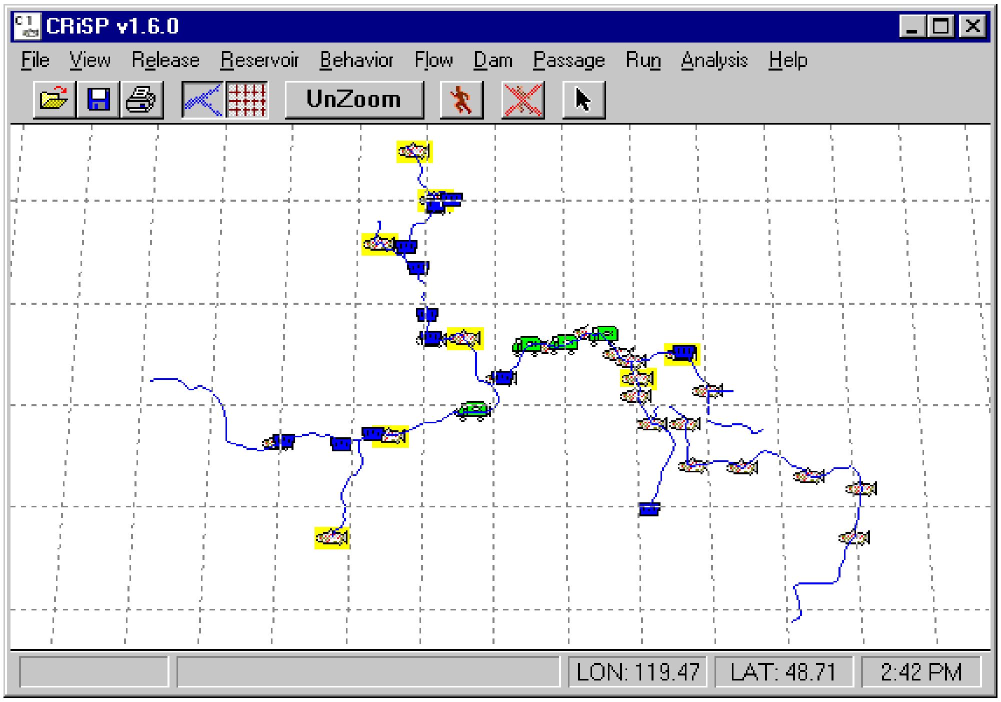
Columbia River Salmon Passage Model



CRiSP.1.6

Theory and Calibration

Developed by

Columbia Basin Research

School of Aquatic and Fishery Sciences

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The Columbia River Salmon Passage (CRiSP.1) model was developed as a team effort involving scientists, managers, and computer programmers.

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I. Introduction

This document describes the theory and calibration of the Columbia River Salmon Passage model (CRiSP.1). The model tracks the downstream migration and survival of juvenile salmon through the tributaries and dams of the Columbia and Snake Rivers to the estuary.

CRiSP.1 describes in detail the movement and survival of individual stocks of natural and hatchery-spawned juvenile salmonids through hundreds of miles of river and hydrosystem. Constructed from basic principles of fish ecology and river operation, CRiSP.1 provides a synthesis of current knowledge on how the Columbia/Snake river hydroelectric system interacts with the juvenile salmonid populations of the system. Biologists, managers and others interested in the river system can use this interactive tool to evaluate the effects of river operations on smolt survival. The model is used to predict the realtime in-season water quality and fish passage conditions through the Columbia and Snake River system. This information is provided on the web at www.cbr.washington.edu/crisprt/index.html.

There are two modes that CRiSP.1 can use: a Scenario Mode that illustrates the interactions of model variables, and a Monte Carlo Mode, which is stochastic, providing measures of variability and uncertainty in predicted passage survival. Between any two points in the river system, estimates of probability distributions for smolt survival and travel time can be determined for any stock.

The model's hydrological and ecological parameters and the hydrosystem and fish operations are calibrated from information available between 1954 and 1999. For additional information, also see the website www.cbr.washington.edu/crisp/crisp.html.

CRiSP.1 has advanced programming features including:

- *graphical interface* to access and change model variables and equations
- *flexible data structure* that allows expansion of the model while assuring backwards compatibility with earlier versions
- *configurability* to a different river without reprogramming
- *online help* system.

The model runs on Win32 operating systems (Windows95/98/NT/2000) and on Sun SPARCstations under the Solaris2 and X Windows graphical interfaces.

CRiSP.1 was developed at the University of Washington's School of Aquatic and Fishery Sciences under a contract from the Environment, Fish and Wildlife (formerly Fish and Wildlife Division), Bonneville Power Administration.

I.1 - General Description

CRiSP.1 models passage and survival of multiple salmon substocks through the Snake and Columbia rivers, their tributaries, and the Columbia River Estuary (Fig. 1). The model recognizes and accounts for several aspects of the life-cycle of migratory fish—fish survival, migration, and passage—and their interaction with the river system in which they live.

Fish survival through reservoirs depends on:

- predator density and activity
- total dissolved gas (TDG) supersaturation levels dependent on spill
- travel time through a reservoir.

Fish migration rate depends on:

- fish behavior and age
- water velocity which in turn depends on flow, cross-sectional area of a reach, and reservoir elevation.

Fish passage through dams (Fig. 2) depends on:

- water spilled over the lip of the dam
- turbine operations
- bypass screens at turbine entrances and fish guidance sluiceways
- fish delay at dams.

CRiSP.1 computes daily fish passage on a release-specific basis for all river segments and dams. In CRiSP.1, passage and survival of fish through a reservoir is expressed in terms of the fish travel time through the reservoir, the predation rate in the reservoir, and a mortality rate resulting from fish exposure to total dissolved gas supersaturation, an effect called gas bubble disease (GBD). Fish enter the forebay of a dam from the reservoir and may experience predation during delays due to diel and flow related processes. They leave the forebay and pass the dam mainly at night through spill, bypass or turbine routes, or the fish are diverted to barges or trucks for transportation. Once they leave the forebay, each route has an associated mortality rate and fish returning to the river are exposed to predators in the dam tailrace before they enter the next reservoir.

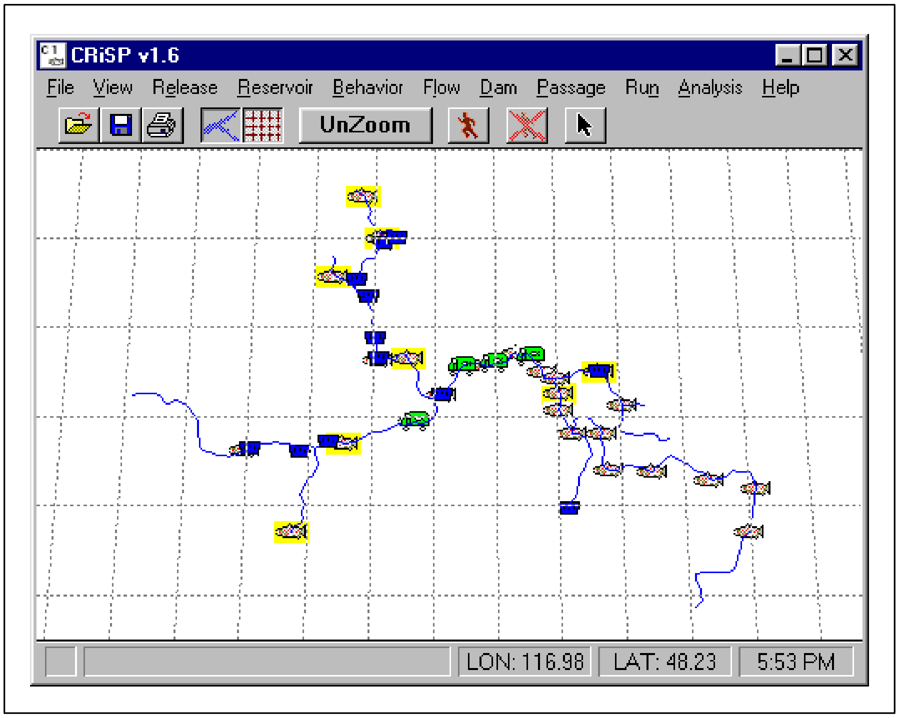

Fig. 1 CRiSP.1 map of an abbreviated Columbia Basin river system which includes about thirty fish release points and the major dams

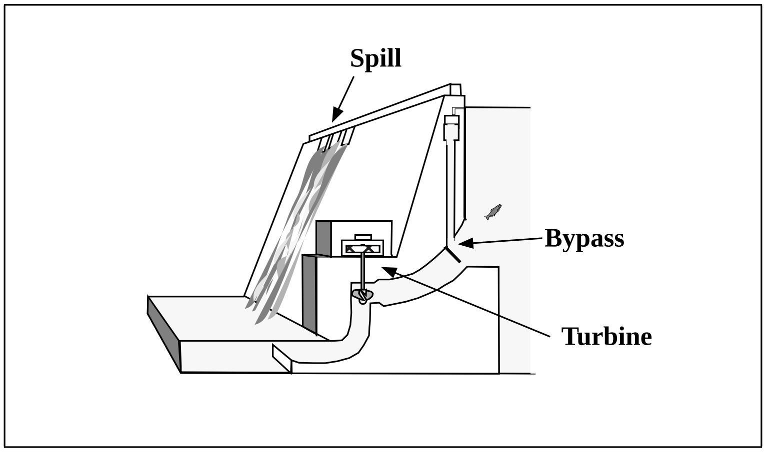

Fig. 2 Dam showing fish passage routes. Fish collected in bypass systems are returned to the tailrace or, in some situations, transported downstream.

I.1.1 - CRiSP.1 Submodels

CRiSP.1 integrates a number of submodels that describe interactions of isolated components. Together they represent the complete model. These elements include submodels for: fish travel time, reservoir mortality, dam passage, total dissolved gas supersaturation, and flow/velocity relationship. The structure of CRiSP.1 allows the user to select different formulations of these submodels at run time. In this sense, CRiSP.1 can be configured to simple interactions or it can be set up to consider several ecological interactions. CRiSP.1, as it is presently calibrated, has an intermediate level of complexity: age dependent travel time is implemented (the temporal components of the active migration equation cause the migration rate to increase with time of year), but other age dependent factors are switched off. A brief description of the submodels follows.

Travel Time

The smolt migration submodel, which moves and spreads releases of fish down river, incorporates flow, river geometry, fish age and date of release. The arrival of fish at a given point in the river is expressed through a probability distribution. All travel time factors can be applied or they can be switched off individually, resulting in a simplified migration model.

The underlying fish migration theory was developed from ecological principles. Each fish stock travels at an intrinsic velocity as well as a particular velocity relative to the water velocity. The velocities can be set to vary with fish age. In addition, within a single release, fish spread as they move down the river.

The travel time parameters are calibrated for spring and fall chinook and steelhead from the Snake River Basin and the Upper Columbia River Basin. See also the Juvenile Salmon Travel Time web page at www.cbr.washington.edu/crisp/tt/.

Predation Rate

The predation rate submodel distinguishes mortality in the reservoir, the forebay, and the tailrace of dams. The rate of predation can depend on temperature, smolt age, predator density, and reservoir elevation.

The predation rate parameters are calibrated using laboratory studies of the response of predators to temperature and field studies of smolt migration survival. The model is calibrated for spring and fall chinook and steelhead from the Snake River Basin and the Upper Columbia River Basin.

Gas Bubble Disease

A separate component of the mortality submodel is mortality from gas bubble disease produced by total dissolved gas (TDG) supersaturation. The mortality rate is species specific, and it is adjusted to reflect the relationship of fish length and population depth distribution to TDG supersaturation experienced by the fish.

The gas bubble disease rate is calibrated from laboratory studies.

Dam Passage

Timing of fish passage at dams is developed in terms of a species dependent distribution factor and the distribution of fish in the forebay. Fish guidance efficiency (FGE) can be held constant over a season or it can vary with fish age and reservoir level.

Fish guidance efficiency parameters are calibrated from fish guidance efficiency studies.

