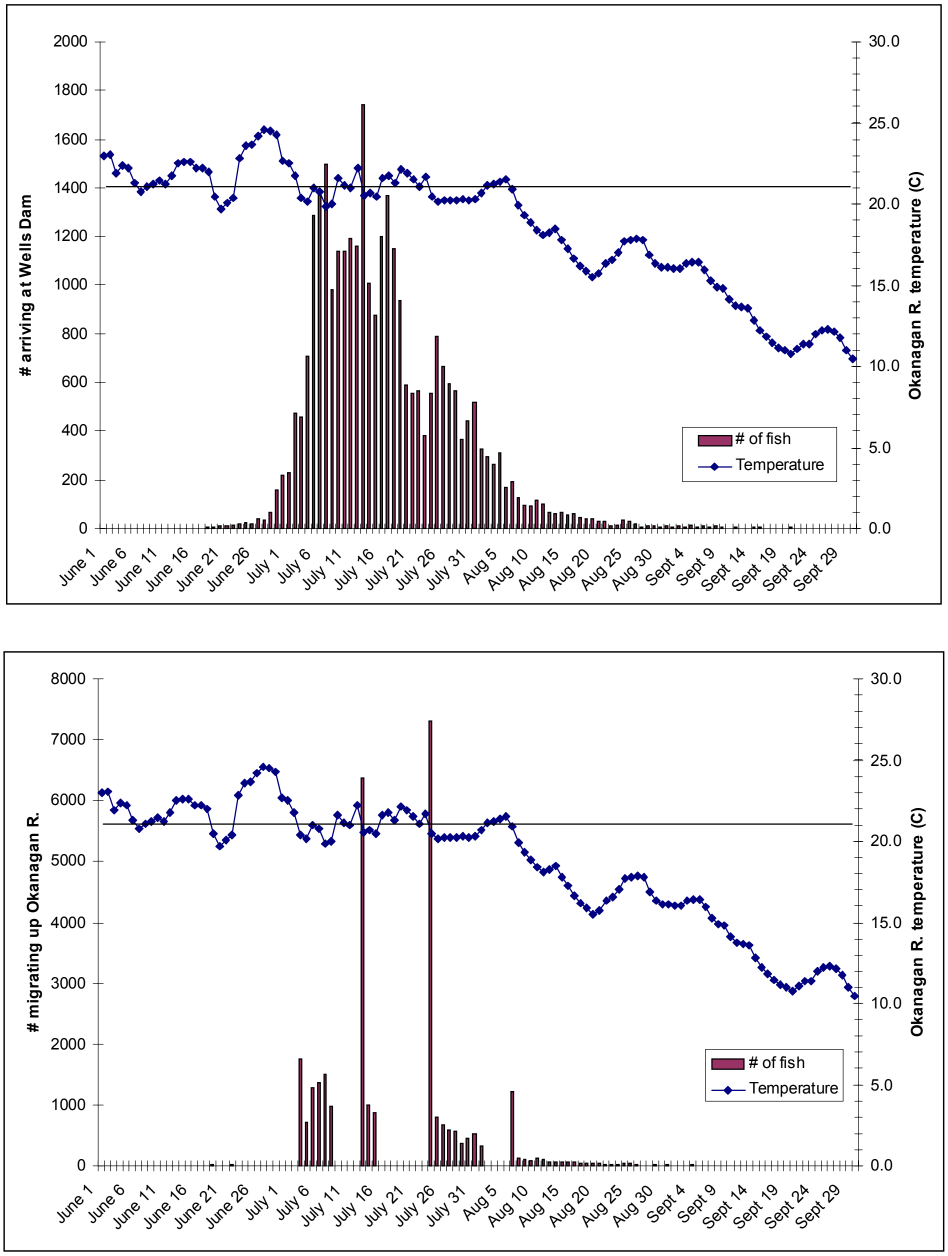


**Figure 4.16.** Top: Number of fish arriving at Wells Dam (example only; assumes 30,000 fish and 1992 arrival timing), and daily water temperature in lower Okanagan River. Bottom: Computed number of fish entering Okanagan River, assuming fish hold in Columbia as long as Okanagan River temperature is greater than 21 degrees. Temperature data from Stockwell et al. 2001.

Radio-tagging in 1997 suggested that a small number of Okanagan sockeye spawn in areas other than the main spawning grounds upstream from Osoyoos Lake (Alexander et al. 1998); because these numbers are small we will assume that all fish that spawn do so in the main spawning grounds.

### 4.6.2 Prespawning Survival Rate

Differences between Wells Dam counts and spawning ground surveys has been well-documented and discussed (Hyatt and Rankin 1999). On average, spawning ground counts are 43% of the Well Dam counts (Hyatt and Rankin 1999). Prespawning mortality is one contributor to this discrepancy, possible others include fallback and double-counting at Wells Dam, inadequate spatial or temporal coverage during spawning ground surveys, and small Indian and First Nations catches along the Okanagan River.

Other reviews (Chapman et al. 1995) have estimated prespawning mortality to be at least 25%; the 1997 radio-tag study by Alexander et al. (1998) estimated prespawning losses of 17%. Both of these studies suggested that prespawning mortality was probably higher when water temperatures in the Okanagan River were high and fish were forced to hold in the Columbia River. Data presented by Alexander et al. (1998) showed that radio-tagged fish that passed Wells Dam late in the spawning period had higher mortality than fish that passed early in the migration period. Given this information, it seems reasonable to hypothesise a relationship between survival rate from Wells Dam to the spawning grounds as a function of entry time into the Okanagan River (which would account for both late arrival at Wells Dam and holding in the Columbia River due to high Okanagan river temperatures) as shown in Figure 4.17.

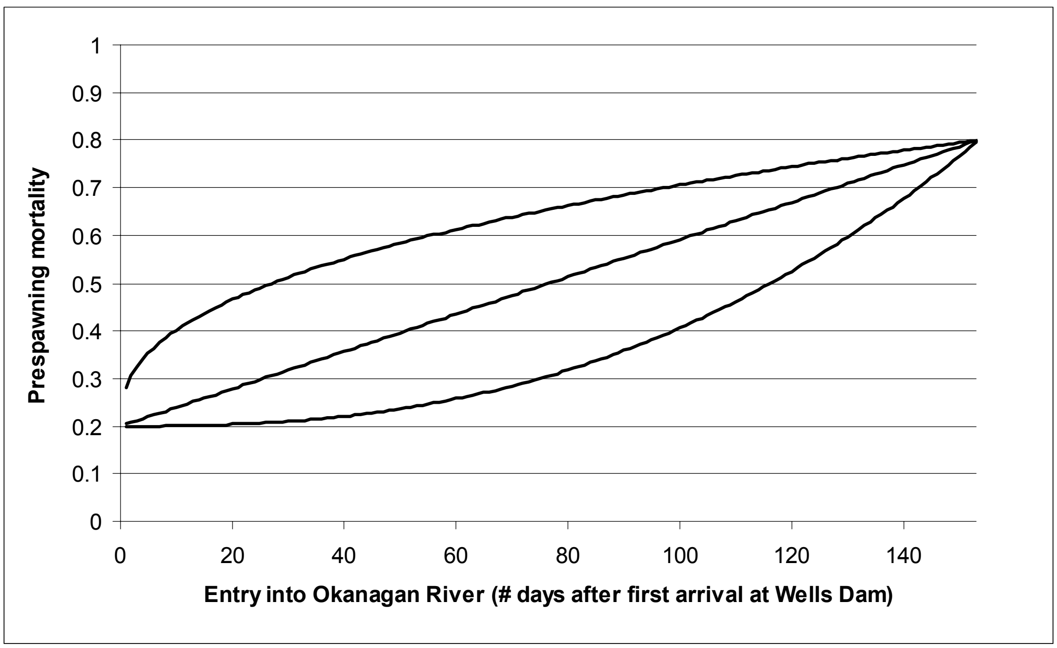


**Figure 4.17.** Relationship between prespawning mortality rate and entry into Okanagan River. Entry days are counted from June 1.

The relationship shown in Figure 4.17 has the equation:

$$PrespawnMort = [(MaxPreMort-MinPreMort)*e^{(-5.3*PreMortShape)}] * EntryDay^{PreMortShape} \quad \text{[eq. 4-34]}$$

where: MaxPreMort = maximum mortality rate (user-defined parameter; mortality experienced by latest entrants into Okanagan River)

MinPreMort = minimum mortality rate (user-defined parameter; mortality experienced by earliest entrants into Okanagan River)

| | |
|---|---|
| PreMortShape | = shape parameter (user-defined parameter; function of the length of the upstream migration period) |
| EntryDay | = # days after arrival at Wells Dam |

The shape parameter determines whether mortality increases at an increasing rate with delayed entry into Okanagan Lake (bottom line in Figure 4.17), at a decreasing rate (top line), or a constant rate (middle line). This relationship is theoretical (although consistent with available information), but could in theory be tested with field data. For example, one could place thermographs along the river, then track radio-tagged fish to see how their mortality is affected by temperature. Model users can define a constant prespawning mortality rate by setting MinPreMort = MaxPremort = constant mortality fraction.

The model will also allow the user to set some constant Tribal and First Nations harvest rate. The total number of fish arriving on the spawning grounds is:

$$\#Spawners_{Total,wild} = [\Sigma_d \#MigrateOkan_d * (1\text{-}PrespawnMortality_d)] * (1\text{-}OkanHarvest) \quad \text{[eq. 4-35]}$$

| where: | | |
|---|---|---|
| | $\#MigrateOkan_d$ | = computed as in Figure 4.16 |
| | $PrespawnMort_d$ | = computed as in equation 4-34 |
| | OkanHarvest | = constant Tribal and First Nations harvest rate (user-defined parameter) |

### 4.6.3 Distribution of Spawners between Skaha and Osoyoos spawning grounds

A key question to resolve is: once passage is restored to Skaha Lake, how should the model initially allocate spawners between Osoyoos spawning grounds and Skaha spawning grounds? Workshop participants suggested the following two hypotheses:

1. Assume that the earliest-returning fish (those that return to the upper Okanagan River in July) will continue to migrate upstream as long as water temperatures are below some critical temperature (15 degrees). If temperatures between Vaseaux and Skaha Lakes (at Okanagan Falls) are below this threshold, spawners will hold in Skaha Lake before spawning in spawning areas between Skaha and Okanagan Lakes. This hypothesis would be implemented as:

$$\#Spawners_{Skaha,wild} = \Sigma_d(\#Spawners_{Total,wild,d} \text{ if } WaterTemp_{OkFalls} < UpstreamCritTemp) \quad \text{[eq. 4-36]}$$
$$\#Spawners_{Osoyoos,wild} = \#Spawners_{Total,wild} - \#Spawners_{Skaha,wild}$$

| where: | | |
|---|---|---|
| | $\#Spawners_{Total,wild,d}$ | = total # of Okanagan sockeye on day d (in July), derived from equation 4-35 |
| | $WaterTemp_{OkFalls}$ | = water temperature at Ok Falls, derived from equation 3-3. |
| | UpstreamCritTemp | = critical water temperature for upstream migration |

2. Assume that Osoyoos-origin spawners will continue to spawn in current spawning habitat even if passage to Skaha Lake is restored. This may be a reasonable assumption if the straying rate is low and fidelity to spawning grounds is high. In this case, re-establishment of Skaha sockeye would require direct transplantation of Osoyoos smolts or spawners into Skaha rearing or spawning habitat (see Section 4.6.3). Transplanted smolts and progeny of transplanted spawners would then return to Skaha spawning areas. This hypothesis could be implemented using equation 4-36 by setting the upstream critical temperature for the Osoyoos population to a very low value (e.g. 0 degrees) to effectively prevent any naturally-returning spawners from making it upstream to Skaha Lake, and setting the upstream critical temperature for the Skaha population to a very high

value (e.g. 99 degrees) to ensure that all Skaha-origin spawners return to Skaha Lake spawning grounds.

### 4.6.4 Adult Supplementation

*Note: The formulation of Adult supplementation has been revised in version 2.2. Adult supplements to Skaha Lake are now taken from the Osoyoos population, up to some conservation constraint.*

The model will allow the user to specify a constant number of spawners each year taken from the Osoyoos population and transplanted to Skaha spawning grounds as a reintroduction strategy:

$\#Spawners_{Skaha,Total} = \#Spawners_{Skaha,wild} + \#Spawners_{Skaha,supp}$ [eq. 4-37]
$\#Spawners_{Osoyoos,Total} = \#Spawners_{Osoyoos,wild} - \#Spawners_{Skaha,supp}$

where: $\#\ Spawners_{Skaha,wild}$ = computed from equation 4-36, depending on the hypothesis about distribution of Okanagan sockeye spawners
$\#Spawners_{Skaha,supp}$ = number of Osoyoos spawners used to supplement the Skaha population (user-defined, year-specific parameter)
$\#\ Spawners_{Osoyoos,wild}$ = computed from equation 4-36, depending on the hypothesis about distribution of Okanagan sockeye spawners

The model includes a conservation constraint on the number of spawners that can be removed from the Osoyoos stock for supplementation purposes, similar to the constraint imposed on the removal of females for hatchery broodstock (section 4.2.6). Since with adult supplementation both males and females would be removed, the model computes a minimum level of total spawners (male and female) that must be maintained:

$MinSpawners_{Os} = MinFemale_{Os} / FemaleProp$ [eq. 4-38]

where: $MinFemale_{Os}$ = minimum level of Osoyoos females that must be maintained (user-defined parameter)
FemaleProp = average proportion of the population that are female (user-defined parameter)

If the user-specified number of spawners to supplement in a given year would cause the spawner abundance to go below this level, then the model will extract as many spawners as possible given the minimum constraint and use this value in equation 4-37 to obtain the total number of spawners in each population. In years when the Osoyoos spawner population is below the minimum level, no spawners are removed from supplementation. We assume that the spawners removed from the Osoyoos population have the same age and sex characteristics as the population at large.