Transportation Passage

Transportation of fish at collection dams is in accordance with the methods implemented by the U.S. Army Corps of Engineers. The start and termination of transportation and separation of fish according to species can be determined for any dam under the same rules used to manage the transportation program. Time in transportation and transportation mortality can also be set.

Transportation operations information was used to identify the individual transportation operations from 1975 through 1999.

Total Dissolved Gas Supersaturation

Total dissolved gas (TDG) supersaturation, resulting from spill at dams, can be described by empirical submodels which are an empirical fit of spill data and monitoring data collected by the U.S. Army Corps of Engineers. Alternatively, supersaturation can be described by mechanistic models which include information on geometry of the spill bay and physics of gas entrainment.

The TDG generation equations used for gas production include the newest developments by U.S. Army Corps of Engineers, Waterways Experiment Station (WES) as well as additional work done by Columbia Basin Research. The gas calibration has been verified for 13 dams for the years 1995 through 1999.

Flow

Flow is modeled in two ways: it can be specified at dams using results of system hydroregulation models and historical flows or it can be described in terms of daily flows at system headwaters. When flow is described in headwater streams, the flow submodel generates a random set of seasonal flows that have statistical properties in accordance with the available water over a year. In this fashion, the model statistically reproduces flow for wet, average and dry years. The user controls the mainstem river flows by adjusting the outflow of the storage reservoirs within their volume constraints.

In the historical data files daily flow information, including temperatures and dam operations, are specified for the years 1954 through 1999.

Water Velocity

Water velocity is used in CRiSP.1 as one of the elements defining fish migration. Velocity is determined from flow, reservoir geometry and reservoir elevation.

Reservoir Drawdown

Reservoir elevation is set on a daily basis from elevation information in system hydroregulation models files or from user specified files. As water levels drop, part of the reservoir may become a free-flowing stream.

Stochastic Processes

CRiSP.1 can be run in a Monte Carlo Mode in which flows and model parameters vary within prescribed limits. In this mode, survival to any point in the river can be determined as a probability distribution.

Geographical Extent

CRiSP.1 can describe a river to any desired level of detail by changing a single file—the river description file—containing the latitudes and longitudes of all possible release sites, dams, and river segments as well as many of the physical attributes of these features. All menus and input and output tools automatically configure from the information in this file. In the current distribution, three river description files are available. The default **columbia.desc** file contains an abbreviated description of the Columbia Basin river system with about thirty fish release points and major dams. Some rivers in the basin are not represented (e.g., Imnaha River or Grande Ronde River).

Additional river description files are available in the CRiSP.1 distribution. They have been modified to reflect changes in the river that could occur under certain proposed management actions. The file **columbia_snakedraw.desc** does not include any of the Snake River dams—Lower Granite, Little Goose, Lower Monumental, and Ice Harbor—that are in the default **columbia.desc** file. This simulates a Snake River drawdown in order to make the Snake River free-flowing. The file **columbia_drawdown.desc** is similar to **columbia_snakedraw.desc**. In addition to the removal of the four Snake River dams, the John Day dam has also been removed. This represents the most extensive drawdown scenario that has been considered.

II. Theory

II.1 - Model Computation Diagram

CRiSP.1 is a composite of individual integrated process submodels that jointly determine smolt migration and survival. The equations underlying some submodels are mechanistic and are derived from underlying theory. In these equations, the parameters have ecological or physical meaning. For example, the equation relating water flow to velocity is based on principles of hydrology. A second type of equation is empirical and has no underlying ecological or physical meaning. These equations are used because they fit the data and are amenable to statistical fitting techniques. The parameters of the empirical equations seldom have ecological interpretations. For example, in the total dissolved gas (TDG) supersaturation submodel four alternative equations are available to relate TDG supersaturation to spill. Here, the parameters just determine the shape of the response. A third type of equation is a mixture of empirical and mechanistic. The predation rate equation (submodel) is an example of this mix with predation activity and density parameters multiplying the empirical predation temperature response.

The CRiSP.1 model calculates changes in fish population numbers as fish move through tributaries, reservoirs, and dams. Figure 3 is a diagram of the computational tree. Shaded boxes represent fish entering the system of dams and reservoirs on a daily basis. Unshaded square boxes represent calculations for travel time and survival of fish through the system. Rounded boxes represent input data to the calculation modules.

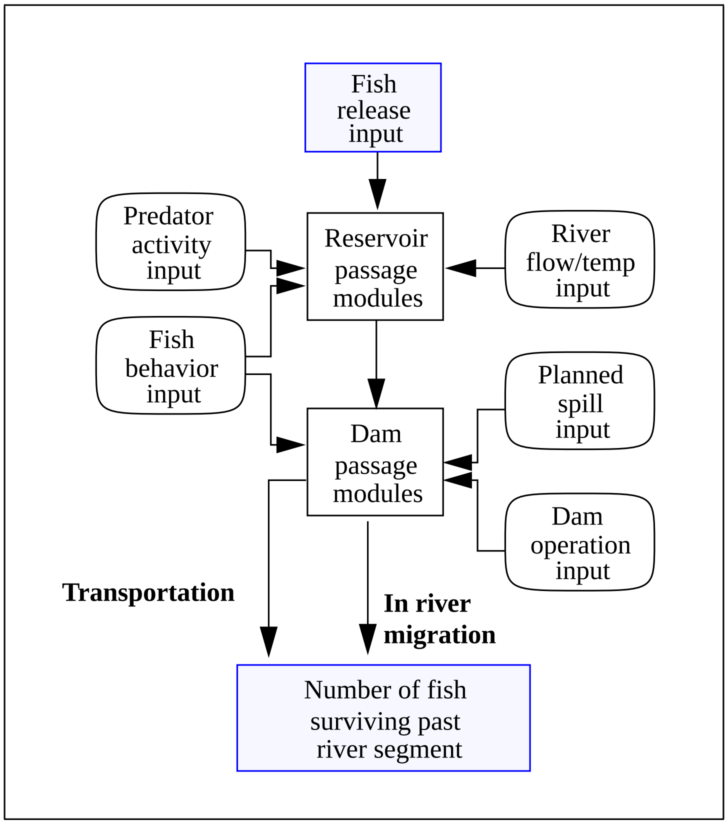

Fig. 3 Diagram of model elements

Reservoir Passage

In CRiSP.1, passage and survival of fish through a reservoir is expressed in terms of the fish travel time through the reservoir, the predation rate in the reservoir and a mortality rate resulting from fish exposure to total dissolved gas supersaturation, an effect called gas bubble disease (GBD). CRiSP.1 combines these individual mortality factor models (Fig. 4).

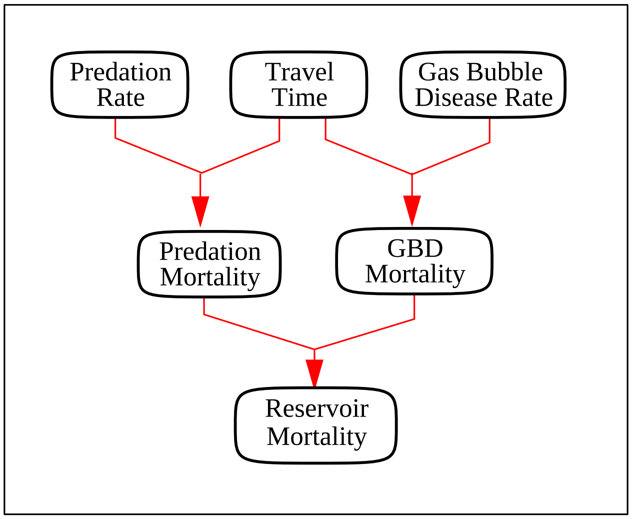

Fig. 4 Reservoir mortality processes

The modeling approach has been to develop alternative submodels of reservoir mortality factors so that various hypotheses can be evaluated and compared.

Ecological Submodels

Ecological submodels were developed from first principles relating environmental variables with fish behavioral and physiological factors to determine fish passage. Environmental variables—including weather-related factors such as temperature, and system operating factors such as flow, spill and fish transportation—describe the observable state of the environment in which fish live and characterize the rates of fish passage and survival which, through the model equations, generate predicted passage. In the model, these variables are contained in the **Reservoir**, **Behavior, Flow**, and **Dam** menus.

The model can use both raw information and statistically analyzed data. The model runs on data expressed as initial release numbers and numbers of fish passing any point or bypass route in the river system. Release information is accessed through the **Release** menu. The **Passage** menu provides access to passage histograms for each reach and dam in the model and for each of the four dam passage methods: bypass, turbine, spillway, and transport. The model run output provides detailed information on passage at any level from passage of a specific dam route to passage through the entire system.

II.2 - Flows

II.2.1 - Overview of Flow Computation

This section defines the theory for calculation of flows in CRiSP.1. Flow information is treated differently for the Monte Carlo and Scenario modes. In the Monte Carlo Mode, average flows over defined periods at the dams are read as input from flow archive files (see Hydroregulation Models section on page 9 for more information on flow archive files). The period average flows are then *modulated* to give simulated daily flows at the dams. Using this information, flows in the headwaters are calculated with an *upstream propagation* algorithm. Finally, flows through river segments are calculated from the headwaters with the *downstream propagation* algorithm. In the Scenario Mode, flows can be specified at headwaters using modulators based on historical flows or using the pointer to draw a curve in the GUI. Outflows from storage reservoirs are specified according to the volume constraints of the reservoirs. Finally, river flows are produced using the *downstream propagation* algorithm which combines storage reservoir flows and unregulated headwater flows.

II.2.2 - Monte Carlo Flow Calculation

When running CRiSP.1 in the Monte Carlo Mode, flow information is specified at dams from flow archive files generated by one of several hydroregulation models. CRiSP.1 uses a step-wise process to calculate daily headwater flows. These steps are as follows:

1. read period-averaged flows at dams from the flow archive file
2. modulate period-averaged dam flows to give daily dam flows
3. modulate losses in reservoirs
4. propagate upstream flows to determine daily headwater flows as well as gains and losses from river segments
5. propagate downstream flows through all river segments using the headwater flows and gains and losses in river segments.

Calculation of river flows in Monte Carlo Mode begins with flows at the dams and distributes upstream flows to achieve a mass balance. The procedure uses water conservation equations for losses/gains in river segments, flows in unregulated streams, and flows from storage reservoirs. Definitions for flow calculations (Fig. 5) are as follows:

- **Regulated headwater**: a segment containing a dam, a storage reservoir, and a river source.
- **Unregulated headwater**: a segment containing a confluence at its downstream end and a river source at its upstream end.
- **Loss**: a withdrawal (+) or deposit (-) of water to a river segment from an unspecified source. Losses are used to represent irrigation removals and ground water returns to river segments.
- **Dam**: a point that regulates flow; however, only dams specified in the flow archive file are considered to be regulation points.
- **Confluences**: a point where two upstream flows combine to create the flow downstream of the point.

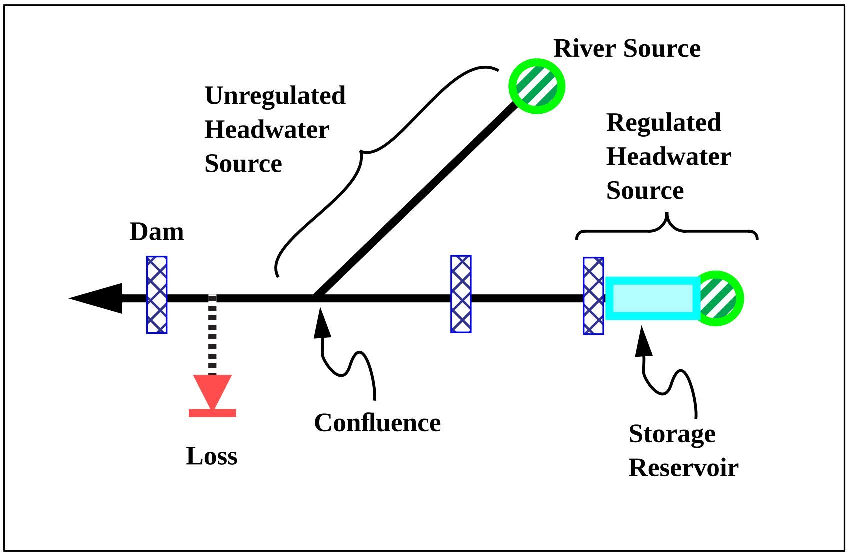

Fig. 5 Main objects for the Flow submodel

Hydroregulation Models

Flow for the Monte Carlo runs are usually obtained from flow archive files that are generated from runs of hydroregulation models maintained by two agencies:

- HYDROSIM maintained by the Bonneville Power Administration
- HYSSR maintained by the U.S. Army Corps of Engineers.

The models provide flow on a monthly or bimonthly basis over the entire Columbia Basin hydrosystem and are themselves complex models with many variables and special conditions. As a result, these models are not available to be run directly, although outputs of model runs are available for use in CRiSP.1 (the **flow.data** directory distributed with CRiSP.1 contains flow archive files for 1961 through 1994).

The models use information on natural runoff, regional electrical demand and storage capacity of the reservoirs to model the stream flow on a period averaged basis. The models use historical flow records for natural runoff and generate river flows that meet power generation demand in monthly periods. The exceptions to the monthly periods are April and August which are each divided into two periods. In addition, the HYDROSIM model provides elevations of all reservoirs.

The flow archive file can be used in Monte Carlo Mode as the source for flow, planned spill, and elevation. Information contained in a flow archive file includes:

- number of water years (number of games in flow archive header)
- number of power years (number of years in flow archive header)
- number of dams
- number of periods within years (i.e. weeks, months)
- spill information
- reservoir elevation information
- flow information.

Flow Modulation

Flow inputs in the Monte Carlo Mode runs consist of predicted daily flow averaged over monthly or bimonthly intervals at each dam used in CRiSP.1. This input generated from HYDROSIM or HYSSR flow archive files typically looks like Fig. 6 below. While this record retains most of the annual and seasonal flow variations, actual historic river flows (Fig. 7) exhibit considerable weekly and daily variations that are not replicated by the hydroregulation models used as flow data for CRiSP.1.

The purpose of the flow modulator is to more accurately simulate real flow patterns encountered by adding variations at finer time-scales consistent with historic flows. These variations include both random and deterministic components.

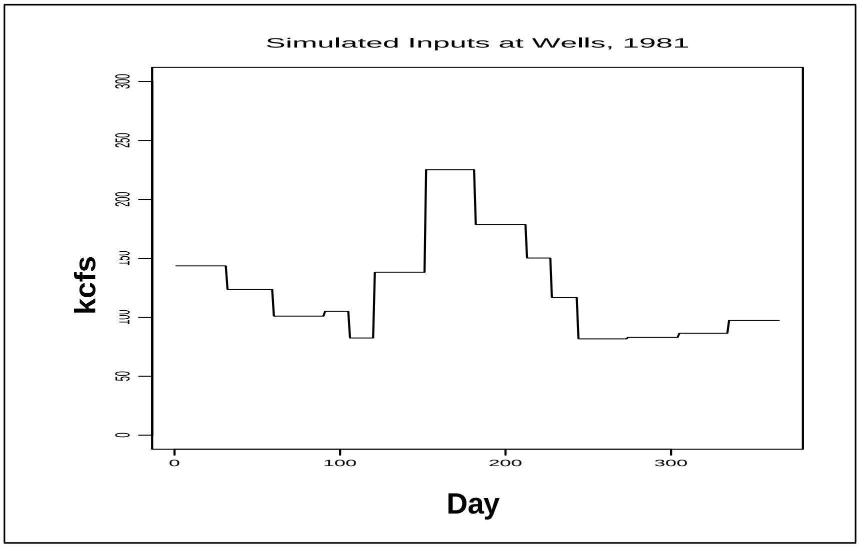

Fig. 6 Hydroregulation model simulated input - Wells, 1981

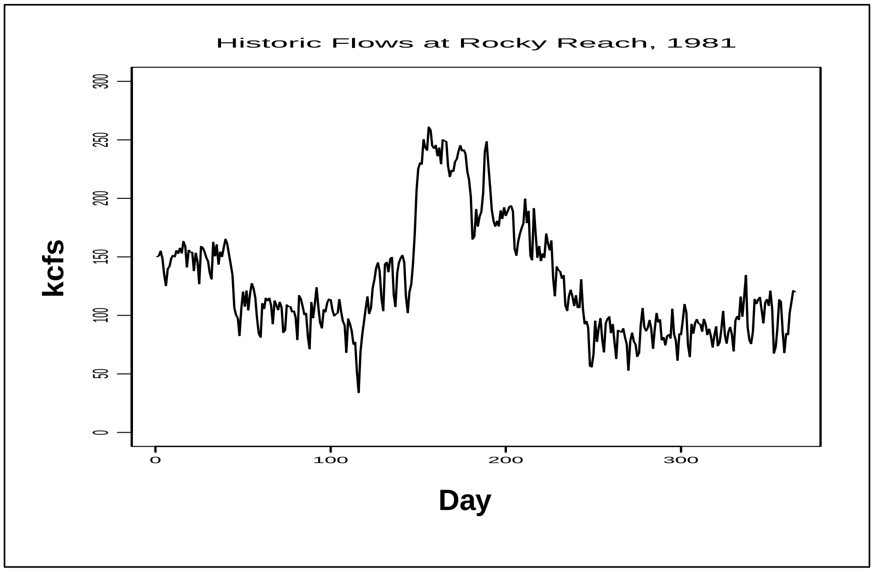

Fig. 7 Historic flows at Rocky Reach (next dam downstream from Wells), 1981

Spectral Analysis of Flow

The CRiSP.1 modulators were developed from the following analysis of flows in the Columbia River system. The goal was to develop a modulator that represented daily and weekly variations in flow and had the same spectral qualities as the flows in the river system as it is now operated.

A spectral analysis of an eleven-year time series (1979-1989) of flows revealed the general trend is a decline in spectral power that is qualitatively similar to a pink noise spectrum[1]. In addition, the spectrum has distinct peaks at frequencies of 1/7, 2/7, 3/7 etc., indicating a seven day cycle (Fig. 8).

This spectrum suggest several distinct processes. The weekly component is the result of flow decreasing on weekends when electric power consumptions is less. The pink noise element of the spectrum is probably the result of seasonal and short term correlations in weather patterns that alter the power consumption and unregulated runoff directly.

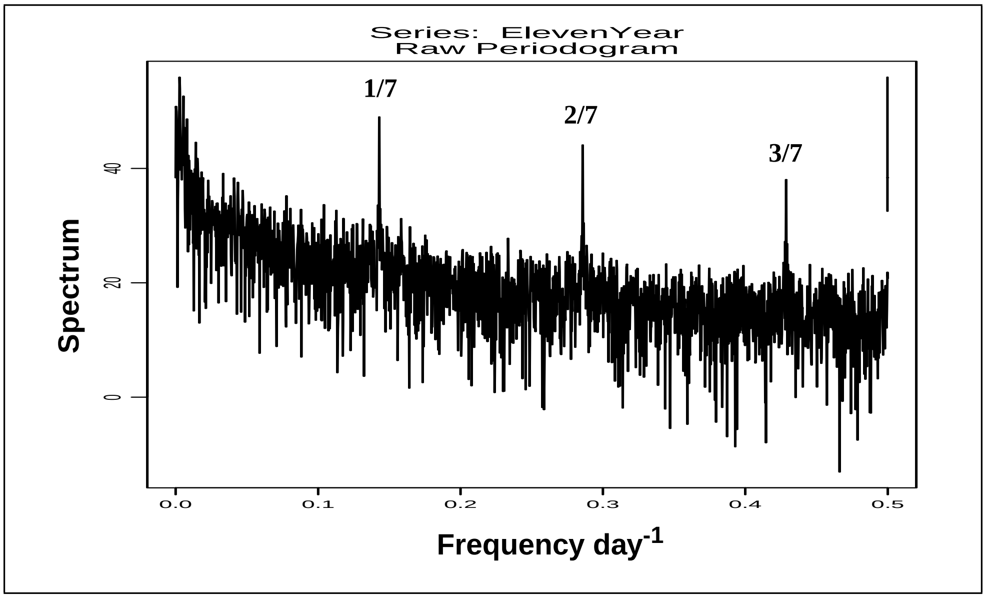

Fig. 8 Spectrogram: eleven year time series

Modulator Applications

The strategy for using period averaged archive flows to simulate flows with the spectral qualities of the actual ones involves adding flow variations at several points in the system (Fig. 5). These variations are produced by modulators. Since flows start in the headwaters and are summed downstream, flow variation can be added sequentially according to the manner by which they are produced. First, the archive flows are prescribed at all dams. Next, three modulations are applied. *Weekly* and *daily* modulations are added at the regulated headwaters to reproduce variations that occur between dams from additions and subtractions of water in the river segments and a *loss* modulation is added at downstream dams. After modulation, an upstream propagation process is applied to calculate the flows in unregulated headwaters. This forces the total modulation into the unregulated streams. In the case of the weekly modulation

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1. Pink noise is random pattern that exhibits some correlation for short time scales

this is an artifact since it is induced by hydrosystem operation. The error is not significant though, since the weekly modulation is a small fraction of the total variation.

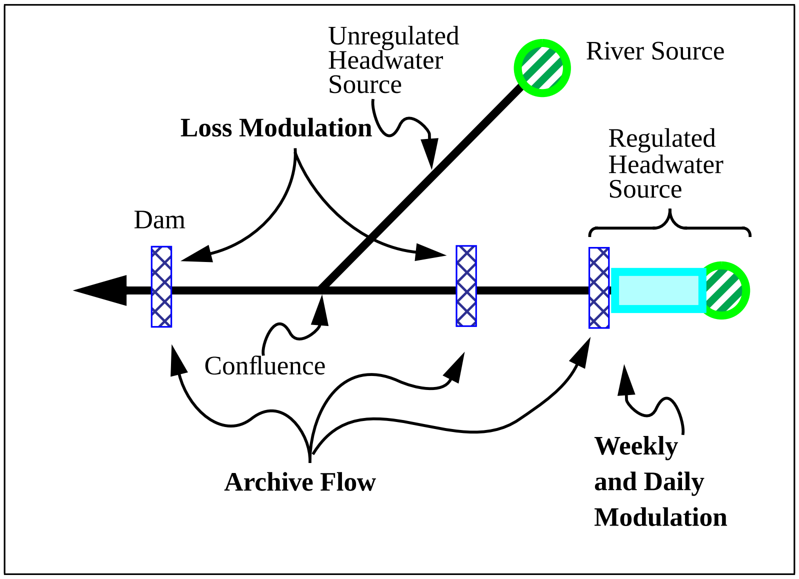

Fig. 9 Points of flow modulation in system based on Fig. 5

Weekly Modulators

The weekly modulation, applied in the regulated headwaters, simulates hydrosystem power generation patterns in which electrical demand decreases on weekends. The modulators, producing lower flows on weekends and higher flows midweek (Fig. 10), are approximated with a three-term Fourier series with fixed amplitude. The equation is:

$$F(t)_{\text{week(j)}} = -G \sum_{n=1}^{3} a_n \cos(b_n(t+\delta)) \qquad (1)$$

where

- $F(t)_{\text{week (j)}}$ = weekly variation in flow for headwater dam j
- G = flow scaling factor in kcfs

  This is set to 12.0 to reproduce the observed weekly variation in flow at Wells Dam for the years 1979 to 1989 excluding 1983 for which flows are missing.
- a_n, b_n = Fourier coefficients

  $a_1 = 1$, $a_2 = 2/3$, $a_3 = 1/3$

  $b_1 = 6\pi/7$, $b_2 = 4\pi/7$, $b_3 = 2\pi/7$
- t = day of the year
- δ = offset for day of week alignment.

The offset is calculated so that for any year from 1900 to 2100 the minimum value of *F(t)* occurs on Sunday.