# 5.0 Kokanee Submodel

The kokanee submodel is largely based on the Large Lakes Kokanee Model (LLKM), developed by ESSA with close cooperation of fisheries scientists from the (former) B.C. Ministry of Environment, Lands, and Parks[6] (Korman et al. 1993). The LLKM is an age-structured model designed to explore the effects of a wide range of kokanee management actions such as stocking, fishing regulations, and habitat enhancement. The LLKM therefore includes detailed modules for:

- kokanee population dynamics;
- fishing effort;
- competitor population dynamics; and
- predator population dynamics.

The scope of the Okanagan sockeye model we are building is much more limited than the LLKM, so we have incorporated only the kokanee and predator population dynamics modules (the predator population module is discussed in section 7).[7] The kokanee module includes four basic processes: Growth, predation losses, survival, and maturation (Figure 5.1). Each of these is discussed below. All computed quantities represent the state of the population in the fall.

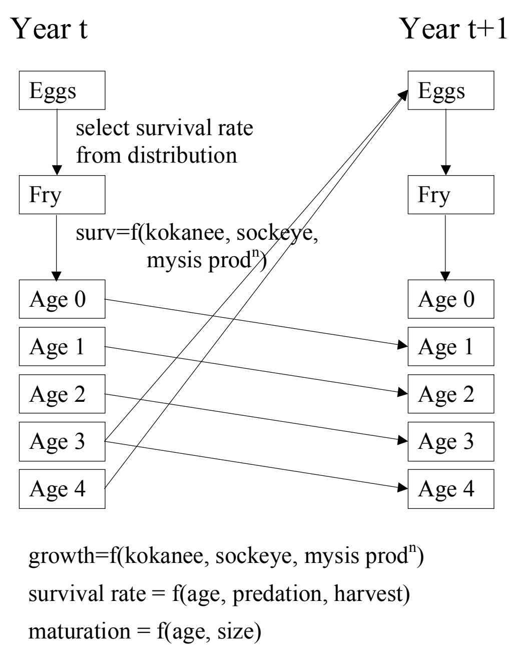


**Figure 5.1.** General structure of kokanee submodel.

[6] BC MELP scientists included Eric Parkinson, Jay Hammond, and Bruce Shepherd).
[7] Because of software incompatibilities, we are unable to directly incorporate the existing LLKM model into this model.

Skaha Lake has a relatively small kokanee population (Figure 5.2), compared to Okanagan Lake. The Okanagan Lake Action Plan (Andrusak et al. 2001) has generated some relatively good data for Okanagan Lake kokanee, but we have not been able to obtain significant data for Skaha Lake kokanee. In the absence of specific data, we have relied where possible on data for Okanagan Lake kokanee to generate preliminary parameter values. Where Okanagan Lake kokanee data were not available, we use the default parameter values supplied in the Large Lakes Kokanee Model. Many of these defaults are based on provincial standards supplied by BC MELP fisheries scientists involved in LLKM development.

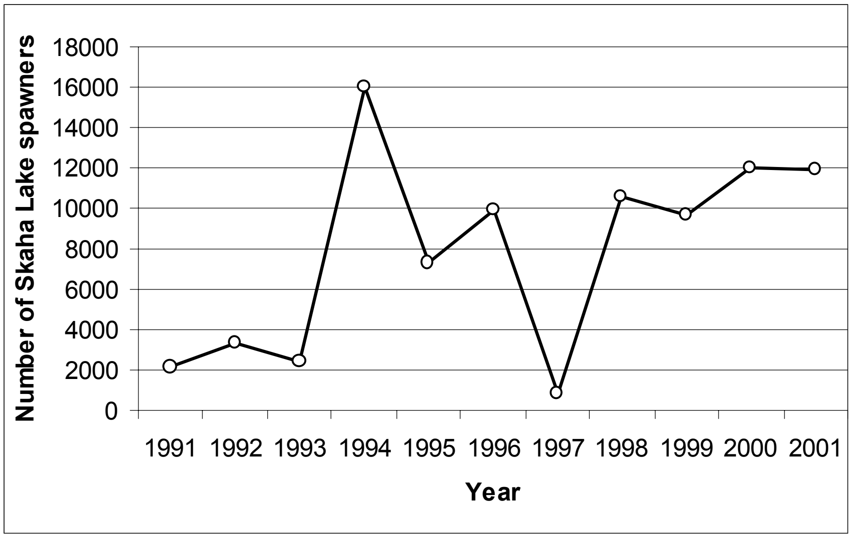


**Figure 5.2.** Annual estimates of Skaha Lake kokanee spawning abundance, 1991-2000. Source: WLAP 2001.

## 5.1 Growth

### 5.1.1 Von Bertalanffy growth equation

Kokanee size at age a is modelled using the difference formulation of the Von Bertalanffy growth equation (Ricker 1975):

$$Length_{a,t} = Length_{a-1,t-1} + K_{Brody}(Length_{Max} - Length_{a-1,t-1}) \quad \text{[eq. 5-1]}$$

where: $Length_{a-1}$ = average length of fish of age a-1 in previous year
$K_{Brody}$ = Brody growth coefficient (a user-defined parameter; standard Provincial value = 0.55)
$Length_{Max}$ = mean asymptotic length (an estimated parameter)

This function produces age-dependent growth rates as shown in Figure 5.3. These growth rates are also density-dependent as explained in section 5.1.2. $Length_{Max}$ represents the maximum size reached by the oldest age classes. $K_{Brody}$ represents the initial growth rate, or how quickly the maximum size is reached.

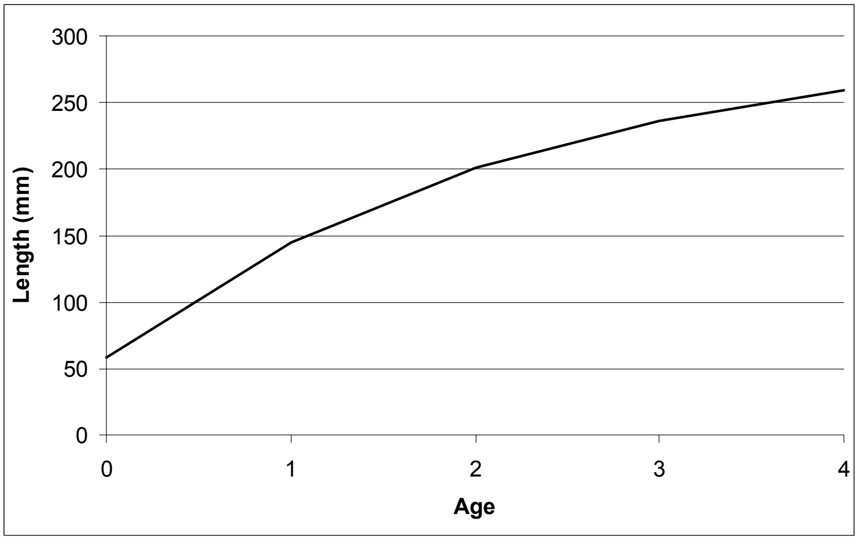


**Figure 5.3.** Example length-at-age curve produced by equation 5-1.

Equation 5-1 is parameterised using the following procedure. The parameter LengthMax in a particular simulation year can be calculated by assuming a constant value for $K_{Brody}$ (the provincial standard for this value is 0.55) and deriving independent estimates of $Length_0$ and $Length_3$. Length at age 0 is assumed to be a user-defined constant value; mean lengths of age 0 Okanagan kokanee have generally been between 50 and 60mm (Andrusak et al. 2001). Length at age 3 is estimated from lake productivity and the biomass of competitors (explained in the next section). Having estimates of $Length_0$, $Length_3$, and $K_{Brody}$, equation 5-1 can be used to estimate $Length_{Max}$. Note that this will change from year to year as a result of changes in density of Age 2 equivalent kokanee. The estimated LengthMax can be used to calculate lengths of all ages of kokanee in that year using equation 5-1.

### 5.1.2 Computation of age 2 kokanee equivalents

Length at age 3 in year t is estimated as a function of the density of Age 2 kokanee equivalents in the previous year and lake productivity (Figure 5.4) based on Rieman and Myers (1992):

$$Length_{3,t} = MaxLength_3 - ProdCoeff * \log(ProdAge2Eq_{t-1}) - SecchiCoeff * SecchiDepth \quad \text{[eq. 5-2]}$$

where:

| | |
|---|---|
| $MaxLength_3$ | = maximum length (mm) of age 3 fish at 0 density (user-defined parameter) |
| ProdCoeff | = coefficient relating age 3 length to age 2 equivalent production (user-defined parameter) |
| $ProdAge2Eq_{t-1}$ | = production of Age 2 kokanee and equivalents (kg/ha) in year t-1 (computed value; explained below) |
| SecchiCoeff | = coefficient relating age 3 length to Secchi Depth (user-defined parameter) |
| SecchiDepth | = Secchi Depth of lake (m) (from equation 3-5) |

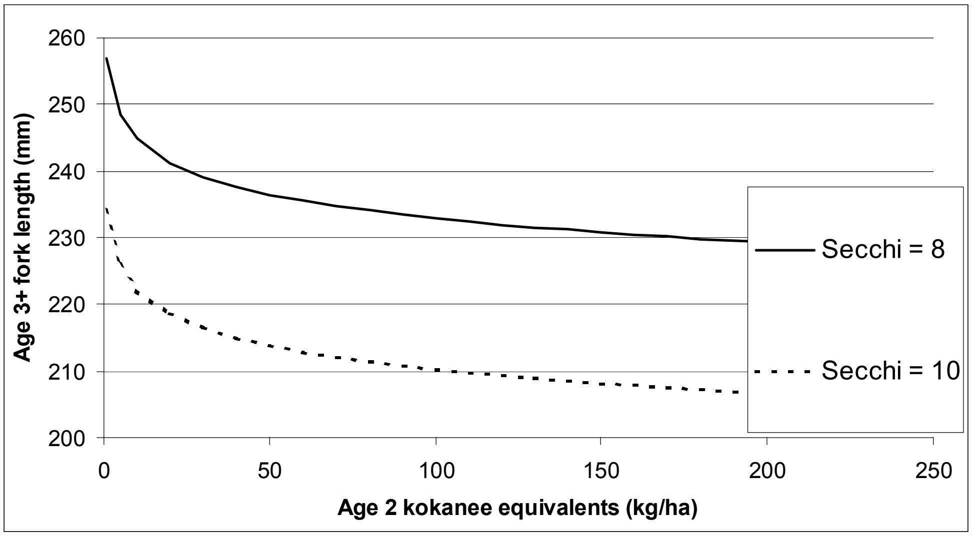


**Figure 5.4.** Age 3 length as a function of age 2 equivalent density and Secchi Depth.

Age 2 equivalent production includes all organisms that can compete with Age 2 kokanee for food, which in the Skaha Lake model includes kokanee of other ages, juvenile sockeye, and mysis.

**Kokanee equivalents**

Production of age 0, 1, 3, and 4 kokanee is converted to age 2 kokanee production based on the Production:Biomass ratios of each age relative to that of age 2 fish. Production:Biomass ratios are derived for each age class from conversion efficiency (kg production per kg consumed) and feeding rates (kg consumed per kg biomass) using equation 4-13. Conversion efficiency is based on average body size (Figure 5.5). Smaller kokanee with higher conversion efficiencies than age 2 fish thus place a smaller drain on total food resources

Conversion efficiency is predicted from body sizes at each age using equation 5-3:

$$ConvEff_{k,a} = ConvEffConst_k + ConvEffSlope_k * \log(Weight_a) \qquad \text{[eq. 5-3]}$$

where: $ConvEffConst_k$ = constant (user-defined parameter)
$ConvEffSlope_k$ = coefficient relating log(body weight) to conversion efficiency (user-defined parameter)
$Weight_a$ = body weight of age a kokanee (from equation 5-9)

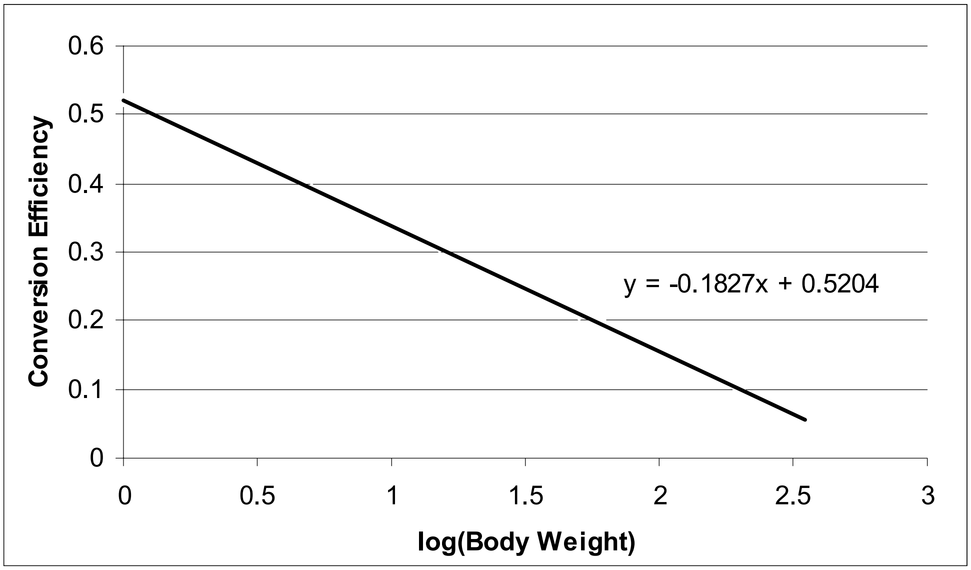


**Figure 5.5.** Conversion efficiency as a function of average body size. Based on data from Korman et al. 1993.

Based on computed body sizes and equation 5-3, kokanee production in terms of Age 2 equivalents is:

$ProdAge2Eq_{k,a,t-1} = KokAdProd_{a,t-1}* (P{:}B_{k,2,t-1}/P{:}B_{k,a,t-1})$ [eq. 5-4]

where:

| | | |
|---|---|---|
| where: | $ProdAge2Eq_{k,a,,t-1}$ | = production of age a kokanee (kg/ha) in age 2 kokanee equivalents |
| | $KokAdProd_{a,t-1}$ | = production from age a kokanee biomass (kg/ha) in previous year; computed from equation 5-31 using the equivalence factor $KokAdEquiv_{AdGrowth}$ (which by definition = 1) |
| | $P{:}B_{k,2,t-1}$ | = Production:Biomass of age 2 kokanee in year t-1 (derived from equation 4-13 and 5-3) |
| | $P{:}B_{k,a,t-1}$ | = Production:Biomass of age a kokanee (derived from equation 4-13 and 5-3) |

The total production of all age classes of kokanee in age 2 equivalents is:

$ProdAge2Eq_{k,t-1} = \Sigma_a ProdAge2Eq_{k,a,t-1} + KokFryProd_t* (P{:}B_{k,2,t-1}/P{:}B_{k,fry,t})$ [eq. 5-5]

| | | |
|---|---|---|
| where: | $ProdAge2Eq_{k,a,t-1}$ | = production of age a kokanee in age 2 kokanee equivalents (equation 5-4) |
| | $KokFryProd_t$ | = production from kokanee fry biomass (kg/ha) in current year; computed from equation 5-27 using the equivalence factor $KokFryEquiv_{AdGrowth}$ |
| | $P{:}B_{k,2,t-1}$ | = Production:Biomass of age 2 kokanee in year t-1 (derived from equation 4-13 and 5-3) |
| | $P{:}B_{k,fry,t}$ | = Production:Biomass of kokanee fry (derived from equation 4-13 and 5-3) |

### Sockeye equivalents

Growth and survival predictions in the kokanee model are assumed to be representative of conditions in the fall. Length at age 3 in the fall of year t is therefore determined by age 2 kokanee equivalent production in the fall of year t-1. Ideally, the sockeye model would compute a biomass of juveniles in the fall, but with the proposed model design juvenile biomass can be computed only for fry after emergence (in the spring) or smolts prior to migration (also in the spring). As a simplifying assumption, we will assume that kokanee length at age 3 (as measured in the fall of year t) is potentially affected by production of sockeye fry that emerge in the spring of year t. The influence of sockeye fry on growth of kokanee adults is determined by the $SxEquiv_{AdGrowth}$ adjustment factor used in equation 4-14 to determine the production of sockeye fry in equation 5-5:

$$ProdAge2Eq_{s,t-1} = SxFryProd_t * (P:B_{k,2}/P:B_{SxFry}) \quad \text{[eq. 5-6]}$$

where: $SxFryProd_t$ = production of sockeye fry (kg/ha) from equation 4-14, using the equivalence factor $SxEquiv_{AdGrowth}$
$P:B_{k,2}$ = Production:Biomass of age 2 kokanee (derived from equation 4-13 and 5-3)
$P:B_{SxFry}$ = Production:Biomass of sockeye fry (from equation 4-13 and 5-3)

### Mysis equivalents

Length at age 3 kokanee in year t is assumed to be determined by production from mysis biomass in the previous year. Mysis are assumed to have similar conversion efficiencies to kokanee (Cooper et al. 1992), but different feeding rates. The conversion of mysis biomass to age 2 kokanee equivalents is:

$$ProdAge2Eq_{m,t-1} = MysImmProd_{t-1}*(P:B_{k,2}/P:B_{m,imm})+MysMatProd_{t-1}*(P:B_{k,2}/P:B_{m,mat}) \quad \text{[eq. 5-7]}$$

where: $ProdAge2Eq_{m,t-1}$ = production of mysis in age 2 kokanee equivalents
$MysImmProd_{t-1}$ = production of immature mysis (kg/ha) from mysis submodel equation 6-11b, using equivalence factor $ImmMysEquiv_{AdGrowth}$
$MysMatProd_{t-1}$ = production of mature mysis (kg/ha) from mysis submodel equation 6-11a, using equivalence factor $MatMysEquiv_{AdGrowth}$
$P:B_{k,2}$ = Production:Biomass of age 2 kokanee (from equation 4-13 and 5-3)
$P:B_m$ = Production:Biomass of mysis (from equation 6-10)

### Total Age 2 Equivalents

The total production (kg/ha) of age 2 equivalents in year t-1 for calculating age 3 length in year t is:

$$ProdAge2Eq_{t-1} = ProdAge2Eq_{k,t-1} + ProdAge2Eq_{s,t-1} + ProdAge2Eq_{m,t-1} \quad \text{[eq. 5-8]}$$

where: $ProdAge2Eq_{k,t-1}$ = production of kokanee in age 2 kokanee equivalents (from equation 5-5)
$ProdAge2Eq_{s,t}$ = production of sockeye in age 2 kokanee equivalents (from equation 5-6)
$ProdAge2Eq_{m,t-1}$ = production of mysis in age 2 kokanee equivalents (from equation 5-7)

The $ProdAge2Eq_{t-1}$ value is used in equation 5-2 to estimate the length of age 3 kokanee in year t, as illustrated in Figure 5-3.

### 5.1.3 Length-Weight relationship

Lengths at age t (mm) are converted to weights (g) using the equation:

$$Weight_a = WeightA_a * Length_a^{WeightBa} \quad \text{[eq. 5-9]}$$

where: $Length_a$ = average length (mm) at age a, computed from equation 5-1
$WeightA_a$, $WeightB_a$ = age-specific coefficients (user-defined parameters; LLKM default values are shown in Table 5.1)

**Table 5.1.** LLKM default (provincial standard) values for length-weight coefficients (Korman et al. 1993).

| Age | WeightA | WeightB |
|---|---|---|
| 0 | 6.76E-06 | 3.08 |
| 1 | 2.63E-06 | 3.28 |
| 2 | 1.35E-06 | 3.40 |
| 3 | 1.17E-06 | 3.43 |
| 4 | 1.17E-06 | 3.43 |

## 5.2 Predation losses

The predator submodel (see Section 7) calculates the maximum biomass of kokanee that must have been consumed during the previous year to produce the biomass at each predator age class in the current year (predator age classes are designated as subscript p to distinguish them from kokanee age classes, which are designated as subscript a). This section describes the process to compute the kokanee losses due to consumption that have occurred between year t-1 and year t. Predation losses for age 0 and older fish during this year are determined by kokanee density and size at year t-1. Because fry emerge during the spring, predation losses for this age class are determined from density and fry size in year t. The notation in the following discussion is for age 0-4 fish, but otherwise the equations and approach apply to both fry and the 0-4 age classes.

The biomass required by the predator population is based solely on its consumptive requirements, and must be adjusted to account for the density of kokanee that was available. At low prey densities, predators will presumably shift to an alternate prey source and realised predation rates will decline. This relationship is illustrated in Figure 5-6.

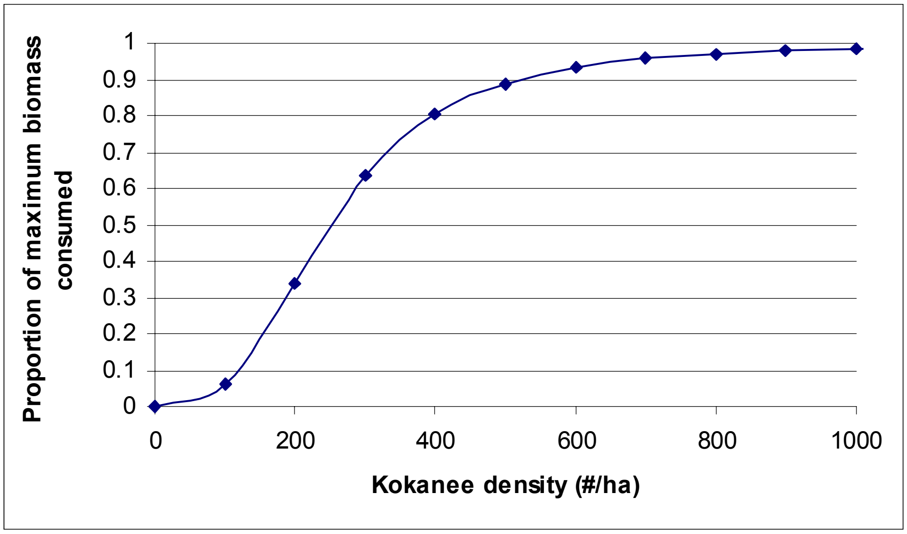


**Figure 5.6.** Density-dependent adjustment of biomass consumed by predators.

The relationship is Figure 5.6 determines the actual proportion of kokanee biomass consumed by a predator age class p during year t (between year t-1 and year t) and has the equation:

$$PropCons_{p,t} = KokDensity_{t-1}^{KokConsShape} / (KokConsHalf^{KokConsShape} + KokDensity_{t-1}^{KokConsShape}) \quad \text{[eq. 5-10]}$$

where: KokConsShape = shape parameter (user-defined parameter)
KokConsHalf = kokanee density giving half of the maximum proportion consumed (user-defined parameter)
$KokDensity_{t-1}$ = total kokanee density (#/ha)
$= \Sigma_a \#Kokanee_{a,t-1} / LakeArea$

The proportion of kokanee biomass consumed by each predator age class must be allocated among the vulnerable kokanee age classes. The LLKM includes two alternative mechanisms for determining the size preference of predators. One mechanism bases size preference entirely on relative body size of predator and prey; the other bases size preference on both relative body size and relative density of kokanee age classes. In this model, we will implement only the second (size and density-dependent).

Relative vulnerability of kokanee to predation is assumed to be a function of the relative prey/predator fork lengths, based on rainbow trout stomach content data from Kootenay and Quesnel Lakes (Korman et al. 1993). This ratio for a particular combination of predator age class p and kokanee age class a is calculated as:

$$PreyLengthRatio_{a,p,t-1} = Length_{a-1,t-1} / Length_{p-1,\,t-1} \quad \text{[eq. 5-11]}$$

where: $Length_{a,t-1}$ = length of kokanee at age a in year t-1 (from equation 5-1)
$Length_{p-1,\,t-1}$ = length of predators at age p-1 in year t-1 (user-defined parameter)

The relationship between relative vulnerability and size ratios can be closely approximated by a normal distribution with mean of 0.16 and standard deviation of 0.06 (Figure 5.7). This function defines the relative vulnerability of kokanee in age class a to predation by predators in age class p. The equation for this function is:

$RelVuln_{a,p,t-1}$= Normal($PreyLengthRatio_{a,p,t-1}$, RelVulnMean, RelVulnStDev) [eq. 5-12]

where: $PreyLengthRatio_{a,p,t-1}$ =ratio of fork lengths (from equation 5-11)
RelVulnMean = user-defined parameter
RelVulnSteDev = user-defined parameter

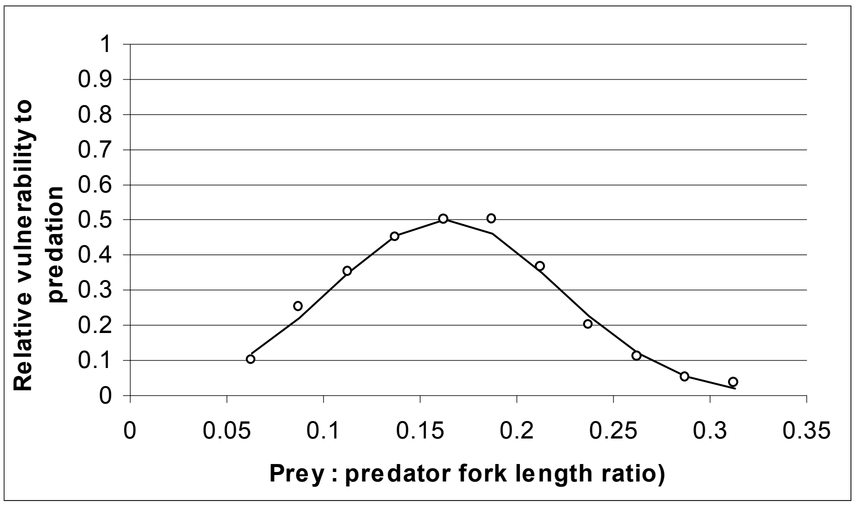


**Figure 5.7.** Size-dependent relative vulnerability to predation.

Once the relative vulnerability has been determined, the relative biomass (kg) of kokanee in each age class a consumed by predators in age class p during year t can be computed as:

$RelBio_{a,p,t}$= $\#Kokanee_{a,t-1}$ * $RelVuln_{a,p,t-1}$ * $Weight_{a,t-1}$ [eq. 5-13]

where: $\#Kokanee_{a,t-1}$ = # of kokanee in age class a in previous year (from equation 5-23)
$RelVuln_{a,p,t-1}$ = relative vulnerability of age class a (from equation 5-12)
$Weight_{a,t-1}$ = weight (g) of fish in age class a (from equation 5-8)

The actual biomass consumed in each age class of kokanee by each predator age class during year t is determined from the biomass required by predators, the density-dependent proportion of the required biomass that is consumed, and the relative biomass in each kokanee age class:

$BiomassCons_{a,p,t}$= $PropCons_{p,t}$ * $KokBioCons_{a,t}$ * $RelBio_{a,p,t}$ / $\Sigma_a RelBio_{a,p,t}$ [eq. 5-14]

where: $PropCons_{p,t}$ = proportion of biomass consumed (from equation 5-10)
$KokBioCons_{a,t}$ = kokanee biomass required by predators (from equation 7-8)
$RelBio_{a,p,t}$ = relative biomass in age a consumed (from equation 5-13)