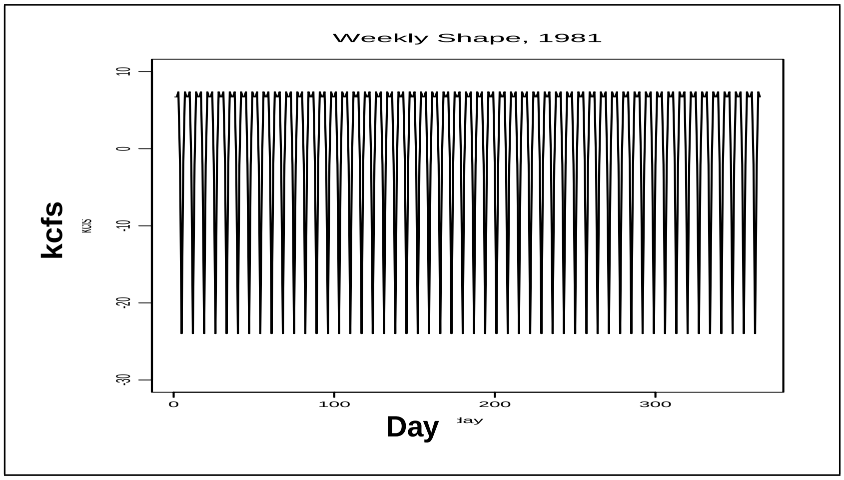

Fig. 10 Weekly shape pattern

Daily Modulators

Daily modulation simulates all variations not associated with the weekly and seasonal variations. A discrete realization of an Ornstein-Uhlenbeck (O-U) process (Gardiner 1985) was used to generate the daily variation. The process has two important characteristics: variations are slightly correlated from one day to the next and variances stabilize over time. This is a correlated random walk in which autocorrelation decays in time. The stochastic differential equation for an O-U process is:

$$\frac{dF_{day}}{dt} = -r \cdot F_{day} + \sigma \cdot w(t) \tag{2}$$

where

- F_{day} = daily variation in flow in kcfs at headwater dam
- r = deterministic rate of change of flow per unit of flow (the range is confined such that $0 < r < 1$)
- σ = intensity on the random variations in flow
- $w(t)$ = Gaussian white noise process describing the temporal aspects of the flow variation.

An O-U process has a conditional probability density function (Goel and Richter-Dyn 1974):

$$\mathrm{P}(x|y, t) = \frac{\exp\left[-\frac{1}{2}\left(\frac{x - m(t)}{V(t)}\right)^2\right]}{\sqrt{2\pi V^2(t)}} \tag{3}$$

where the mean and variance of the process are defined:

$$m(t) = y \cdot \exp(-rt) \tag{4}$$

$$V^2(t) = \frac{\sigma^2}{2r}(1 - \mathrm{e}^{-2rt}) . \tag{5}$$

When *rt* is large enough that exp(-2*rt*) is negligible, *m* and V^2 tend to be constant values and the time series is stationary.

Changing the continuous differential equation into a discrete one with $\Delta t = 1$ reservoir time step, and rearranging gives:

$$F(t+1)_{day(j)} = (1 - r_j) \cdot F(t)_{day(j)} + \sigma_j \cdot w(t)\,. \tag{6}$$

The value $r = 0$ gives an unbiased random walk and $r = 1$ gives a series of uncorrelated normal variates.

For the modulators, a system in stochastic equilibrium is sought such that $m = 0$. Taking $F_0 = y = 0$ gives $m = 0$, and discarding the first 35 iterations yields stable variance for any value of *r* useful in this context. Modulator parameters selected for the different portions of the system are given in Table 1 and are based on daily flow data for the years 1979 to 1989 at Wells and Lower Granite dams.

Table 1 Daily modulator parameters

River	σ_j	r_j
Upper Columbia	13	0.5
Lower Columbia	13	0.5
Snake	7	0.5

Random daily variation is added by a numerical form of an Ornstein-Uhlenbeck (O-U) random process created for each run (Fig. 11).

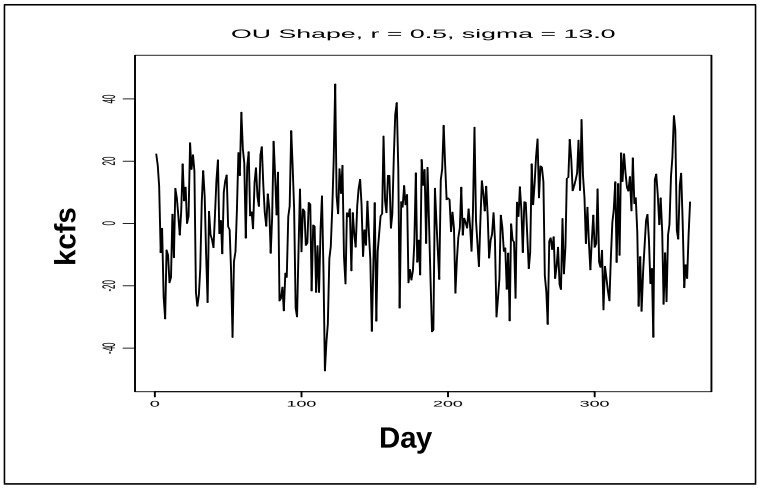

Fig. 11 O-U shape; $r = 0.5$, $\sigma = 13$

Monte Carlo Flow Modulator Validation

Using daily flow records for Ice Harbor, Priest Rapids and John Day dams during 1981, monthly and bimonthly (April and August) average daily flows were computed and appended to a CRiSP.1 flow archive from which CRiSP.1 generated modulated flows for these dams. Graphs of observed and model-produced flows for the first 300 days of the year at John Day Dam appear in Fig. 12. The model appears to produce realistic patterns of flow variation that mimic natural flows very well.

At a finer scale, however, note that CRiSP-modulated flows generally exhibit less variability than do observed flows, e.g. compare January and July (Fig. 13). In general, modulated flows are about as variable as observed flows in January, but clearly less variable than observed flows in July. This is also reflected in the variance around the mean flow, given in Table 2. This phenomenon is probably due at least partially to “step-like changes” of flows in July that do not occur in January. There is some variation around the mean due solely to that trend, and this will not be captured in a purely random modulation scheme.

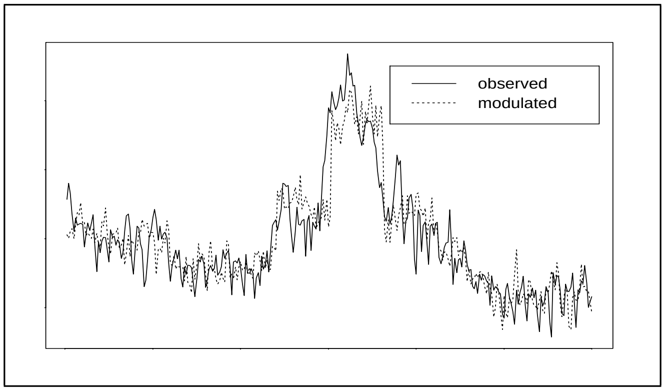

Fig. 12 Flows at John Day Dam, 1981

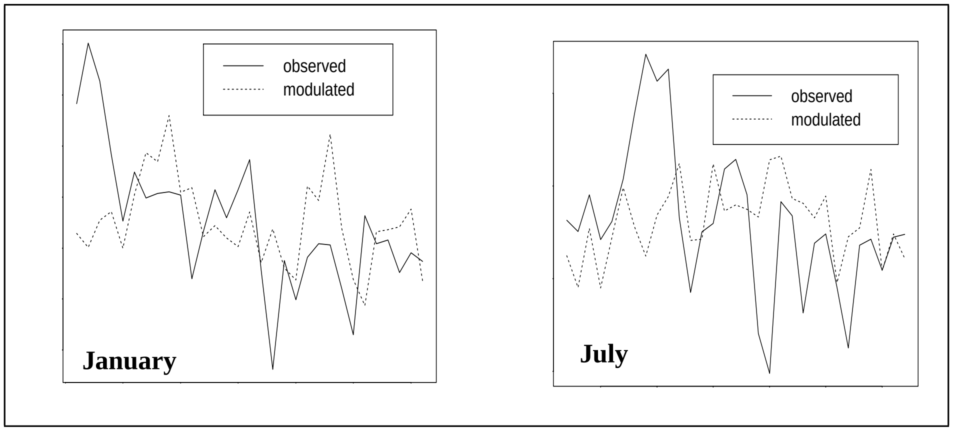

Fig. 13 January and July flows at John Day Dam, 1981

Table 2 Variance about mean flow for observed and modulated flows at three dams in 1981

Dam	Month	Variance about monthly mean flow	
		Observed	Modeled
John Day	January	728.38	287.54
	July	1620.08	401.74
Priest Rapids	January	67.34	160.29
	July	512.97	170.42
Ice Harbor	January	247.65	156.96
	July	149.83	61.83

Flow Loss

The term *loss* represents withdrawals from the system, mainly for irrigation. These withdrawals are positive in CRiSP.1. Negative losses are return flows through ground water.

The loss data in a segment represents the change in flow that occurs between the flow input (calculated from the flow of upstream segments) and the flow output (stored as data in the segment). Where not specified, flow loss is set to zero.

During the upstream propagation operation, new flow loss values are computed for reaches that lie between two dams. A dam is said to have no component of unregulated flow if no unregulated headwater flow enters the dam without first flowing through some regulation point.

For each reach r enclosed between a dam and upstream regulation points (Fig. 14), a new flow loss $F_{L(r)}$ is set by distributing any mass imbalance over all reaches between the dam and/or regulated inflow points in proportion to the maximum allowable flow in each reach:

$$F_{L(r)} = \left[\sum_{j=1}^{n} F_{R(j)} - F_{D(r)} \right] \frac{F_{M(r)}}{\sum_{i=1}^{p} F_{M(i)}} \tag{7}$$

where

- $F_{D(r)}$ = flow output at dam immediately below reach r
- $F_{L(r)}$ = new flow loss at reach r, as adjusted for mass imbalance
- $F_{M(r)}$ = flow maximum at reach r
- $F_{M(i)}$ = flow maximum at reach i
- $F_{R(j)}$ = flow at regulation point j
- n = number of upstream regulated points
- p = number of reaches between dam r and all regulation point.

Note: maximum allowable flows are set in the river description file, **columbia.desc**, using the `flow_max` token.

Flow loss is not modified by the upstream propagation in any reach not fully enclosed by regulated headwaters or dams. After appropriate loss values are set, flow loss in every segment is used as input data for unregulated headwater calculations.

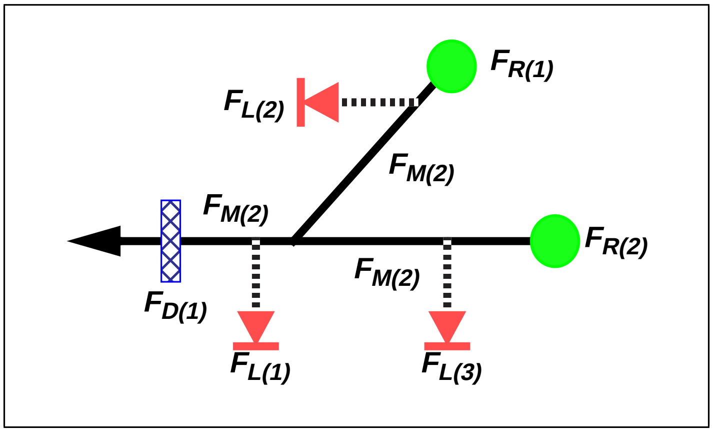

Fig. 14 Diagram of reach structure for loss calculation

Reservoir Loss Modulation

At downstream dams, variations in flow from losses due to irrigation and evaporation and additions from surface and subsurface ground water flows are accounted for with *loss* modulators. The intensity of this variation is based on the differences in flows observed at adjacent dams as indicated in period averaged hydroregulation model flows (Fig. 15).

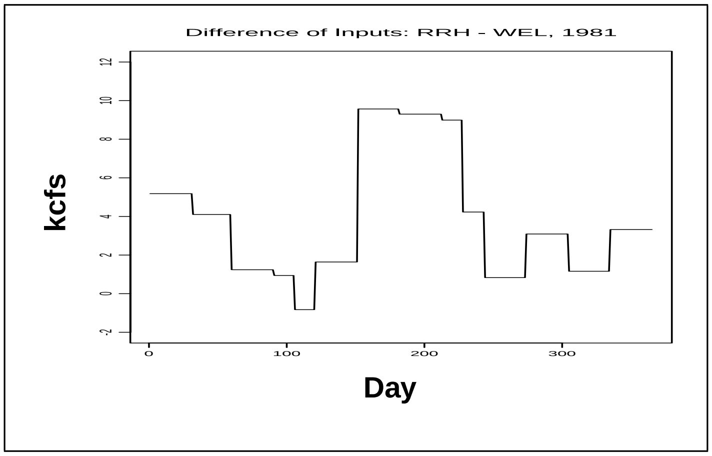

Fig. 15 Inputs at Rocky Reach minus inputs at Wells, 1981

The loss modulation is simulated with a white noise process (Fig. 16). A normal variate random factor is added to modulated flows of all run-of-river dams. The equation is:

$$F_{loss(i)} = \sigma_i \cdot \mathrm{Norm}(0, 1) \qquad (8)$$

where

- $F_{loss\ (i)}$ = modulated flow loss at downstream dam *i*
- σ_i = the standard deviation of the difference in flows (kcfs) at dam *i* and *i* +1 as computed by daily observed flows at all dams over the years 1979-1981.

Table 3 Flow loss modulator parameter for eq (8)

Dam	σ_i (kcfs)	Dam	σ_i (kcfs)
Bonneville	11.0	Little Goose	5.4
The Dalles	4.1	Priest Rapids	4.0
John Day	17.0	Wanapum	5.0
McNary	12.75	Rock Island	2.65
Ice Harbor	2.75	Rocky Reach	3.0
Lower Monumental	2.4	Wells	6.5

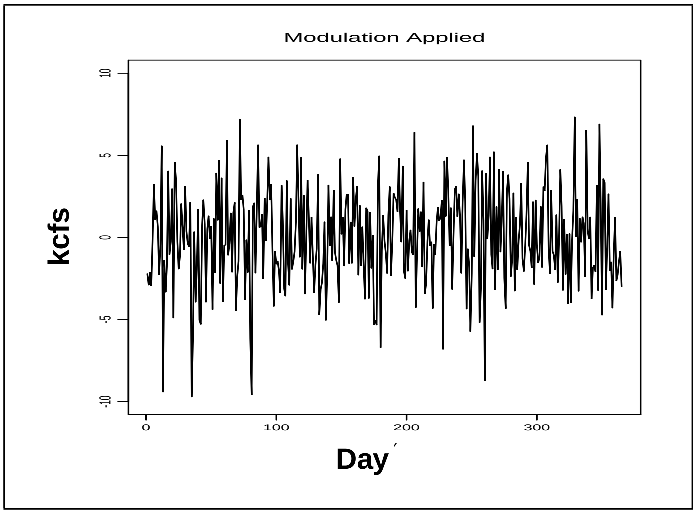

Fig. 16 Random factor modulation at Rocky Reach, 1981

Headwater Computation

Once flows are modulated at dams and the losses and gains are calculated, the headwater flows can be calculated with the algorithms described below.

Regulated Headwater

Regulated headwaters are storage reservoir outflows for the Monte Carlo Mode. No losses are considered for storage reservoir flows other than the dam outflow.

Unregulated Headwaters

Each unregulated headwater is examined. If the flow for a given headwater has not yet been computed, then flow for that and all adjacent unregulated headwaters are calculated.

The *region* of computation for a segment is defined as all segments within the river map subgraph with endpoints consisting of the nearest downstream dam, and the nearest regulation points or headwaters upstream from the dam. An example of a region with several unregulated headwaters is given in Fig. 17.

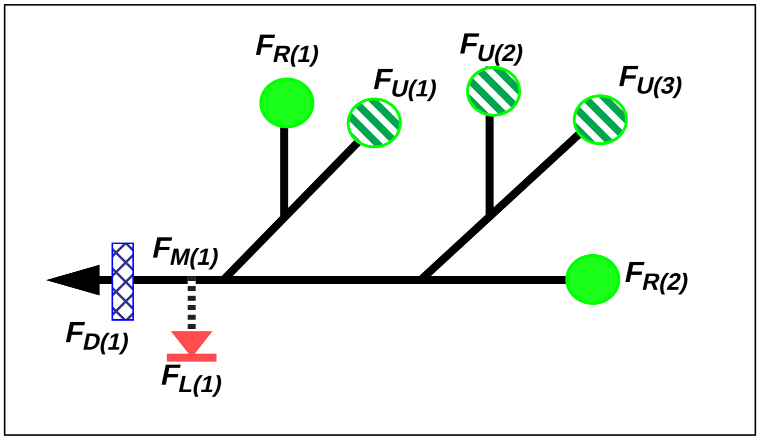

Fig. 17 Region of regulated F_R and unregulated F_U rivers

To calculate the unregulated headwater flows, first the total unregulated flow input to dam *r* (*D*(1) in Fig. 17) is computed by subtracting the total regulated flow from flow at dam *r*. The equation is:

$$F_{TU(r)} = F_{D(r)} - \sum_{j=1}^{p} F_{R(j)} \tag{9}$$

where

- $F_{TU(r)}$ = total unregulated flow input to dam *r*
- *p* = number of regulated flows in region
- $F_{D(r)}$ = flow output at dam *r*
- $F_{R(j)}$ = flow output at regulation point *j*.

The total unregulated flow is then distributed over all unregulated tributaries upstream of dam *r* in proportion to each tributary’s maximum flow, as specified in **columbia.desc** by the `flow_max` token. The flow coefficient *K* at each unregulated headwater *i* is the percentage of total unregulated flow contributed by that headwater and is defined:

$$K_i = F_{\mathrm{U}max(i)} \Big/ \left(\sum_{j=1}^{q} F_{\mathrm{U}max(j)} \right) \tag{10}$$

where

- K_i = flow coefficient at unregulated headwater *i*
- *q* = number of adjacent unregulated headwaters in region
- $F_{\mathrm{U}\,max\,(i)}$ = maximum flow at unregulated headwater *i* or *j*.

Finally, the flow at each unregulated headwater in the region of the dam $F_{U(i)}$ is defined:

$$F_{U(i)} = K_i \cdot F_{TU}. \tag{11}$$

The logic for the unregulated flow calculation is complete except when flow at any unregulated headwater falls below the minimum set in **columbia.desc** for that headwater, which can be zero.

In this case:

$$\begin{aligned} &\text{if} \quad F_{U(i)} < F_{\mathrm{U}(i)min} \\ &\text{then} \quad F_{U(i)} = F_{\mathrm{U}(i)min} \end{aligned} \tag{12}$$

and then for each reach *r* enclosed by dams the new loss $F_{L(r)}$ is:

$$F_{L(r)} = \left[\sum_{j=1}^{n} F_{R(j)} - F_{D(r)} + \sum_{i=1}^{m} F_{U(i)}\right] \frac{F_{M(r)}}{\sum_{i=1}^{p} F_{M(i)}} \tag{13}$$

where

- $F_{D(r)}$ = flow output at dam immediately below reach *r*
- $F_{L(r)}$ = new flow loss at reach *r*, as adjusted for mass imbalance
- $F_{M(r)}$ = flow maximum at reach *r* or *i*
- $F_{R(j)}$ = flow at regulation point *j*
- $F_{U(i)}$ = flow at unregulated headwater *i*
- *m* = number of unregulated headwaters above *r* (*m* = 3 in Fig. 17)
- *n* = number of regulated points adjacent to nearest upstream regulation point (*n* = 2 in Fig. 17)
- *p* = number of reaches between dam *r* and all upstream regulation points (*p* = 9 in Fig. 17).

Downstream Propagation

Downstream propagation of flow in the Monte Carlo Mode is computed after modulation, flow loss and unregulated headwater flows are computed. Starting at a headwater, flow is propagated by traversing the downstream segments, subtracting loss at each to determine new flow values, and adding flows together at confluences. Thus, flows are assigned at each segment in a downstream recursive descent traversal. The flow for each day is:

$$F_i(t) = \sum_{i+1} F_j(t) - F_{L(i)} \tag{14}$$

where

- $F_i(t)$ = flow at regulation point *i* at reservoir time increment *t*
- $F_{L(i)}$ = flow loss at reach *i*
- $F_j(t)$ = flow at regulation point *j* immediately upstream at reservoir time increment *t*.

Combined Modulated Flow

The modulators are combined with archive flows to give daily flows at the dams according to the equation:

$$\begin{gathered} F(t)_i = F(t)_{\mathrm{arch}(i)} + \sum_{j}^{J} \{F(t)_{\mathrm{day}(j)} + F(t)_{\mathrm{week}(j)}\} + \sum_{i}^{I} F_{\mathrm{loss}(i)} \\ \text{if} \quad F(t)_i < F_{\min(i)} \quad \text{then} \quad F(t)_i = F_{\min(i)} \end{gathered} \tag{15}$$

where

- $F(t)_i$ = modulated flow at dam *i*

- $F(t)_{\mathrm{arch}(i)}$ = archive flow at dam i
- $F(t)_{\mathrm{day}(j)}$ = daily modulated flow in regulated headwater j
- $F(t)_{\mathrm{week}(j)}$ = weekly modulated flow in regulated headwater j
- $F_{\mathrm{loss}(i)}$ = loss modulated flow in river segment upstream of dam i
- $F_{\mathrm{min}(i)}$ = minimum allowable flow at dam i
- J = number of regulated headwaters upstream of dam i
- I = number of dams upstream of dam i, including dam i.

Minima are defined at each dam in the yearly input data file, **base.dat** by default, under the `flow_min` token. If the flow drops below the minimum, it is set to the minimum flow. Note: flow minima also exist in the **columbia.desc** file and are used to set minimum flows in river segments.

Table 4 Flow minimum (kcfs) at dams.

Dam	$F_{\mathrm{min}(i)}$	Dam	$F_{\mathrm{min}(i)}$
Bonneville	100.0	Dworshak	1.0
The Dalles	0.0	Hells Canyon	5.0
John Day	50.0	Priest Rapids	0.0
McNary	0.0	Wanapum	0.0
Ice Harbor	9.5	Rock Island	0.0
Lower Monumental	11.5	Rocky Reach	0.0
Little Goose	11.5	Wells	0.0
Lower Granite	11.5	Chief Joseph	35.0

II.2.3 - Scenario Mode Flow Generation

In the Scenario Mode, seasonal flows for unregulated (i.e., un-dammed) streams are identified on a daily basis. These can be set by the user simply by drawing headwater seasonal flows when using the graphical user interface, or they can be generated from modulators that distribute the total annual headwater runoff according to the historical seasonal patterns.

Unregulated headwater flows connect directly to the river mainstem or to storage reservoirs. For storage reservoirs, the user can set the schedule of outflow according to constraints of the volume of the reservoir and the inflow. System flows are determined by unregulated stream flows and regulated flows from storage reservoir dams.

Headwater Modulation

In the Scenario Mode, flow from unregulated headwaters are modeled by the following equation:

$$Y_t = mp \cdot (F_t + e_t) \tag{16}$$

where

- t = julian day (t = 1 to 365)
- Y_t = estimated daily flow
- m = mean annual flow computed over a 10 year period
- p = fraction of mean annual flow for the scenario

  The switch from dry year to wet year variance parameters occurs at $p = 0.4$.
- e_t = stochastic error term
- F_t = Fourier term

$$F_t = 1 + \sum_{k=1}^{4} a_k \cdot \cos(k\omega t) + \sum_{k=1}^{4} b_k \cdot \sin(k\omega t) \tag{17}$$

- a_k, b_k = Fourier coefficients estimated for each river
- $\omega = 2\pi/365$.