The total biomass (kg) of kokanee in age class a is obtained by summing equation 5-14 over all predator age classes:

$BiomassCons_{a,t} = \Sigma_p BiomassCons_{a,p,t}$ [eq. 5-15]

where: $BiomassCons_{a,p,t}$ = biomass of age a kokanee consumed by age p predators (from equation 5-14)

Finally, the fraction of age a kokanee consumed by predators is calculated as:

$FractionCons_{a,t} = (BiomassCons_{a,t} / (Weight_{a,t-1} * 1000)) / \#Kokanee_{a,t-1}$ [eq. 5-16]

where: $BiomassCons_{a,t}$ = biomass of age a kokanee consumed during year t (kg; from equation 5-15)
$Weight_{a,t-1}$ = weight of age a kokanee in year t-1 (g; from equation 5-8)
$\#Kokanee_{a,t-1}$ = # of age a kokanee in year t-1 (from equation 5-)

## 5.3 Survival from Age 0 to Adult

The survival rate of Age 0 and older fish (age classes that reside in rearing lakes) in year t-1 to year t is determined by natural survival rates, predation losses during the year by lake-residing predators, and harvest during the year. Survival and harvest rates for age classes 0 and older are assumed to be density- and size-independent, and are held constant for the duration of the simulation. Predation losses are calculated as described in the previous section. The number of fish surviving to ages 1 and older in year t is given by:

$\#Kokanee_{a,t} = \#Kokanee_{a-1, t-1} * NatSurvFrac_{a-1} * (1-FractionCons_{a-1,t}) * (1-HarvRate_a)$ [eq. 5-17]

where: $\#Kokanee_{a-1,t-1}$ = number of kokanee of age a-1 in the previous year
$NatSurvFrac_{a-1}$ = natural survival fraction for kokanee of age a-1 (user-defined parameter)
$FractionCons_{a-1,f}$ = fraction of age a-1 kokanee consumed by predators during year t (from equation 5-16)
$HarvRate_a$ = harvest rate of age a kokanee (user-defined parameter)

## 5.4 Maturation and age 0 production

### 5.4.1 Spawner abundance

The LLKM calculates the proportion of mature Age 3 adults as a function of average length for that age (Figure 5.8). The X-intercept of this function is the minimum spawning length of age 3 fish (200 mm in Figure 5.8), while the size at 100% spawning is the average length of age 4 fish (260 mm in Figure 5.8). This assumes that no age-2 fish spawn, and that all age 4 fish spawn. The slope of this line will change from year to year as density-dependent growth processes determine the length of age 4 fish. All mature fish are assumed to die after spawning.

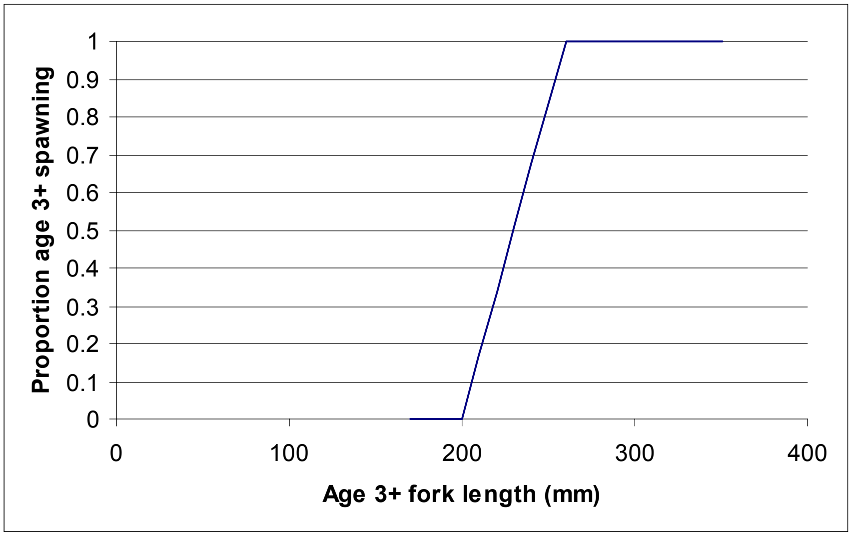


**Figure 5.8.** Maturation function in LLKM.

The equation to calculate the proportion of age 3 fish maturing is:

$PropMature_3$ = ($Length_3$-MinMatLength) / (MaxMatLength-MinMatLength) [eq. 5-18]

where: $Length_3$ = average length (mm) at age 3, computed from equation 5-1
MinMatLength = minimum spawning length (user-defined parameter) (mm)
MaxMatLength = maximum spawning length (average length of age 4 fish, derived from equation 5-1) (mm)

The number of spawners is therefore given by:

$\#Spawners_{kokanee}$ = $\#Kokanee_4$ + $\#Kokanee_3$ * $PropMature_3$ [eq. 5-19]

where: $\#Kokanee_4$ = # of age 4 kokanee (from equation 5-17)
$\#Kokanee_3$ = # of age 3 kokanee (from equation 5-17)
$PropMature_3$ = proportion of age 3 fish maturing (from equation 5-18)

### 5.4.2 Spawner capacity

Determination of spawning habitat for Skaha Lake kokanee uses a similar approach as Skaha sockeye. Potential spawning habitat for Skaha Lake sockeye and kokanee is available in the channelled portion of the Okanagan River between Okanagan Lake and Skaha Lake. The amount of spawning habitat is related to flows, as shown in Figure 4.3 and equation 4-2; only the area designated as "medium quality" is assumed to be suitable for kokanee spawning. Overlap between sockeye and kokanee spawners is modelled using a similar approach to the one described for Skaha Lake sockeye in equation 4-4. As described there, the SpawnOverlap parameter represents the degree of spatial and temporal overlap between the two spawning populations. Because the two populations overlap to some extent in both space and time, this value should be set close to 1. The equation for determining the amount of spawning habitat for kokanee is:

$$SpawnHabFrac_{kokanee} = \#Spawners_{kokanee} / (\#Spawners_{sockeye} + \#Spawners_{kokanee}) * (SpawnOverlap) + (1 - SpawnOverlap) \qquad [eq.\ 5\text{-}20]$$

where: $\#Spawners_{sockeye}$ = obtained from equation 4-37
$\#Spawners_{kokanee}$ = obtained from equation 5-19
SpawnOverlap = fraction of habitat competed over by kokanee and sockeye (user-defined parameter)

The total habitat available for use by Skaha Lake kokanee is calculated using equation 5-21:

$$SpawnHab_{Total,kokanee} = (SpawnHab_{Current,med} + SpawnHab_{New,\ med}) * SpawnHabFrac_{kokanee} \qquad [eq.\ 5\text{-}21]$$

where: $SpawnHab_{Current,med}$ = amount of medium quality habitat, obtained from equation 4-3 and parameter values given in Figure 4.3 (bottom panel).
$SpawnHabFrac_{kokanee}$ = obtained from equation 5-20
$SpawnHab_{New,med}$ = amount of new medium-quality spawning habitat created (user-defined parameter)

Calculated values of spawning habitat are used to estimate the spawning capacity (maximum number of female spawners on the spawning grounds) based on an optimal female density. The equation is:

$$SpawnCapacity = SpawnHab_{Total,kokanee} * FemaleDensity_k \qquad [eq.\ 5\text{-}22]$$

where: $SpawnHab_{Total,kokane}$ = obtained from equation 5-21
$FemaleDensity_k$ = # of females per sq. m of spawning habitat (user-defined parameter)

### 5.4.3 Spawner-egg (fecundity)

Fecundity (# eggs per female) is assumed to be a function of fork length of mature females:

$$\log_{10}(Fecundity_a) = FecA + FecB*\log_{10}(Length_a) \qquad [eq.\ 5\text{-}23]$$

where: $Length_a$ = average length (mm) of mature fish at age a, computed from equation 5–1
FecA, FecB = coefficients (user-defined parameters)

For Okanagan lake kokanee the FecA and FecB parameters are –5.275 and 3.2899, respectively (Andrusak et al. 2001).

The number of eggs laid in a brood year is a Beverton-Holt function based on the number of spawners. This function produces a density-dependent relationship between spawner abundance and egg abundance. The function is mediated by spawning flow through its effect on the capacity of spawning habitat (equation 5-22).

$$\#Eggs = \frac{\#Spawners_{kokanee} * FemaleProp * AveFecundity}{[1+(AveFecundity/EggCap * (\#Spawners_{total} * FemaleProp))]} \qquad [eq.\ 5\text{-}24]$$

where: #Eggs = total number of eggs deposited
$\#Spawners_{kokanee}$ = total number of kokanee spawners from equation 5-19

| | | |
|---|---|---|
| | AveFecundity | = age-weighted average fecundity (using equation 5-23) |
| | EggCap | = egg capacity of spawning habitat<br>= SpawnCapacity (equation 5-22) * FemaleProp * AveFecundity (equation 5-23) |

### 5.4.4 Egg - Emergent Fry

Egg-fry survival rates are selected from a log-normal distribution with user-specified mean and standard deviation:

EggFrySurv = N(EggSurvMean, EggSurvStDev) [eq. 5-25]

| | | |
|---|---|---|
| where: | EggSurvMean | = mean of loge-transformed distribution of survival rates (user-defined parameter) |
| | EggSurvStDev | = standard deviation of loge-transformed distribution of survival rates (user-defined parameter) |

Presumably these survival rates are affected by flows and temperatures in spawning areas during the incubation period, but at this point we have no data to formulate any hypotheses about these relationships. The geometric mean egg-fry survival rate in Mission Creek spawning channel from 1990-1999 was 21.3% (Andrusak et al. 2001).

The number of fry in year t produced from eggs deposited in year t-1 is:

$\#EmergFry_t = \#Eggs_{t-1} * EggFrySurv$ [eq. 5-26]

| | | |
|---|---|---|
| where: | $\#Eggs_{t-1}$ | = computed from equation 5-23 |
| | EggFrySurv | = computed from equation 5-25 |

The production of kokanee fry is needed to calculate rearing capacities for sockeye, kokanee, and mysis juveniles, and to calculate kokanee adult growth rates:

$KokFryProd = (\#EmergFry * Weight_{EmFry}/1000) / LakeArea * P{:}B_{k,fry} * KokFryEquiv$ [eq. 5-27]

| | | |
|---|---|---|
| where: | #EmergFry | = number of emerging fry (from equation 5-26) |
| | $Weight_{EmFry}$ | = body weight (g) of kokanee fry (user-defined parameter) |
| | $P{:}B_{k,fry}$ | = Production:Biomass of kokanee fry (from equation 4-13 and 5-3) |
| | LakeArea | = area of rearing lake(ha) |
| | KokFryEquiv | = as defined below |

Two equivalence factors (KokFryEquiv) are required for determining the effects of kokanee fry on sockeye and mysid survival, and on growth of kokanee adults:

1. The equivalence factor $KokFryEquiv_{JuvSurv}$ is needed for partitioning lake carrying capacity for survival of sockeye and mysis juveniles. Because the juvenile survival equivalence factors for sockeye and mysis are expressed in terms of kokanee fry, $KokFryEquiv_{JuvSurv} = 1$ by definition.

2. The equivalence factor $KokFryEquiv_{AdGrowth}$ is needed to account for the effects of kokanee fry production on growth rates of adult kokanee. As a preliminary assumption, we assume that $KokFryEquiv_{AdGrowth} = 1$.

### 5.4.5 Emergent Fry – Rearing Fry (Age 0)

Survival of emerging fry is assumed to be a density-dependent Beverton-Holt function (Figure 5.9).

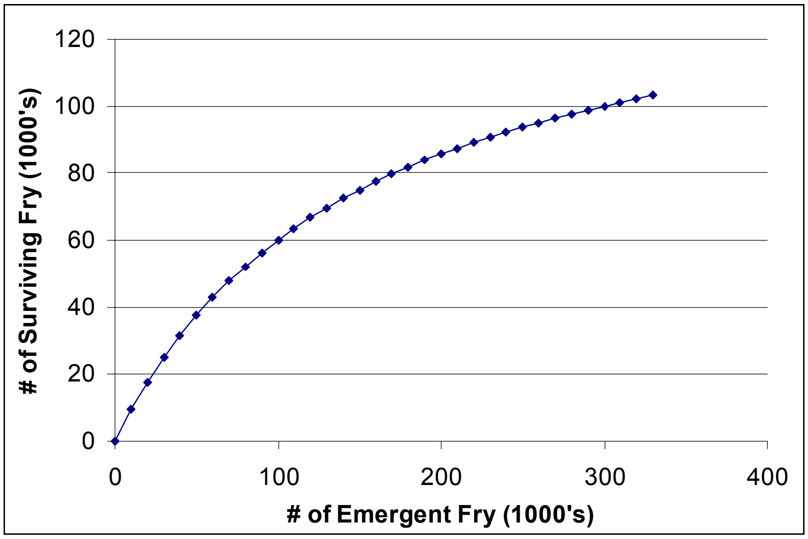


**Figure 5.9.** Relationship between # of surviving fry and # of emerging fry (example only).

The function assumes that survival rate approaches 100% at very low fry densities, and approaches 0% as the number of fry approaches the capacity of the lake. The fry production capacity can be inferred from the phosphorus concentration of Skaha Lake as described above in section 4.3.1 for sockeye. As with sockeye juveniles, the rearing capacity must be adjusted to account for kokanee-sockeye-mysis interactions. The analogous equation for kokanee is:

$$TotalCap_{k,t} = \frac{KokFryProd_t * TotalCap_t}{(SxFryProd_t + KokFryProd_t + KokAdProd_{t-1} + ImmMysProd_{t-1} + MatMysProd_{t-1})} \quad \text{[eq. 5-28]}$$

where:
- $TotalCap_t$ = derived from equation 4-19 (kg/ha)
- $KokFryProd_t$ = production of kokanee fry from equation 5-27, using the equivalence factor $KokFryEquiv_{JuvSurv}$ (which by definition = 1)
- $SxFryProd_t$ = sockeye fry production (kg/ha) from equation 4-14, using the equivalence factor $SxEquiv_{JuvSurv}$
- $KokAdProd_{,t-1}$ = kokanee ages 0-4 production (kg/ha) from equation 5-31, using the equivalence factor $KokAdEquiv_{JuvSurv}$
- $ImmMysProd_{t-1}$ = production (kg/ha) of immature mysis in year t-1 from mysis submodel equation 6-11b, using the equivalence factor $ImmMysEquiv_{JuvSurv}$
- $MatMysProd_{t-1}$ = production (kg/ha) of mature mysis in year t-1 from mysis submodel equation 6-11a, using the equivalence factor $MatMysEquiv_{JuvSurv}$

The kokanee age 0 capacity (in numbers of fish) is:

$Age0Cap = TotalCap_{k,t} * LakeArea / (Weight_0 /1000)$ [eq. 5-29]

where: $TotalCap_{s,t}$ = capacity of lake for kokanee age 0 (kg/ha); derived from equation 5-28
LakeArea = area of the rearing lake (ha)
$Weight_0$ = derived from Length0 (user-defined parameter) and equation 5-9 (g)

The equation to determine the number of Age 0 kokanee in a given year is then:

$\#Kokanee_0 = \#EmergFry/(1+(\#EmergFry/Age0Cap)) * (1- FractionCons_{fry,t})$ [eq. 5-30]

where: #EmergFry = # of emerging fry (from equation 5-26)
Age0Cap = rearing capacity for kokanee fry (from equation 5-29)
$FractionCons_{fry,t}$ = fraction of fry consumed (from equation 5-16)

The fraction of fry consumed represents both predation on smolts at the time of migration into the lake and predation during the summer while they are rearing.

## 5.5 Total production

Total production of adult kokanee (defined for documentation purposes as age 0+) in kg/ha is required to partition lake rearing capacity among kokanee, sockeye, and mysis. As for sockeye, kokanee fry, and mysis, we first calculate a base production rate then adjust that production using different equivalence factors to account for inter- and intra-specific differences in competitive ability and ecological overlap. Base production is calculated as

$KokProd_a = \#Kokanee_a*(Weight_a/1000) / LakeArea * P:B_{K,a} * KokAdEquiv$ [eq. 5-31]

where: $\#Kokanee_a$ = number of kokanee of age a (0-4, from equation 5-30)
$Weight_a$ = body weight (g) of kokanee of age a (from equation 5-8)
$P:B_{K,a}$ = Production:Biomass of age a kokanee (from equation 4-13 and 5-3)
LakeArea = area of rearing lake(ha)
KokAdEquiv = equivalence factor

Two equivalence factors are required:

1. The equivalence factor $KokAdEquiv_{JuvSurv}$ is needed for partitioning lake carrying capacity for survival of sockeye, kokanee and mysis juveniles. As a preliminary assumption, we assume that $KokAdEquiv_{JuvSurv} = 1$.
2. The equivalence factor $KokAdEquiv_{AdGrowth}$ is by definition = 1.

Total kokanee production is the sum of the kokanee production over all adult age classes.

# 6.0 Mysis Submodel

The mysis submodel provides annual estimates of mysis biomass to allow for effects of competitive interactions between mysis and nerkids on the productive capacity of the lake. Sampling for mysis has occurred in Okanagan Lake since 1989, where mean densities have varied from $150/m^2$ to $450/m^2$. Mysis densities in Skaha Lake are around $90/m^2$ and around $6/m^2$ in Osoyoos Lake (data provided by workshop participants). The downstream gradient is thought to be a result of gradual downstream migration from Okanagan Lake (where it was first stocked in 1966) to downstream lakes. Overall trends in mysis densities in Okanagan Lake appear to be highly variable from year to year but the average since the mid-1990's has been relatively constant (Andrusak et al. 2001). This is consistent with Kim Hyatt's observation that it takes about 30 years or so for mysis to become fully established after introduction (workshop comment).

## 6.1 Survival, harvest, and predation

Our proposed modelling approach is based on a logistic growth function over time. We assumed, based on comments by workshop participants, that Okanagan mysis populations have a 2-year life cycle. We model two life stages: immature (1 year-olds) and mature (2-year olds). The maturation process is continuous but this division of life stages provides a reasonable approximation.

Density of immature mysis is calculated from the # of mature mysis the previous year:

$$MysisDensity_{Imm,t} = MysisDensity_{Mat,t-1} * MysisFemProp * MysisRecruitRate \quad \text{[eq. 6-1]}$$

where: $MysisDensity_{Mat,t-1}$ = density of mature mysis in year t-1 (#/ha; from equation 6-9)
MysisFemProp = proportion of mature mysis that are female (user-defined parameter)
MysisRecruitRate = # of immature mysis produced per mature mysis female (user-defined parameter). This incorporates the # of eggs/female and the survival rate from egg to immature mysis

Survival from the immature to mature life stage is density-dependent (Figure 6.1). Recruitment is represented as the density of mature mysis in year t+1 per immature mysis in year t). Density is expressed as the percentage of total capacity in year t that is occupied. The capacity will change from year due to fluctuations in phosphorus concentrations (which drive total lake productivity) and kokanee and sockeye abundance. As the % capacity filled increases, mysis survival rate declines.

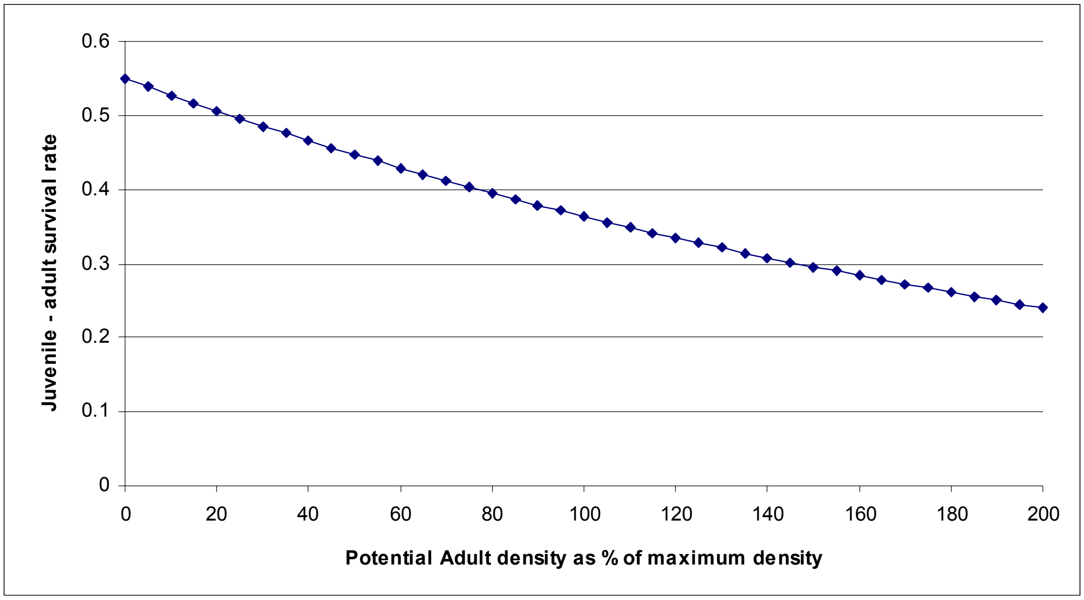


**Figure 6.1.** Mysis survival rate as a function of density.

Parameterisation of the relationship in Figure 6.1 requires two pieces of information. The first is the maximum survival rate at very low adult densities (i.e., the y-intercept). This is a user-defined parameter, representing the rate of population increase in the absence of significant intra-specific competition. Maximum survival rate can theoretically be measured in controlled experiments or in lakes with low mysis densities. We use information from Okanagan Lake to develop a rough estimate of the maximum survival rate. Current density of mysis in Okanagan Lake is around 300/m2 and has been relatively constant over the last several years (Andrusak et al. 2001). We assume that this density represents the current carrying capacity of Okanagan lake for mysis (i.e., mysis in Okanagan Lake are at 100% of capacity). Kim Hyatt (workshop comments) suggested that mysis generally take about 30 years to reach constant densities. Based on these two pieces of information, we estimate that the maximum survival rate from immature to mature would have had to be around 0.55 to account for the temporal trend in Okanagan Lake. This value is likely a function of lake productivity and the model will allow for lake-specific values, but this preliminary estimate provides an order of magnitude approximation as a preliminary parameter value for Skaha and Osoyoos Lakes.

The second piece of information defines how steeply the curve in Figure 6.1 declines. To determine this, we make the simple assumption that the recruitment rate is 1 (i.e., the population replaces itself) when the capacity is 100% filled. That is, population densities remain constant once capacity has been reached. The survival rate at 100% capacity value can be computed from the maximum survival rate, the proportion of mature individuals that are female, and the rate of immature mysis production.

The equation describing the survival rate function is:

$$MysSurvRate_t = MaxSurvRate * exp(-SurvShape * (MysisDensity_{Imm,t-1} / TotalCap_{m,t})) \quad [eq.\ 6\text{-}2]$$

where: MaxSurvRate = maximum survival rate at low adult density (user-defined parameter)
SurvShape = calculated steepness parameter

= ln(1/(MysisFemProp*MysisRecruitRate)/MaxSurvRate)/-100 assuming that the recruitment rate is 1 at 100% of capacity

$MysisDensity_{Imm,t-1}$ = density of immature mysis in year t-1 (#/ha); from equation 6-1

$TotalCap_{m,t}$ is the rearing capacity in the lake for mysis in the year t, assuming that the total rearing capacity is partitioned between sockeye, kokanee, and mysis according to their relative production. The equation to calculate capacity for producing mature mysis from immature mysis in a given year is:

$$TotalCap_{m,t} = \frac{ImmMysProd_{Mysis,t-1} * (TotalCap_t / MysisWeight_{Mat} * 1000)}{(SxFryProd_t + KokFryProd_t + KokAdProd_{t-1} + ImmMysProd_{t-1} + MatMysProd_{t-1}} \quad \text{[eq. 6-3]}$$

where:
- $TotalCap_t$ = derived from phosphorus concentrations (equation 4-19; kg/ha)
- $MysisWeight_{Mat}$ = body weight per mysis (g; user-defined parameter)
- $KokFryProd_t$ = production of kokanee fry in year t from equation 5-27, using the equivalence factor $KokFryEquiv_{JuvSurv}$ (which by definition = 1)
- $SxFryProd_t$ = sockeye fry production (kg/ha) in year t from equation 4-14, using the equivalence factor $SxEquiv_{JuvSurv}$
- $KokAdProd_{,t-1}$ = kokanee ages 0-4 production (kg/ha) from the fall of year t-1 to the fall of year t from equation 5-31, using the equivalence factor $KokAdEquiv_{JuvSurv}$
- $ImmMysProd_{t-1}$ = production (kg/ha) of immature mysis in year t-1 from mysis submodel equation 6-11b, ($ImmMysEquiv_{JuvSurv}$ = 1 by definition).
- $MatMysProd_{t-1}$ = production (kg/ha) of mature mysis in year t-1 from mysis submodel equation 6-11a, using the equivalence factor $MatMysEquiv_{JuvSurv}$

The potential mature mysis density in year t is then:

$$MysisDensity_{Mat,t} = MysisDensity_{Imm,t-1} * MysSurvRate_t \quad \text{[eq. 6-4]}$$

where:
- $MysisDensity_{Imm,t-1}$ = density of immature mysis (#/ha) from equation 6-1.
- $MysSurvRate_t$ = survival rate from immature to mature from equation 6-2

Equations 6-1 and 6-4 describe potential mysis production. This can be adjusted to account for potential reductions in mysis densities due to mysis harvest and predation by kokanee. Harvest is modelled using a simple loss adjustment representing the fraction of a particular cohort removed in each year. The harvest rate is assumed to take the same proportion of mature and immature mysis.

There was disagreement over the importance of predation by kokanee adults in controlling mysid populations. We have included kokanee predation on mysis, in which the maximum contribution of mysis to the diet of kokanee is a function of age of kokanee. The actual contribution of mysis to kokanee diet is a function of mysid density (higher contribution at higher density; Figure 6.2). Such a function is likely to be difficult to parameterise with existing data but could in theory be tested through controlled field experiments.

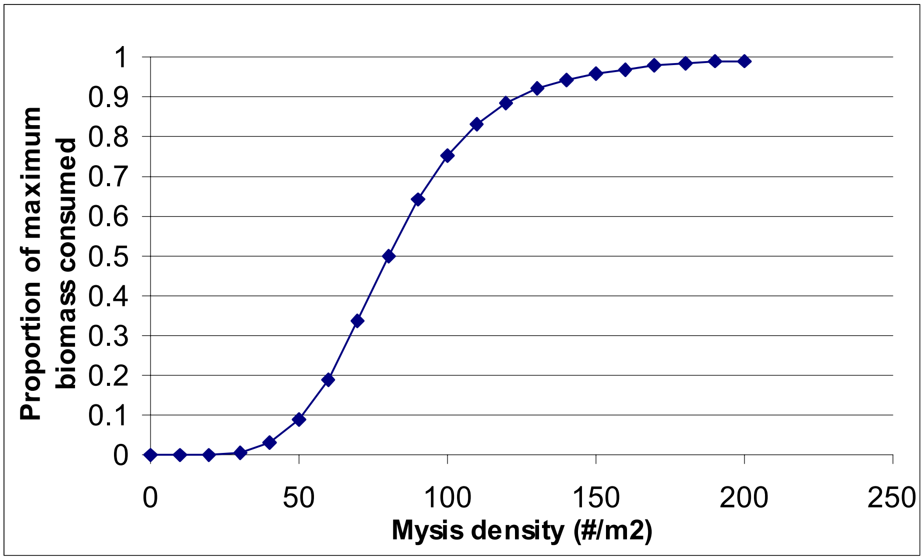


**Figure 6.2.** Example relationship between mysis contribution to kokanee diet and mysid density.

The contribution of mysis to the diet of age a kokanee is:

$$MysisContr_a = MaxContr_a * \frac{(MysisDensity_{Mat+Imm})^{ContrShape}}{(ContrHalf_a^{ContrShape} + (MysisDensity_{Mat+Imm})^{ContrShape})} \quad \text{[eq. 6-5]}$$

where: $MaxContr_a$ = maximum contribution of mysis to age a kokanee (user-defined parameter)

$MysisDensity_{Mat+Imm}$ = total (mature + immature) mysis density from equation 6-1 and 6-4

ContrHalf = mysis density at which actual mysis contribution is half of the maximum (user-defined parameter)

ContrShape = shape parameter (user-defined parameter; assume same for all kokanee age classes)

This function can be parameterized to represent the hypothesis of no kokanee predation on mysis by setting the $MaxContr_a$ parameter to zero for all age classes.