The equation given for F_t above is a smooth Fourier estimate for the annual stream flow for each river, in units of multiples of the mean. For each scenario, an error term is randomly generated to incorporate the expected fluctuations. In the wet season (spring) when the exact fluctuations are more difficult to predict, there tends to be more pronounced deviations from the modeled curve. For this reason, the error component is generated from a low variance normal distribution in the dry season, and a higher variance normal distribution in the wet season. Also, since daily flows tend to be highly correlated, the generated (independent) error estimates (r_t) are artificially correlated according to the following equation:

$$e_t = 0.925 \cdot e_{t-1} + r_t \tag{18}$$

where

- r_t = randomly generated variable from a normal distribution centered on 0 with variance appropriate for dry and wet years as described above
- $e_0 = 0$.

The user chooses the type of year to be modeled relative to an average year, which is designated by $p = 1$. CRiSP.1 multiplies this proportion of the appropriate average flow parameter, m times ($F_t + e_t$), which yields an estimate for daily flow for the Scenario Mode flow.

Reservoir Volume and Flow

The storage reservoirs receive flows from the headwaters which are set by the Scenario Flow Modulators or directly by the user. The flow out of the storage reservoirs can be set by the user under constraints established by the maximum and minimum volume of the storage reservoirs. The equation describing the reservoir usable volume is:

$$\frac{\mathrm{d}V}{\mathrm{d}t} = F_U - F_R \tag{19}$$

where

- dV = change in reservoir volume in acre-ft.
- dt = time increment, typically 1 day
- F_U = unregulated natural flow into the reservoir in kcfs

- F_R = regulated flow out of the reservoir, which is controlled by the user under volume constraints in kcfs.

The volume for each reservoir is determined by a reservoir time step increment from a numerical form of the volume equation:

$$V(i+1) = V(i) + \mathrm{c}[F_U(i) - F_R(i)]\Delta t \tag{20}$$

where

- $V(i)$ = reservoir volume time step i with units of acre-ft.
- Δt = one day increment
- F_U = unregulated flows in kcfs
- F_R = regulated flows in kcfs
- c = 1983.5, which is a conversion factor

acre-ft. = (86400 sec/day) * (0.023 acre-ft./ k ft.^{3}) * (k ft.^{3} / sec) * (day)
V = (86400) * (0.023) *(F) * (Δt)
V = 1983.5 * (F) * (Δt)

The user requests reservoir output F_R with the following constraints. 1) The user is allowed to draw any flow curve for reservoir withdrawal as long as the reservoir is between minimum and maximum operating volumes. 2) If a request requires a volume exceeding the allowable range, CRiSP.1 alters the request to fit within the volume constraints. The algorithm is:

$$V_{\text{request}}(i+1) = V(i) + \mathrm{c}[F_U(i) - F_R(i)] \tag{21}$$

with constraints on reservoir outflow and volume defined by the algorithm[1]
where

- F_R = outflow from reservoir according to the constraints
- F_U = unregulated inflow to reservoir
- V_{request} = requested volume from reservoir
- F_{request} = requested outflow from reservoir

---

[1]

```
if $V_{request}(i+1) > V_{max}$ then
    $V_{request}(i+1) = V_{max}$
    $F_R(i) = F_U(i) + [V(i) - V_{max}] / c$
else
    if $V_{request}(i+1) < V_{min}$ then
        $V_{request}(i+1) = V_{min}$
        if $F_{request}(i) > F_U$ then
            $F_R(i) = F_U(i)$
        else
            $F_R(i) = F_{request}(i)$
    else
        $F_R(i) = F_{request}(i)$
```

- $V(i)$ = reservoir volume in reservoir time step i
- $V_{\max}$ = maximum reservoir volume
- $V_{\min}$ = minimum reservoir volume.

Theory for Parameter Estimation

Average daily flow (designated `flow_mean`) was computed for all available years. Each daily flow was divided by that year's average. Elements of the resulting series were denoted by X_t, where t = `day_of_year`. Next, the first nine terms of a Fourier series were computed with a fast Fourier transform. Since the mean of each series was 1, corresponding to the normalized annual mean flow, it follows $a_0 = 1.0$. The remaining Fourier coefficients were estimated according to the equations:

$$a_k = \frac{2}{365} \cdot \sum_{t=1}^{365} X_t \cos(k\omega t) \qquad b_k = \frac{2}{365} \cdot \sum_{t=1}^{365} X_t \sin(k\omega t) \tag{22}$$

where

- $\omega = 2\pi/365$
- k = value between 0 and 4.

The residual time series, R_t were computed by the equation:

$$R_t = X_t - \sum_{k=0}^{4} [a_k \cdot \cos(k\omega t) + b_k \cdot \sin(k\omega t)] . \tag{23}$$

The residuals were split into high-variance and low-variance parts, and sample standard deviations computed. The julian day when high flow variance begins and ends are `mod_start_hi_sigma` and `mod_end_hi_sigma`, respectively. Period average high and low standard deviation are `mod_hi_sigma` and `mod_lo_sigma`, respectively.

Data

Daily flows from *Hydrodata*, a CD-ROM database marketed by Hydrosphere, Inc., were obtained for the following locations and dates.

- Clearwater River @ Orifino, Idaho: Oct. 1980 - Sept. 1989
- Salmon River @ Whitebird, Idaho: Oct. 1980 - Sept. 1989
- Grande Ronde River @ Troy, Oregon: Oct. 1980 - Sept. 1989
- Imnaha River @ Imnaha, Oregon: Oct. 1980 - Sept. 1989

Flow modulator parameter estimates derived from flow data listed above were compared to modulator parameters estimated from flows over the previous 10 years at the same location (Oct 1970-Sep 1980). The parameters were slightly different, but graphs of smooth flow curves were nearly identical for Clearwater, Salmon, and Imnaha rivers. The Grande Ronde had a different shape, so for this river the parameters were adjusted to include all data from 1970 to 1989.

Table 5 shows parameters estimated for the unregulated headwater modulators. Parameters `mod_coeffs_a` and `mod_coeffs_b` correspond to a_k and b_k respectively. Table 6 shows data for regulated headwaters, i.e., Columbia above Grand Coulee Dam, North Fork Clearwater above Dworshak Dam, and Snake River above Brownlee Dam. Daily mean flow observations for each year were obtained from the U.S. Army Corps of Engineers, North Pacific Division and processed as in Table 6. Data were obtained for the following locations and dates.

- North Fork Clearwater River: Oct. 1973 - Sept. 1991
- Grand Coulee Dam: Oct. 1971 - Sept. 1991
- Brownlee Dam: Oct. 1981 - Sept. 1991

Table 5 Unregulated headwater flow parameter values

	Deschutes	Clear-water	Middle Fork	Salmon	Wenatchee	Methow
flow mean	5.00	8.79	5.00	11.24	5.00	5.00
mod coeffs a_0	1.00	1.00	1.00	1.00	1.00	1.00
mod coeffs a_1	0.00	-0.76	0.00	-0.84	0.00	0.00
mod coeffs a_2	0.00	0.09	0.00	0.34	0.00	0.00
mod coeffs a_3	0.00	0.10	0.00	-0.06	0.00	0.00
mod coeffs a_4	0.00	-0.14	0.00	-0.09	0.00	0.00
mod coeffs b_0	0.00	0.00	0.00	0.00	0.00	0.00
mod coeffs b_1	0.00	0.87	0.00	0.50	0.00	0.00
mod coeffs b_2	0.00	-0.72	0.00	-0.64	0.00	0.00
mod coeffs b_3	0.00	0.35	0.00	0.44	0.00	0.00
mod coeffs b_4	0.00	-0.16	0.00	-0.25	0.00	0.00
mod lo sigma	0.05	0.06	0.05	0.04	0.05	0.05
mod hi sigma	0.25	0.29	0.25	0.20	0.25	0.25
mod start hi sigma	46.00	46.00	46.00	86.00	46.00	46.00
mod end hi sigma	196.00	196.00	196.00	196.00	196.00	196.00

Table 6 Regulated headwater flow parameter values

	Columbia Headwater	Snake Headwater	North Fork Clearwater
flow mean	110.00	21.50	5.00
mod coeffs a_0	1.00	1.00	1.00
mod coeffs a_1	-0.24	0.03	-0.51
mod coeffs a_2	0.20	-0.13	-0.04
mod coeffs a_3	0.00	0.01	0.16
mod coeffs a_4	-0.04	0.00	-0.15
mod coeffs b_0	0.00	0.00	0.00
mod coeffs b_1	0.13	0.35	0.88
mod coeffs b_2	-0.10	-0.16	-0.62

Table 6 Regulated headwater flow parameter values

	Columbia Headwater	Snake Headwater	North Fork Clearwater
mod coeffs b_3	0.10	0.05	0.16
mod coeffs b_4	-0.02	-0.06	-0.08
mod lo sigma	0.06	0.05	0.23
mod hi sigma	0.08	0.10	0.31
mod start hi sigma	96.00	96.00	46.00
mod end hi sigma	196.00	196.00	196.00

Maximum Unregulated Flows

Observed maximum flows in the tributaries were obtained from the peak flow data in *Hydrodata*, a CD-ROM database marketed by Hydrosphere, Inc. The data record length was variable (Table 7).

Table 7 Maximum unregulated flow (kcfs)

Unregulated River	Maximum Flow
Wind	30
Hood	30
West Fork Hood	15
East Fork Hood	15
Klickitat	39
Warm Springs	8
Umatilla	18
Walla Walla	21
Tucannon	5
Clearwater	166
Middle Fork Clearwater	78
Red	10
Salmon	129
Little Salmon	10
Rapid River	10
South Fork Salmon	19
Pahsimeroi	1
East Fork Salmon	4

Table 7 Maximum unregulated flow (kcfs)

Unregulated River	Maximum Flow
Redfish	1
Yakima	64
Wenatchee	31
Entiat	6
Methow	33
Grande Ronde	36
Imnaha	6

Storage Reservoirs Parameter Values

Storage reservoirs volumes obtained from U.S. Army Corps of Engineers (1989a, 1989b) are given in Table 8.

Table 8 Storage reservoirs; shaded items are used in model

Reservoir	Max Pool ft.	Min Pool ft.	Usable Storage in acre-ft.	Powerhouse Hydraulic Capacity (kcfs)
Grand Coulee	1290	1208	5,185,500	280
Libby Dam	2459	2287	4,979,599	24.1
Hungry Horse	3565	3336	3,161,000	8.9
Duncan	1897	1794	1,398,600	20
Mica	2478	2320	7,770,000[a]	41.6
Coulee total[b]			22,494,699	
Dworshak	1605	1445	2,015,800	10.5
Brownlee	2080	1976	975,318	34.5

[a] estimated

[b] In the model, all storage reservoirs above Grand Coulee are summed to represent the combined storage capacity of the upper Columbia system.

Desired reservoir elevation levels for flood control obtained from U.S. Army Corps of Engineers (1989a, 1989b) are presented in Table 9. This is not used by CRiSP.1 at the present time.

Table 9 Storage reservoirs flood control elevation rule curves

Reservoir	Date (Elevation in ft.)			
Libby Dam	Nov 1 (2459)	Dec 1 (2448)	Jan 1 (2411)	-

Table 9 Storage reservoirs flood control elevation rule curves

Reservoir	Date (Elevation in ft.)			
Dworshak	Sept. 1 (1600)	Oct 1 (1586)	Nov 15 (1579)	Dec 15 (1558)

II.2.4 - Flow / Velocity / Elevation

The river velocity used in fish migration calculations is related to river flow and pool geometry and varies with pool drawdown as a function of the volume. The pool is represented as an idealized channel having sloping sides and longitudinal sloping bottom. As a pool is drawn down, part of it may return to a free flowing stream that merges with a smaller pool at the downstream end of the reservoir. The submodel is illustrated in Fig. 18 on page 30 and Fig. 19 on page 32. The important parameters are as follows:

- H_u = full pool depth at the upstream end of the segment
- H_d = full pool depth at the downstream end of the segment
- L = pool length at full pool
- x = pool length at lowered pool
- E = pool elevation drop below full pool elevation
- W = pool width averaged over reach length at full pool
- θ = average slope of the pool side
- F = flow through the pool in kcfs
- U_{free} = velocity of free flowing river.

Other parameters illustrated in Fig. 18 are used to develop the relationships between the parameters listed above and water velocity and pool volume. They are not named explicitly.

Pool Volume

Reservoir volume depends on elevation. Elevation is measured in terms of E, the elevation drop below the full pool level. The volume calculation is based on the assumptions that the width of the pool at the bottom and the pool side slopes are constant over pool length. As a consequence of these two assumptions, the pool width at the surface increases going downstream in proportion to the increasing depth of the pool downstream. When $E > H_u$, the drawn down elevation is below the level of the upstream end and the upper end of the segment becomes a free flowing river section that connects to a pool downstream in the segment. When $E < H_u$, the reservoir extends to the upper end of the segment and for mathematical convenience CRiSP.1 calculates a larger volume and subtracts off the excess. The volume relationship (as a function of elevation drop for E positive measured downward) is developed below.

The total volume is defined:

$$\begin{aligned} V(E) &= V_1(E) && E \geq H_u \\ V(E) &= V_1(E) - V_2(E) && E < H_u \end{aligned} \quad . \tag{24}$$

The equation for V_1 is developed as follows. Note that when $E \geq H_u$, the volume V_1 divides into two parts:

$$V_1 = 2V' + V'' \tag{25}$$

where V' is a side volume and V'' is the thalweg[1] volume. They are defined:

$$V' = \frac{zxy'}{6} \qquad V'' = \frac{zxy''}{2} \tag{26}$$

where

$$x = L\frac{H_d - \mathrm{E}}{H_d - H_u} \tag{27}$$

$$z = H_d - E \tag{28}$$

$$y' = z\tan\theta \qquad y'' = W - (H_d + H_u)\tan\theta\ . \tag{29}$$

Combining these terms, when $E \geq H_u$ it follows pool volume is:

$$V_1 = \frac{zxy'}{3} + \frac{zxy''}{2}\ . \tag{30}$$

In terms of the fundamental variables in equations (25) to (30) this is:

$$V_1(E) = L\left[\frac{(H_d - E)^2}{H_d - H_u}\right]\left[\frac{W}{2} - \left(\frac{H_d}{6} + \frac{H_u}{2} + \frac{E}{3}\right)\tan\theta\right] \tag{31}$$

for $E \geq H_u$ and $x \leq L$.

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[1] A thalweg is the longitudinal profile of a canyon.

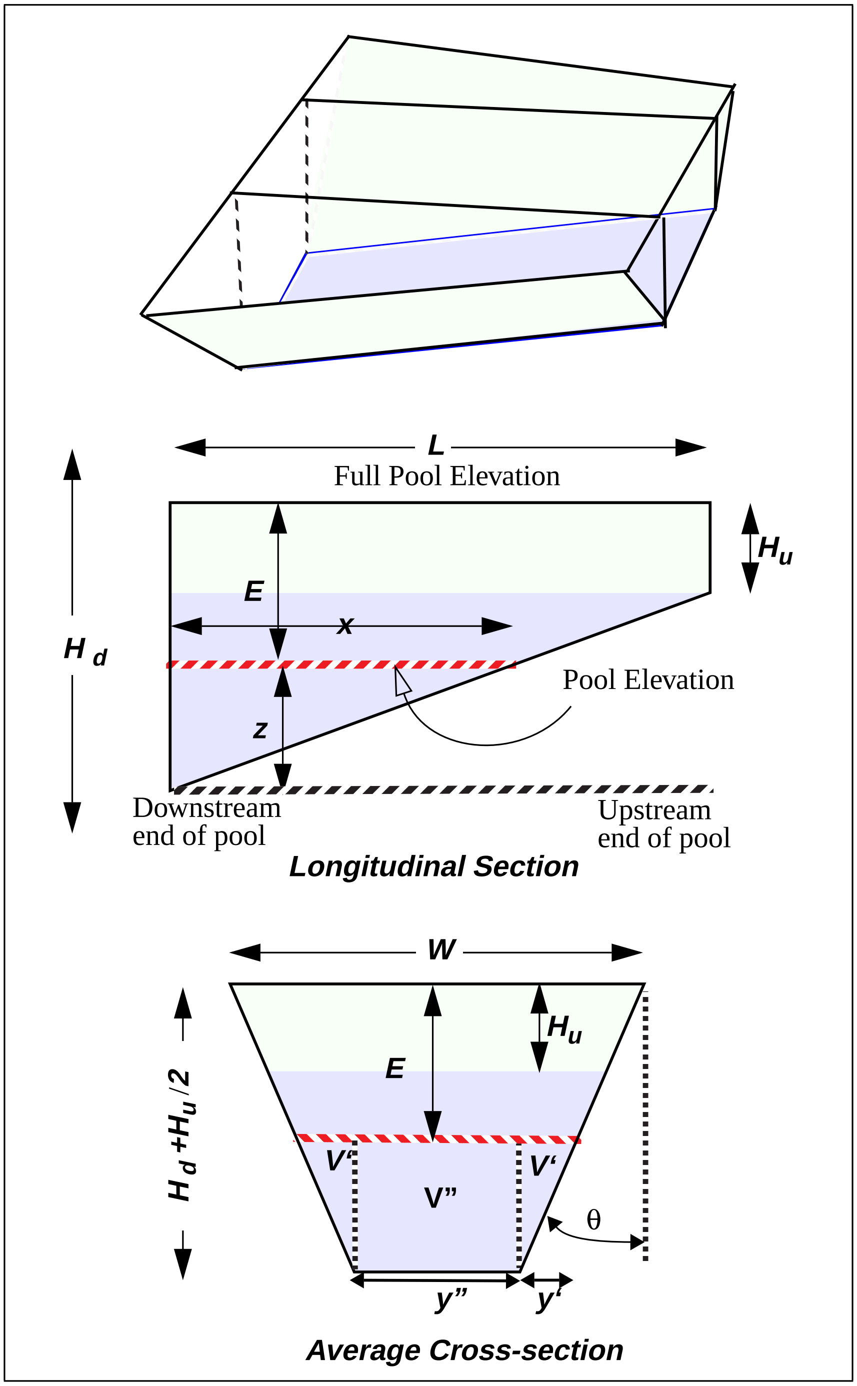

Fig. 18 Pool geometry for volume calculations showing perspectives of a pool and cross-sections; the pool bottom width remains constant while the surface widens in the downstream direction.

Recall from eq (24) on page 28 that when the pool elevation drop is less than the upper depth (so $E < H_u$ and $x = L$), the pool volume is described by the equation $V(E) = V_1(E) - V_2(E)$. The term $V_1(E)$ is the volume of the pool extended longitudinally above the dam where the depth is H_u, so as to form the same triangular longitudinal cross-section as before. This is done so that the volume can still be expressed by eq (31). The term $V_2(E)$ is the excess volume of the portion of the pool above the dam and can be expressed:

$$V_2(E) = L\left[\frac{(H_u - E)^2}{H_d - H_u}\right]\left[\frac{W}{2} - \left(\frac{H_d}{2} + \frac{H_u}{6} + \frac{E}{3}\right)\tan\theta\right] . \tag{32}$$

Summarizing, the volume relationship as a function of elevation drop, for E positive measured downward, is:

$$\begin{aligned} V(E) &= V_1(E) && E \geq H_u \\ V(E) &= V_1(E) - V_2(E) && E < H_u \end{aligned}$$

where

$$\begin{aligned} V_1(E) &= L\left[\frac{(H_d - E)^2}{H_d - H_u}\right]\left[\frac{W}{2} - \left(\frac{H_d}{6} + \frac{H_u}{2} + \frac{E}{3}\right)\tan\theta\right] \\ V_2(E) &= L\left[\frac{(H_u - E)^2}{H_d - H_u}\right]\left[\frac{W}{2} - \left(\frac{H_d}{2} + \frac{H_u}{6} + \frac{E}{3}\right)\tan\theta\right] \end{aligned} .$$

The equation for full pool volume can be expressed:

$$V(0) = L\left[W\frac{H_d + H_u}{2} - \frac{\tan\theta}{3}\left(\frac{(H_d + H_u)^2}{2} + H_d H_u\right)\right] . \tag{33}$$

When the bottom width is zero the full pool volume becomes:

$$V(0) = \frac{LW}{3}\left[\frac{H_d^3 - H_u^3}{H_d^2 - H_u^2}\right] . \tag{34}$$

Water Velocity

Water velocity through a reservoir is described in terms of the residence time T and the length of the segment L. The residence time in a segment depends on the amount of the reservoir that is pooled and free flowing (Fig. 19).

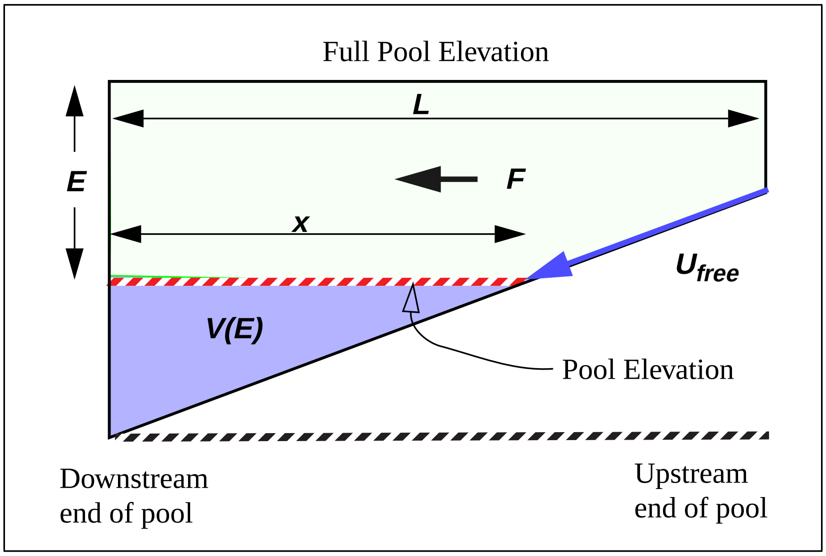

Fig. 19 Reservoir with free flowing and pooled portions

The equations for residence time are:

$$\begin{aligned} T &= \frac{V(E)}{F} + \frac{L-x}{U_{free}} \qquad E \ge H_u \\ T &= \frac{V(E)}{F} \qquad E < H_u \end{aligned} \tag{35}$$

where

- $V(E)$ = pool volume (ft.^{3}) as a function of elevation drop E in feet
- F = flow in 1000 cubic feet per second (kcfs)
- L = segment length in miles
- x = pool length defined by eq (27) and with units of feet
- U_{free} = velocity of water in the free stream (kfs)
  Using the John Day River, the default value is 4.5 ft./s which is 4.5 x 10^{-3} kfs).
- T = residence time in this calculation is in kilo seconds (ks)
- H_u = full pool depth at the upstream end of the segment.

The velocity in the segment is:

$$U = \frac{L}{T}. \tag{36}$$

The velocity with the above units is in thousands of feet per second. Combining equations (31), (32), (35) and (36) the segment velocities are:

$$U = \frac{L}{\frac{V_1(E)}{F} + \frac{L-x}{U_{free}}} \text{ for } E \ge H_u \tag{37}$$

and

$$U = \frac{LF}{V_1(H_u) + V_2(E)} \text{ for } E < H_u \tag{38}$$

where

- U = average river velocity in ft/s
- U_{free} = the velocity of a free flowing stream in ft/s
- F = flow in kcfs
- E = elevation drop (positive downward) in ft
- H_u = depth of the upper end of the segment in ft
- V_1 and V_2 = volume elements defined by eq (31) and (32).