The biomass of mysis (kg/ha) consumed in year t is found from equation 6-5 and the production and conversion efficiency of kokanee in each age class:

$$MysisBiomassCons_t = \Sigma_a([KokProd_{a,t-1} / ConvEff_{a,t-1})*MysisContr_{a,t} \quad \text{[eq. 6-6]}$$

where: $KokProd_{a,t-1}$ = production from age a kokanee (kg/ha)

= $\#Kokanee_a*(Weight_a/1000)$ / LakeArea * $P:B_{K,a}$

\#Kokanee = number of kokanee at age a from equation (5-30)

$Weight_a$ = body weight (g) of kokanee of age a (from equation 5-8)

$P:B_{K,a}$ = Production:Biomass of age a kokanee (from equation 4-13 and 5-3)

$ConvEff_a$ = conversion efficiency of age a (from equation 5-3)

$MysisContr_a$ = contribution of mysis to diet of age a kokanee from equation 6-5

The total biomass consumed (in kg/ha) is apportioned to immature and mature mysis age classes based on their relative biomasses in year t-1:

$$MysisBiomassCons_{Imm,t} = \frac{MysisBiomassCons_t * MysisDensity_{Imm,t-1} * MysisWeight_{Imm,t-1}}{MysisDensity_{Imm,t-1} * MysisWeight_{Imm,t-1} + MysisDensity_{Mat,t-1} * MysisWeight_{Mat,t-1}} \quad \text{[eq. 6-7a]}$$

$$MysisBiomassCons_{Mat,t} = \frac{MysisBiomassCons_t * MysisDensity_{Mat,t-1} * MysisWeight_{Mat,t-1}}{MysisDensity_{Imm,t-1} * MysisWeight_{Imm,t-1} + MysisDensity_{Mat,t-1} * MysisWeight_{Mat,t-1}} \quad \text{[eq. 6-7b]}$$

where: $MysisBiomassCons_t$ = total biomass of mysis consumed (kg/ha)
$MysisDensity_{Mat,t-1}$ = density of mature mysis (#/ha; from equation 6-4)
# $MysisDensity_{Imm,t-1}$ = density of immature mysis (#/ha; from equation 6-1)
$MysisWeight_{Imm,t-1}$ = body weight of immature mysis (user-defined parameter)
$MysisWeight_{Mat,t-1}$ = body weight of mature mysis (user-defined parameter)

The reduction in density in each mysis age class due to predation therefore is:

$$MysisDensityCons = MysisBiomassCons * 1000 / (MysisWeight) \quad \text{[eq. 6-8]}$$

where: MysisBiomassCons = biomass (kg/ha) of mysis consumed by kokanee (from equation 6-6)
MysisWeight = body weight (g) of mysis (user-defined parameter)

The final density of mysis in the lake is found by reducing the potential immature and mature mysis density by the harvest and predation losses:

$$MysisDensity = PotMysisDensity * (1 - MysisHarvRate) - MysisDensityCons \quad \text{[eq. 6-9]}$$

where: PotMysisDensity = potential mysis density (#/ha) (from equation 6-1 or 6-3)
MysisHarvRate = fraction of mysis cohort lost to harvest (user-defined parameter)
MysisDensityCons = # of mysis consumed per ha by kokanee (from equation 6-8)

## 6.2 Total production

Total production of mysis in kg/ha is required to partition lake rearing capacity among kokanee, sockeye, and mysis. Production:Biomass ratios are calculated for immature and mature mysis from each age class's conversion efficiencies and feeding rates:

$$P{:}B_{m,mat} = ConvEff_{m,mat} * FeedingRate_{m,mat} \quad \text{[eq. 6-10a]}$$
$$P{:}B_{m,imm} = ConvEff_{m,imm} * FeedingRate_{m,imm} \quad \text{[eq. 6-10b]}$$

where: $ConvEff_{m,mat}$ = conversion efficiency of mature mysis (user-defined parameter)
$ConvEff_{m,imm}$ = conversion efficiency of immature mysis (user-defined parameter)
$FeedingRate_{m,mat}$ = feeding rate of mature mysis (user-defined parameter)
$FeedingRate_{m,imm}$ = feeding rate of immature mysis (user-defined parameter)

The production for each age class is

$$MatMysProd = MysisDensity_{Mat} * MysisWeight_{Mat} / 1000 * P{:}B_{mysis,mat} * MatMysEquiv \quad \text{[eq. 6-11a]}$$
$$ImmMysProd = MysisDensity_{Imm} * MysisWeight_{Imm} / 1000 * P{:}B_{mysis,Imm} * ImmMysEquiv \quad \text{[eq. 6-11b]}$$

where: MysisDensity = density of mysis (from equation 6-9; #/ha)
MysisWeight = body weight of mysis (g; user-defined parameter)
P:B = Production:Biomass, from equation 6-10
$MatMysEquiv_{Nerkid}$ = mature mysis equivalence factor
$ImmMysEquiv_{Nerkid}$ = immature mysis equivalence factor

Equivalence factors for expressing the effects of mysid production on mysid survival are 1, by definition. Equivalence factors for expressing the effects of mysid production on kokanee and survival rates can be adjusted by the user to represent alternative hypotheses about interactions between these species. As for sockeye and kokanee, two equivalence factors are required for each age class of mysis (four in total):

1. The equivalence factor $MatMysEquiv_{JuvSurv}$ is needed to account for the effects of production by mature mysis on lake carrying capacity for survival of sockeye, kokanee and mysis juveniles. This factor is likely to be zero or close to zero because mature mysis are already fully grown and most of their production goes into eggs and newly-hatched mysids that do not compete directly with nerkids (small mysids are primarily herbivorous; Chipps and Bennett 2000).
2. The equivalence factor $MatMysEquiv_{AdGrowth}$ is needed to account for the effects of production by mature mysis on growth rates of adult kokanee. This factor is likely to be close to zero for the same reasons outlined above for $MatMysEquiv_{JuvSurv}$.
3. The equivalence factor $ImmMysEquiv_{JuvSurv}$ accounts for the effects of production by immature mysis on lake carrying capacity. Immature mysids (1-year olds) are actively growing and feeding on zooplankton and thus have exert more competiive influence on nerkids than mature mysids. The immature mysid-nerkid equivalence factor is potentially a function of lake productivity, as described in section 6.3.
4. The equivalence factor $ImmMysEquiv_{AdGrowth}$ accounts for the effects of production by immature mysis on lake carrying capacity. For convenience, we assume that $ImmMysEquiv_{AdGrowth}$ = $ImmMysEquiv_{JuvSurv}$. The immature mysid equivalence factor is potentially a function of lake productivity, as described in section 6.3.

## 6.3 Immature mysis-nerkid equivalence factor

The mysis-nerkid equivalence factor is intended to represent the relative competitive abilities of mysis and nerkids. Differences in competitive advantage could be due to different feeding efficiencies or degrees of overlap between different species. The model will allow two alternative hypotheses about this equivalence factor:

1. The equivalence factor is dependent on nutrient status (total Phosphorus concentration) of the lake (Figure 6.3). The hypothesis is that mysis are generally more efficient than nerkids at obtaining common food items, and that this advantage is more pronounced when food resources are scarce.
2. Mysis-nerkid equivalence is independent of trophic status.

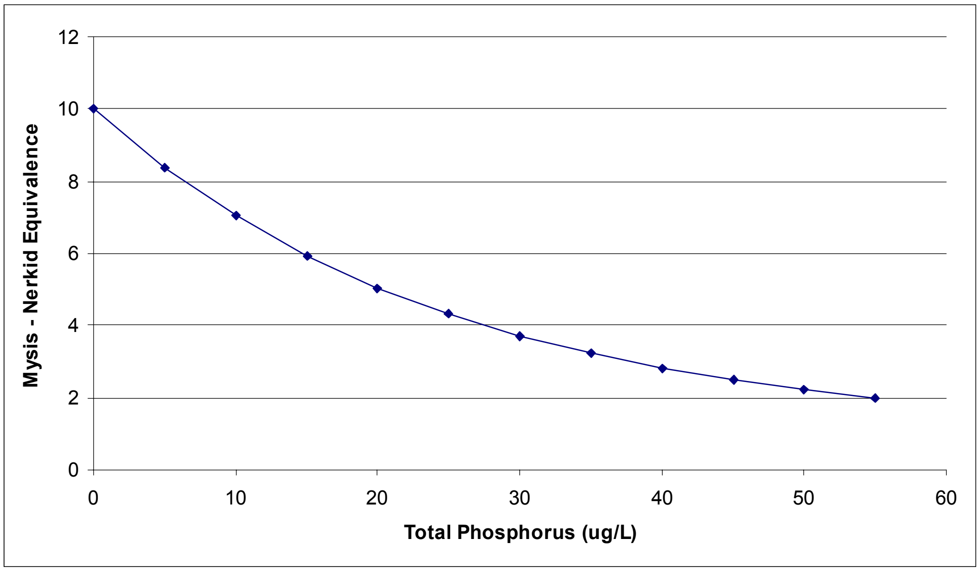


**Figure 6.3.** Mysis-nerkid equivalence factor as a function of lake productivity (represented by total P concentrations). Function shown is an example only.

The equation to calculate the nerkid equivalency is:

$$MysEquiv_{Nerkid} = MysEqMax - MysEqMin * e^{(-MysEqShape*TotalP)} + MysEqMin \quad \text{[eq. 6-12]}$$

where: MysEqMax = maximum mysis equivalence factor at very low productivities (user-defined parameter)

MysEqMin = minimum mysis equivalence factor at very high productivities (user-defined parameter)

MysEqShape = shape parameter; determines how quickly minimum value is reached (user-defined parameter)

TotalP = Total P concentration, selected according to water year (see Section 3.6).

Evidence for hypothesis (1) is equivocal. Cooper et al. 1992 review mysid Production:Biomass ratios (which, if one assumes that conversion efficiencies and feeding rates of mysids and nerkids are equal, approximates the equivalence factor) in lakes with different trophic status (Figure 6.3). Higher P:B ratios are generally associated with lower productivity measures, but this observation is confounded by the fact that the mysids with the highest P:B ratios were all of the species Neomysis rather than Mysis. Among the Mysis populations, there appears to be no clear relationship between P:B and trophic status. Hypothesis (2) can be represented using equation 6-12 by setting MysEquivMax = MysEquivMin = some constant value.

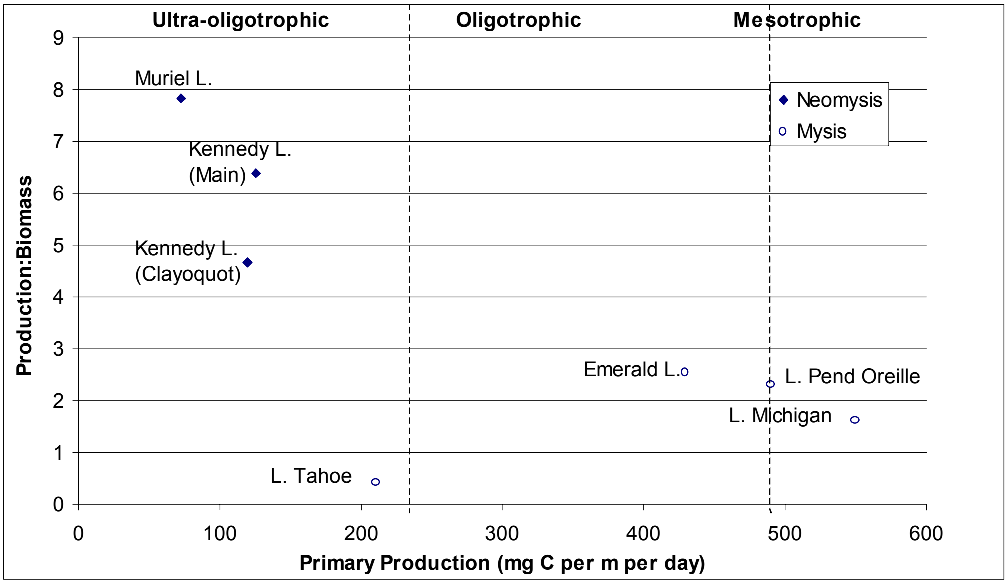


**Figure 6.4.** Mysid Production:Biomass ratios in lakes of different trophic status (from Cooper et al. 1992).

# 7.0 Predator submodel

Workshop participants suggested that the model should include an explicit predator submodel to allow exploration of management scenarios in which predator populations (primarily rainbow trout and smallmouth bass) are controlled through directed harvests. There are two potentially important predation processes that could affect sockeye and kokanee rearing in Osoyoos and Skaha lakes.

1. Predation on sockeye fry and kokanee juveniles while rearing in rearing lakes.
2. Predation during specific migration events, such as the outmigration of sockeye smolts in the spring. This is particularly important for sockeye smolts migrating through Vaseaux Lake, which has a high density of predaceous fish.

Specific migration predation is modelled separately in the kokanee and sockeye submodels. In this section, we describe predation by lake-resident predator populations.

The LLKM includes detailed, age-structured predator modules for lake trout, rainbow trout, dolly varden, and other predator species. We have adapted the LLKM predator module for use in the Okanagan sockeye model. This module is a generic "predator" submodel, which can be parameterised to represent any potential predator species. In this version of the model, we have chosen to parameterize the predator submodel to represent rainbow trout as the primary predator species, for two reasons. First, there has been a considerable amount of research on this species in B.C. lakes and the LLKM includes preliminary default parameter values. In contrast, very little is known about smallmouth bass. Second, rainbow trout are probably more significant predators than smallmouth bass because migrating kokanee fry appear to spend little time in the littoral zone where smallmouth bass accumulate. Instead, they appear to migrate directly to the deeper parts of the lake where rainbow trout would have a greater influence (S. Matthews, WLAP Pentiction, pers. comm.).

The predator module of the LLKM calculates egg deposition and emergent fry abundance based on initial age distributions, age-specific fecundities and maturation proportions, and a constant egg-fry survival rate. Rainbow trout are assumed to require at least a year of rearing in a stream before emigration to the lake. The number of fry migrating into the lake is a density-dependent function of the number of emerging fry, and requires assumptions about the carrying capacity of the lake (as a simplifying assumption, we assume that this capacity is fixed and independent of the densities of kokanee, sockeye, and mysis). The number and size of fish at older age classes are determined using constant age-specific weights and survival rates. Equations for each of these life stages are provided below; Table 7.1 summarises the default LLKM parameter values for rainbow trout.

## 7.1 Egg deposition

Egg deposition is calculated using age-specific fecundity and maturation proportions:

$$\#Eggs = \Sigma_p (\#Pred_p * PropMature_p * Fecundity_p * FemaleProp) \qquad \text{[eq. 7-1]}$$

where: $\#Pred_p$ = number of predators at age p (from equation 7-4)
$PropMature_p$ = proportion of fish at age p that are mature (user-defined parameter)

$Fecundity_p$ = fecundity (eggs/female) of fish at age a (user-defined parameter)
FemaleProp = proportion of fish that are female (user-defined parameter; constant for all ages)

## 7.2 Emerging fry

The number of emerging fry is given by:

#EmFry = #Eggs * EggFrySurv [eq. 7-2]

where: #Eggs = number of eggs deposited (from equation 7-1)
EggFrySurv = egg-fry survival rate (user-defined parameter)

## 7.3 Rearing fry

The number of rearing fry in a given year t is computed using a modified Beverton-Holt relationship:

$\#RearingFry_t = \#EmFry_{t-1} / (1 + \#EmFry_{t-1} / PredFryCapacity)$ [eq. 7-3]

where: $\# EmFry_{t-1}$ = number of emergent fry in the previous year (from equation 7-2)
PredFryCapacity = maximum carrying capacity for predator fry (lake-specific user-defined parameter)

Note that for simplicity, we have assumed that the rearing capacity for predator juveniles is unaffected by the densities of kokanee, sockeye, and mysis. That is, we assume that because rainbow trout juveniles rear in streams they do not directly compete with lake-rearing nerkids and mysis.

## 7.4 Adults

The number of fish in older age classes in year t are computed using age-specific natural survival rates, and age-specific harvest rates. This allows the user to explore the effects of actions to reduce predator densities.

$\#Pred_{p,t} = \#Pred_{p-1,t-1} * NatSurvRate_{p-1} * (1-HarvRate_{p-1})$ [eq. 7-4]

where: $\#Pred_{p-1,t-1}$ = number of fish in the previous age class in the previous year
$NatSurvRate_{p-1}$ = natural survival rate of age a-1 fish (user-defined parameter)
$HarvRate_{p-1}$ = harvest rate of age a-1 fish (user-defined parameter)

## 7.5 Predation

The predator submodel calculates predation on juvenile kokanee and sockeye based on the net production of each age class during the previous year, the biomass of prey required to support this production, and the proportion of each species to the predator's diet. The equations to represent this process are:

Net production (kg) of a given age class from simulation year t-1 to year t is computed from the number of fish surviving to that age class * the increase in body weight from one age class to the next:

$Prod_{p,t} = \#Pred_{p-1,t-1} * NatSurvRate_{p-1} * (1-HarvRate_{p-1}) * (Weight_p - Weight_{p-1})$ [eq. 7-5]

where: $\#Pred_{p-1,t-1}$ = number of fish in the previous age class in year t-1 (from equation 7-4)
$NatSurvRate_{p-1}$ = natural survival rate of age p-1 fish (user-defined parameter)
$HarvRate_{p-1}$ = harvest rate of age p-1 fish (user-defined parameter)
Weight = the body weights at ages p and p-1 (user-defined parameter)

The biomass of prey required to support production in each predator age class (p) depends on the conversion efficiency (younger fish are more efficient and require consumption of less biomass). Conversion efficiency is related to body weight by the function:

$ConvEff_r = ConvEffConst_r + ConvEffSlope_r * \log(Weight_p)$ [eq. 7-6]

where: $ConvEffConst_r$ = constant (user-defined parameter)
$ConvEffSlope_r$ = coefficient relating log(body weight) to conversion efficiency (user-defined parameter)
$Weight_p$ = body weight of age p predators (user-defined parameter)

Data to parameterize this relationship for rainbow trout is available from Korman et al. (1993).

The biomass of prey required to support production of predator production at each age p is:

$BioCons_{p,t} = Prod_{p,t} / ConvEff_{p-1}$ [eq. 7-7]

where: $Prod_{p,t}$ = production of age class p (from equation 7-5)
$ConvEff_p$ = conversion efficiency of age p-1 fish (from equation 7-6)

The biomass of kokanee and sockeye consumed during year t depends on the predator diet composition:

$KokBioCons_{p,t} = BioCons_{p,t} * KokDietProp_p$ [eq. 7-8]
$SoxBioCons_{p,t} = BioCons_{p,t} * SoxDietProp_p$

where: $BioCons_{p,t}$ = biomass of prey consumed by age class p (from equation 7-7)
KokDietProp = maximum proportion of kokanee in predator diet (user-defined parameter)
SoxDietProp = maximum proportion of sockeye in predator diet (user-defined parameter)

**Table 7.1.** LLKM default parameter values for rainbow trout.

| Age | Proportion Mature | Fecundity | Natural Survival Rate | Weight (g) | Proportion kokanee in diet |
|---|---|---|---|---|---|
| Egg | 0 | 0 | 0.45 | 0 | 0 |
| Fry | 0 | 0 | 0.61 | 0 | 0 |
| 0 | 0 | 0 | 0.50 | 0 | 0 |
| 1 | 0 | 0 | 0.74 | 3 | 0 |
| 2 | 0 | 0 | 0.80 | 34 | 0 |
| 3 | 0 | 1000 | 0.85 | 302 | 0.20 |
| 4 | 0.2 | 1500 | 0.88 | 920 | 0.60 |
| 5 | 0.6 | 2500 | 0.70 | 1820 | 0.95 |
| 6 | 0.9 | 3000 | 0.64 | 2985 | 0.95 |
| 7 | 1.0 | 3500 | 0.61 | 3740 | 0.95 |
| 8 | 1.0 | 3800 | 0.61 | 5137 | 0.95 |
| 9 | 1.0 | 4000 | 0.61 | 5700 | 0.95 |

# 8.0 Summary of Parameters and Preliminary Parameter Values

Table 8.1 below summarises the parameters required by the proposed model design, and some preliminary parameter values based on our review of relevant literature. Preliminary values should be regarded as representing only one of many possible hypotheses. These hypotheses will be refined over time as the model and underlying data are improved. One of the benefits of models is that it allows users to explore the effects of alternative assumptions about various parameters on model outputs. Sensitivity analyses quantitatively measure the relative influence of each model parameter on the model outcome. This provides a useful approach for identifying critical model assumptions, and is helpful in defining priorities for future research and monitoring.

**Table 8.1.** Preliminary parameter values.

| Functional Relationship | Equation # | Parameter | Prelim. Value | Comments |
|---|---|---|---|---|
| **Hydrology Submodel** | | | | |
| Water temperature at OK Falls | 3-1 | $Slope_{OkFallsTemp}$ | 0.87 | Hyatt and Stockwell (2002) |
| | | $Int_{OkFallsTemp}$ | 3.18 | |
| Water temperature at Oroville | 3-2 | $Slope_{OrovilleTemp}$ | 0.97 | Hyatt and Stockwell (2002). |
| | | $Int_{OrovilleTemp}$ | 1.62 | |
| Water temperature at Similkameen | 3-3 | $Const_{SimTemp}$ | 6.22692 | Estimated from 1991 – 1999 data. |
| | | $TempCoef_{SimTemp}$ | 0.58611 | |
| | | $FlowCoef_{SimTemp}$ | -0.0005 | |
| Secchi Depth | 3-5 | $Int_{SecchiDepth}$ | 1.3892 | Estimated from 1997-2000 Okanagan Lake data (Andrusak et al. 2001) |
| | | $Slope_{SecchiDepth}$ | -0.6529 | |
| **Sockeye Submodel** | | | | |
| Age-specific fecundity | 4-1 | $Fec_a$ | Table 4.2 | Major and Craddock 1965, as reported by Fryer 1995 |
| Current spawning habitat | 4-2 | $MaxHabitat_{Os}$ | 140,000 | Estimated from Environment Canada (1973) estimates of spawning habitat vs. flow (Figure 4.2). |
| | | $FHalfMaxHabitat_{Os}$ | 2.4 cms | |
| | | $MaxHabitat_{Skaha,High}$ | 63 | Based on estimates in ONFC (2002) |
| | | $FHalfMaxHabitat_{Skaha,High}$ | 0.05 cms | |
| | | $MaxHabitat_{Skaha,Med}$ | 7000 | |
| | | $FHalfMaxHabitat_{Skaha,Med}$ | 0.05 cms | |
| Total spawning habitat | 4-3 | $SpawnHab_{New,\ Osoyoos}$ | | Potential management action |
| | | $SpawnHab_{New,\ Skaha,\ High}$ | | |
| | | $SpawnHab_{New,\ Skaha,\ Med}$ | | |
| Fraction of spawning habitat available for sockeye (Skaha only) | 4-4 | SpawnOverlap | 1 | Preliminary assumption. |
| Spawning capacity | 4-6 | $FemaleDensity_s$ | 1.48 | Average from other sockeye stocks (Hyatt and Rankin 1999). |
| #Eggs | 4-7 | FemaleProp | 0.52 | Hyatt et al. (2002) |
| Stranding rate vs. minimum incubation flow | 4-8 | $StrandAdj_{Osoyoos}$ | 0 | Assumes stranding mortality not a major factor |
| | | $StrandAdj_{Skaha}$ | 0 | Assumes stranding mortality not a major factor |

| Functional Relationship | Equation # | Parameter | Prelim. Value | Comments |
|---|---|---|---|---|
| Flushing rate vs. maximum incubation flow | 4-9 | FHalfFlush | 42 cms | Based on data from Hyatt and Rankin (1999) and Stockwell et al. (2001). |
| | | FlushShape | 11 | |
| Egg-Fry survival rate | 4-10 | $EggFrySurvMean_{High}$ | -1.69 | Maximum and standard deviation of ln(EggFry survival) estimated by Bradford (1995) for 9 sockeye stocks. |
| | | $EggFrySurvStDev_{High}$ | 0.5 | |
| | | $EggFrySurvMean_{Med}$ | -2.375 | Mean and standard deviation of ln(EggFry survival) estimated by Bradford (1995) for 9 sockeye stocks. |
| | | $EggFrySurvStDev_{Med}$ | 0.5 | |
| Female broodstock for fry supplementation | 4-12 | $FrySupp_{Sk,t}$ | | Potential management action |
| | | HatcheryEggFrySurv | 0.7 | Workshop comments, October 15 2002 |
| | | $MinFemale_{Os}$ | 5000 | Preliminary value; potential management action |
| $P:B\ Ratio_{SxFry}$ | 4-13 | $FeedingRate_{SxFry}$ | 8.5 | Estimate for kokanee juveniles from Kay (2002) |
| Sockeye fry production | 4-14 | $LakeArea_{Osoyoos}$ | 1000 ha | North basin only |
| | | $LakeArea_{Skaha}$ | 2010 ha | |
| | | $Weight_{SxFry}$ | 0.2 g | Shepherd and Inkster (1995); Burgner (1991). |
| | | $SxEquiv_{JuvSurv}$ | 1 | Assumes sockeye and kokanee fry are ecological analogs. |
| | | $SxEquiv_{AdGrowth}$ | 0 | Assumes sockeye fry do not affect kokanee adults. |
| Length of sockeye fry | | LengthFry | 28 mm | Shepherd and Inkster (1995). |
| Total Lake Capacity | 4-19 | $Int_{TotalCap}$ | 0.7782 | Hyatt and Rankin (1999). |
| | | $Slope_{TotalCap}$ | 0.6529 | |
| Smolt weight | 4-21 | $SmoltSizeMax_{Osoyoos}$ | 0 | Based on data in Hyatt and Rankin (1999) Figure 12b |
| | | $SmoltSizeShape_{Osoyoos}$ | -0.52 | |
| | | $SmoltSizeSlope_{Osoyoos}$ | 719.69 | |
| | | $SmoltSizeMax_{Skaha}$ | 20.387 | |
| | | $SmoltSizeShape_{Skaha}$ | 1 | |
| | | $SmoltSizeSlope_{Skaha}$ | -0.0032 | |
| #Smolts | 4-23 | MaxFrySurv | 0.5 | Highest recorded fry-smolt survival rate in Bradford (1995). |
| Smolt supplementation | 4-24 | $\#Smolts_{supp,Osoyoos}$ | 0 | Cassimer Bar hatchery no longer operating. |
| | | $\#Smolts_{supp,Skaha}$ | 0 | Potential management action. |
| Smolt survival to Wells Dam | 4-25 | $SmoltSurvWells_{Osoyoos}$ | 1 | Preliminary guess; no data on this. Can use the model to game with these values. |
| | | $SmoltSurvWells_{Skaha}$ | 1 | |
| Smolt-adult returns (SARs) | 4-26 | SARMean | -5.6 | Mean of ln(SAR) from Table 4.3. Year effects based on time series from Robertson Creek coho (Hyatt et al. 2000). |
| | | SARYearEffect | Figure 4.11 | |
| Maturity schedule | 4-27 | $PropAge_{1.X}$ | Table 4.1 | Hyatt et al. (2002); assumes all fish are 1.X |
| Fraction of surplus caught | 4-29 | HarvRateFirstYear | 0.1022 | Estimated from harvest and escapement data 1980-2001 (Hyatt et al. 2002; Figure 4.12). MaxFraction is the highest observed fraction over that time period. |
| | | HarvShape | 1.5349 | |
| | | MaxFraction | 2.25 | |
| Commercial harvest | 4-30 | $EscTarget_{Bon}$ | 75,000 | Current values under 2001 – 2003 Interim Management Plan (ODFW&WDFW 2001) |
| | | FracSurplusAvail | 1.0 | |
| Treaty ceremonial and subsistence harvest | 4-31 | TreatyC&SHarvestRate | Table 4.4 | |
| Upstream survival rate | 4-32 | PerProjSurv | Figure 4.14 | Estimated from dam count data 1980-2001. |
| Critical temperature for migrating up lower Okanagan River | | LowerOkCritTemp | 21 degrees | Fryer (1995); Hyatt and Rankin (1999); Alexander et al. (1998). |
| Prespawning mortality | 4-34 | MaxPreMort | 0.13 | No data to support hypothesis that delay causes lower mortality. Assume constant 0.13 from 1997 radio-tag study. |
| | | MinPreMort | 0.0 | |

| Functional Relationship | Equation # | Parameter | Prelim. Value | Comments |
|---|---|---|---|---|
| | | PreMortShape | 0 | |
| Okanagan River harvest rate | 4-35 | OkanHarvest | 0.03 | Average upriver harvest rate 1971-2001; Hyatt et al. 2002 |
| Spawners returning to Skaha Lake | 4-36 | UpstreamCritTemp | 15 degrees | Workshop comments. |
| Adult supplementation | 4-37 | $\#Spawners_{Skaha,supp}$ | | Potential management action |
| **Kokanee Submodel** | | | | |
| Size at age | 5-1 | $K_{Brody}$ | 0.55 | LLKM default value |
| | | $Length_0$ | 55 mm | Average for Okanagan Lake kokanee (Andrusak et al. 2001) |
| $Length_3$ vs. $Length_2$ and Secchi Depth | 5-2 | $MaxLength_3$ | 345 | LLKM default values; based on data from Rieman and Myers (1992). |
| | | ProdCoeff | 12.0 | |
| | | SecchiCoeff | 11.3 | |
| | | $Secchi_{Skaha}$ | 4.5 m | D. Hatch, 1996 Okanagan Sockeye Workshop |
| Conversion efficiency | 5-3 | $ConvEffConst_k$ | 0.5204 | Based on CE lookup table in Korman et al. 1993 |
| | | $ConvEffSlope_k$ | -0.1827 | |
| Length vs. weight | 5-9 | $WeightA_a$ | Table 5.2 | LLKM default values (provincial standards) |
| | | $WeightB_a$ | | |
| Age-specific natural survival and harvest rates | 5-17 | $NatSurvFrac_a$ | 0 = 0.4<br>1 = 0.6<br>2 = 0.7<br>3 = 0.8<br>4 = 0.8 | LLKM default values (Kornan et al. 1993). |
| | | $HarvRate_a$ | | Potential management action |
| Maturation | 5-18 | MinMatLength | 200 mm | Lowest spawner length observed in Mission Creek (Andrusak et al. 2001) |
| Spawning capacity | 5-22 | $FemaleDensity_k$ | 2 | ≈1.4X of sockeye female density, based on relative lengths kokanee and sockeye spawners |
| Fecundity | 5-23 | FecA | -5.275 | Data from Mission Creek; Andrusak et al. 2001 |
| | | FecB | 3.2899 | |
| #Eggs | 5-24 | FemRatio | 0.50 | No data |
| Egg-Fry survival | 5-25 | EggSurvMean | -3.0 | Mean egg-fry in natural streams (Andrusak et al. 2001, citing Redfish Consulting 1999). Standard deviation of ln(EggFry survival) estimated for Okanagan lake kokanee in Mission Creek spawning channel (Andrusak et al. 2001). |
| | | EggSurvStDev | 0.5 | |
| Production of Age 0 fry | 5-27 | $Weight_{EmFry}$ | 0.1 g | Data from Mission Creek; Shepherd and Inkster (1995). |
| | | $KokFryEquiv_{JuvSurv}$ | 1 | By definition |
| | | $KokFryEquiv_{AdGrowth}$ | 1 | Preliminary assumption |
| Kokanee adult production | 5-31 | $KokAdEquiv_{JuvSurv}$ | 1 | Preliminary assumption |
| | | $KokAdEquiv_{AdGrowth}$ | 1 | By definition |
| Maximum contribution of mysis to age a kokanee diet | 6-5 | $MaxContr_a$ | a2 = 0<br>a3 = 0<br>a4 = 0 | Preliminary assumption of no predation by kokanee on mysis. |
| | | MysConsHalf | a2 = 80<br>a3 = 80<br>a4 = 80 | |
| | | MysConsShape | 5 (all ages) | |

| Functional Relationship | Equation # | Parameter | Prelim. Value | Comments |
|---|---|---|---|---|
| **Mysis Submodel** | | | | |
| Immature mysis density | 6-1 | MysisFemProp | 0.55 | Data from Okanagan Lake; Andrusak et al. 2001 |
| | | $MysisRecruitRate_{Osoyoos}$ | 5 | Preliminary guess (workshop participants suggested < 10) |
| | | $MysisRecruitRate_{Skaha}$ | 5 | |
| Mysis survival rate | 6-2 | $MaxSurvival_{Osoyoos}$ | 0.55 | Based on rate of population growth in Okanagan Lake |
| | | $MaxSurvival_{Skaha}$ | 0.55 | |
| Total capacity for mysis | 6-3 | $MysisWeight_{Mat}$ | 0.02g | 15 mm in Lake Ontario (Johannson et al. 2001) |
| Biomass of mysis consumed | 6-7 | $MysisWeight_{Imm}$ | 0.002g | Data from Lake Pend Oreille (Chipps and Bennett 2000) |
| Actual mysis density | 6-9 | MysisHarvRate | | Potential management action |
| Mysis P:B | 6-10 | $ConvEff_{m,mat}$ | 0.15 | Kay (2002) |
| | | $ConvEff_{m,imm}$ | 0.221 | |
| | | $FeedingRate_{m,mat}$ | 18 | |
| | | $FeedingRate_{m,mat}$ | 25 | |
| Mysis Production | 6-11 | $MatMysEquiv_{JuvSurv}$ | 0 | Preliminary assumption that mature mysid production has no effect on nerkids |
| | | $MatMysEquiv_{AdGrowth}$ | 0 | |
| Mysis – nerkid equivalence | 6-12 | ImmMysEqMax | 1 | Preliminary assumption |
| | | ImmMysEqMin | 1 | |
| | | ImmMysEqShape | 0 | |
| **Predator Submodel** | | | | |
| Sockeye fry consumption by predators | 4-15 | SoxConsHalf | 1000 | Preliminary guesses; no data on this. Can use the model to game with these values. |
| | | SoxConsShape | 2 | |
| Kokanee consumption by predators | 5-10 | KokConsHalf | 250 | Default LLKM values; no data on this. Can use the model to game with these values. |
| | | KokConsShape | 3 | |
| Size-dependent vulnerability of kokanee to predators | 5-12 | RelVulnMean | 0.16 | Estimated from rainbow trout gut content data (Korman et al. 1993). |
| | | RelVulnStDev | 0.06 | |
| #Eggs | 7-1 | $PropMature_p$ | Table 7.1 | LLKM default values (Korman et al. 1993). |
| | | $Fecundity_p$ | | |
| | | FemaleProp | 0.50 | No data; assume 50% |
| #Emerging Fry | 7-2 | EggFrySurv | Table 7.1 | LLKM default value (Korman et al. 1993). |
| #Rearing Fry | 7-3 | PredFryCapacity | ??? | No data; use model to game. |
| #Adults | 7-4 | $NatSurvRate_p$ | Table 7.1 | LLKM default values (Korman et al. 1993). |
| | | $HarvRate_p$ | | Potential management action |
| Predator production | 7-5 | $Weight_p$ | Table 7.1 | LLKM default values (Korman et al. 1993). |
| Conversion efficiency | 7-6 | $ConvEffConst_r$ | 0.5514 | Based on CE lookup table in Korman et al. 1993 |
| | | $ConvEffSlope_r$ | -0.1452 | |
| Biomass consumed | 7-8 | $KokDietProp_p$ | Table 7.1 | LLKM default values (Korman et al. 1993). |
| | | $SoxDietProp_p$ | Table 7.1 | No data; assume no predation |

Table 8.2 summarises a preliminary set of initial conditions needed to initialise the model. These values represent the current state of sockeye, kokanee, mysis, and predator populations included in the model. We have used data wherever possible to derive these preliminary values, but in many cases the values are very rough estimates that should be explored through sensitivity analysis.

**Table 8.2.** Initial conditions required to initialise the model (values are preliminary hypotheses).

| Parameter | Osoyoos | Skaha | Comments |
|---|---|---|---|
| ***Sockeye*** | | | |
| Initial fry abundance | 1,500,000 | 0 | Osoyoos: Initial adult abundance approximates recent average; juvenile abundances consistent with initial adult abundance assuming average fry-smolt, SARs.<br>Skaha: No sockeye population at present. |
| Initial smolt abundance | 750,000 | 0 | |
| Initial adult abundance (at Wells) | 15,000 | 0 | |
| ***Kokanee*** | | | |
| Initial Age 0 abundance | 0 | 73,000 | Osoyoos: Assume minimal kokanee population in Osoyoos lake.<br>Skaha: Age 3 and 4 abundance consistent with recent average number of spawners; numbers at ages 0-2 consistent with recent average spawners and approximate age structure in Okanagan Lake. |
| Initial Age 1 abundance | 0 | 24,000 | |
| Initial Age 2 abundance | 0 | 16,000 | |
| Initial Age 3 abundance | 0 | 10,000 | |
| Initial Age 4 abundance | 0 | 900 | |
| Initial Age 0 length | 0 | 55 | Values based on Okanagan lake data. |
| Initial Age 1 length | 0 | 177 | |
| Initial Age 2 length | 0 | 231 | |
| Initial Age 3 length | 0 | 256 | |
| Initial Age 4 length | 0 | 267 | |
| ***Mysis*** | | | |
| Initial immature density (#/m2) | 4 | 63 | Total (immature + mature) densities consistent with estimates from Feb 27th review meeting; immature/mature population structure a preliminary guess. |
| Initial mature density (#/m2) | 2 | 27 | |
| ***Predators*** | | | |
| Initial Age 0 abundance | 0 | 0 | No data on rainbow trout abundance in Skaha Lake. Assume for model testing and validation purposes that rainbow trout population is minimal / predation effects are insignificant. |
| Initial Age 1 abundance | 0 | 0 | |
| Initial Age 2 abundance | 0 | 0 | |
| Initial Age 3 abundance | 0 | 0 | |
| Initial Age 4 abundance | 0 | 0 | |
| Initial Age 5 abundance | 0 | 0 | |
| Initial Age 6 abundance | 0 | 0 | |
| Initial Age 7 abundance | 0 | 0 | |
| Initial Age 8 abundance | 0 | 0 | |
| Initial Age 9 abundance | 0 | 0 | |

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# Appendix B. OkSockeye Version History

| Version | Date | Major Revisions | Comments |
|---|---|---|---|
| 1.0 | Jun 19, 2002 | • Prototype; design as described in June 19th 2002 model Design Document. | • Public release June 19, 2002<br>• demonstrated Oct 15, 2002. |
| 2.0 | Dec 4, 2002 | • Added annual SAR year effects based on Barkley Sound coho SARS<br>• Updated water temperature functions and parameter values to be consistent with FWMT assumptions (Hyatt and Stockwell 2002)<br>• Updated sockeye model parameters using escapement, harvest, age data in CNAT v. 1.0 (Hyatt et al. 2002) | • Internal release |
| 2.1 | Dec 9, 2002 | • Added annual fry supplementation schedule<br>• Added annual adult supplementation schedule<br>• Added SAR and production information to Excel Report | • Internal release |
| 2.1.1 | Dec 12, 2002 | • Corrected minor bugs related to upstream survival (only had an effect on very large sockeye escapement values)<br>• Minor enhancements to data edit screens | • Internal release |
| 2.1.2 | Dec 17, 2002 | • Allow working with different databases<br>• Minor enhancements to user interface (Run listbox and Save As dialog boxes)<br>• Revise scour relationships to be consistent with Summit (2002)<br>• Improved efficiency of initialisation | • Internal release<br>• used to generate results in Jan 8 2003 Experimental Design Report<br>• demonstrated Jan 16, 2003. |
| 2.2 | Jan 23, 2003 | • Revised approach to computing total Okanagan + Wenatchee adult returns | • Public release Jan 31, 2003.<br>• used to generate results in January 31, 2003 Experimental Design Report |