Flow / Velocity Calibration

The calibration of the volume equation requires determining the average pool slope from the pool volume. The equation is the smaller angle of the two forms:

$$\begin{gathered}\theta = \operatorname{atan}\left(\frac{3W(H_d + H_u) - 6\frac{V(0)}{L}}{(H_d + H_u)^2 + 2H_dH_u}\right) \\ \text{or} \\ \theta = \operatorname{atan}\left(\frac{W}{H_d + H_u}\right)\end{gathered} \tag{39}$$

where

- $V(0)$ = pool volume at full pool.

This scheme using eq (39) reflects the volume versus pool elevation relationship developed for each reservoir by the U.S. Army Corps of Engineers. Capacity versus elevation curves were obtained from several dams to check the accuracy of our volume model. The figures below show data points from these curves versus CRiSP.1's volume curve for two dams. Fig. 20 illustrates Lower Granite Pool with model coefficients of H_u = 40 ft., H_d = 118 ft, $\theta = 80.7^o$, L = 53 miles, W = 2000 ft, and Wanapum Pool with model coefficients H_u = 42 ft., H_d = 116 ft, $\theta = 87.0^o$, L = 38 miles, W = 2996.1 ft.

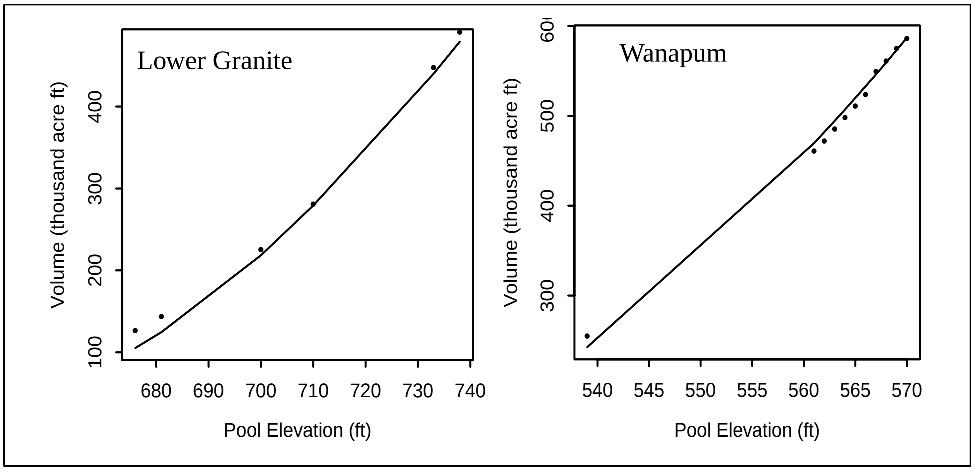

Fig. 20 Pool elevation vs. volume for Lower Granite and Wanapum pools

Table 10 Geometric data on Columbia River system

Segment	L	Elev[a]	MOP[b]	V	A[c]	W	H_u	H_d	θ
Units	miles	ft MSL	ft MSL	kaf	k ft^2	feet	feet	feet	^{o} of arc
Bonneville	46.2	77.0	70.0	565	101.8	3643	22	93	88
The Dalles	23.9	160.0	155.0	332	114.6	3624	60	105	87
John Day	76.4	268.0	257.0	2,370	255.9	5399	34	149	86.9
McNary	61	340.0	335.0	1,350	182.6	5153	40	105	88
Hanford Reach	44	---	---	131	24.6	3213	29	29	---
Priest Rapids	18	488.0	465.0	199	91.2	3208	32	101	87
Wanapum	38	572.0	539.0	587	127.4	2996	42	116	87.0
Rock Island	21	613.0	609.0	113	44.4	982	15	44	64.4
Rocky Reach	41.8	707.0	703.0	430	84.8	1815	37	108	84.5
Wells	29.2	781.0	767.0	300	84.8	3023	91	111	86
Chief Joseph	52	956.0	930.0	516	81.9				
Ice Harbor	31.9	440.0	437.0	407	105.2	2154	18	110	83.3
L. Monumental	28.7	540.0	537.0	377	108.4	1937	42	118	81.3
Little Goose	37.2	638.0	633.0	365	80.9	2200	40	140	78.2
Lower Granite	53	738.0	733.0	484	75.3	2000	48	140	80.7

a. Elev is normal full pool elevation, in feet above mean sea level.
b. MOP is minimum operating pool elevation.
c. A is surface area.

The water particle residence time in a segment is given in eq (35). The pool volume velocity/travel time equation was tested against particle travel time calculations for Lower Granite Pool as reported by the U.S. Army Corps of Engineers in the *1992 reservoir drawdown test* (Wik et al. 1993) (Fig. 21).

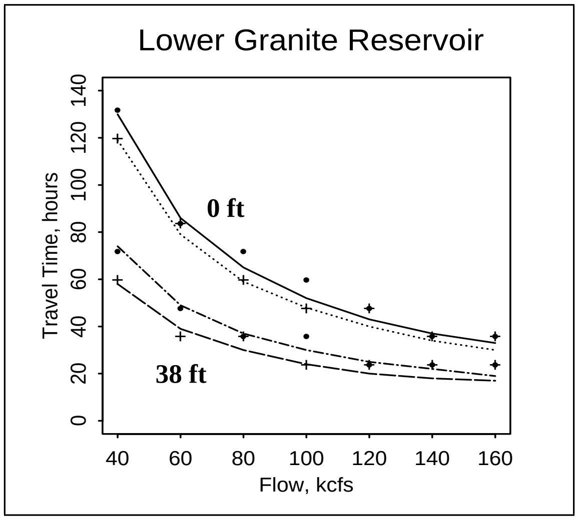

Fig. 21 Water particle travel time vs. flow for CRiSP.1 (points) and Army Corps calculations (lines) at two elevations full pool (0) and 38 ft below full pool for Lower Granite Dam.

II.2.5 - Temperature

River temperature is computed in two stages. First, hydrosystem temperature inputs are calculated from mixing headwater temperatures according to the equation:

$$\theta(t) = \frac{\sum_i \theta_i(t) F_i(t)}{\sum_i F_i(t)} \tag{40}$$

where

- $F_i(t)$ = flow from headwater i through the river segment in question on day t
- $\theta_i(t)$ = temperature from headwater i on day t
- $\theta(t)$ = temperature for selected river segment on day t.

Second, changes to the temperatures within the hydrosystem are made by adding $\Delta\theta(s,t)$ for each day t at site s where the true $\theta(t)$ for the site is known.

Headwater temperatures are identified for the Snake River using measured temperatures from Lower Granite Dam as available in the U.S. Army Corps of Engineers CROHMS database. Head water temperatures for the upper Columbia are identified from CROHMS and supplemented using data collected at streamflow gaging stations by the U.S. Geological Survey (see Fig. 45 on page 90 for locations).

II.3 - Fish Migration

II.3.1 - Theoretical Framework

The movement of fish through river segments is described in terms of an average migration velocity and a stochastic velocity that varies from moment to moment. The migration velocity equation for a group of fish is defined by the Wiener stochastic differential equation:

$$\frac{dX}{dt} = r + \sigma W(t) \tag{41}$$

where

- X = position of a fish down the axis of the river
- dX/dt = velocity of fish in migration
- r = average velocity of fish in the segment; this is a combination of water movement and fish behavior
- σ = spread parameter setting variability in the fish velocity
- $W(t)$ = Gaussian white noise process to represent variation in velocity.

Numerical simulation of time vs. distance traveled according to eq (41) is illustrated in Fig. 22.

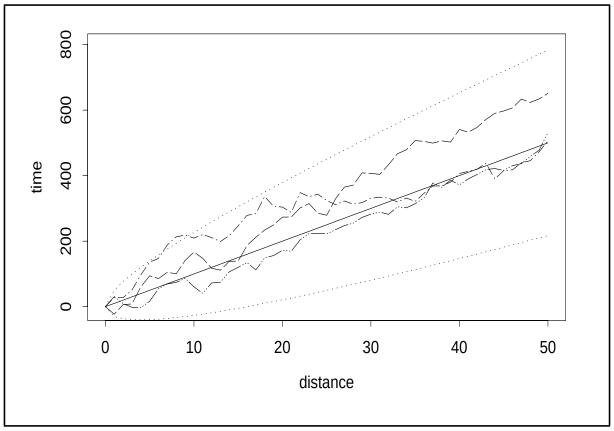

Fig. 22 Movement along axis of segment vs. time. Shown are mean path, three paths, and 95% confidence intervals. For these simulations, r is set at 10 and σ is set at 20.

Probability Density Function

The stochastic equation describing fish positions is random. As a result, we must define the probability distribution of fish position over time instead of the actual position, which changes from one fish to another. The probability density function (pdf) of the stochastic differential equation (41) can be defined with a Fokker-Planck (Gardiner 1985) equation:

$$\frac{\partial p}{\partial t} = -r\frac{\partial p}{\partial x} + \frac{\sigma^2}{2}\frac{\partial^2 p}{\partial x^2} \tag{42}$$

where $p = p(x, t)$ is the pdf describing the probability density of the fish being at position x at time t given it was at position $x = 0$ at time $t = 0$.

Boundary Conditions

To solve the pdf from eq (42), boundary conditions must be identified. We assume that upon release into a segment a fish can move upstream or downstream in the segment; however, once the fish has reached the downstream end of the segment, at $x = L$, it will move into the next segment. The next downstream segment may be a confluence or the forebay of a dam. The boundary conditions are:

$$\begin{aligned} p(L, t) &= 0 \\ p(-\infty, t) &= 0 \end{aligned} . \tag{43}$$

Solution

The solution to the partial differential equation (eq (42)) describing the probability distribution of fish in a river segment is a probability density function for the fish. This is:

$$p(x, t) = \frac{1}{\sqrt{2\pi\sigma^2 t}}\left[\exp\frac{-(x-rt)^2}{2\sigma^2 t} - exp\left(\frac{2Lr}{\sigma^2} - \frac{(x-2L-rt)^2}{2\sigma^2 t}\right)\right] . \tag{44}$$

An example of the distribution of *p* with respect to *x* for different times is illustrated in Fig. 23. The pdf in the figure can be interpreted as probability of where a fish is in the river at any time. It can also be interpreted as the distribution of a group of fish in a river segment if they have experienced no predation. Notice that the group moves down the segment and spreads over time. At the absorbing boundary representing a dam, the fish enter the boundary regions and pass through to the next segment. Note that the equation cannot define the deterministic path of fish with time.

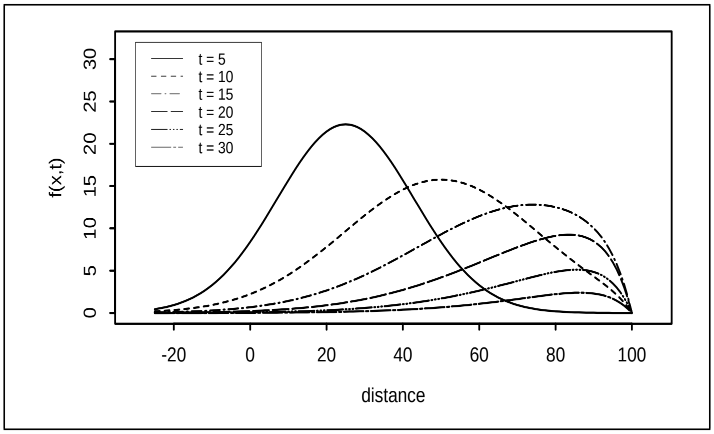

Fig. 23 Plot of eq (44) for various values of *t* where $r = 5$, $\sigma = 8$, and $L = 100$.

Passage Probability

The probability that a fish that entered the river segment at time t_i is still in the river segment at time t_j is obtained by integrating eq (44) over reservoir length. This is expressed:

$$P(t_j|t_i) = \int_{-\infty}^{L} p(x, t_j - t_i)dx = $$

$$= \Phi\left(\frac{L - r \cdot (t_j - t_i)}{\sigma\sqrt{t_j - t_i}}\right) - \exp\left(\frac{2Lr}{\sigma^2}\right)\Phi\left(\frac{-L - r \cdot (t_j - t_i)}{\sigma\sqrt{t_j - t_i}}\right) \tag{45}$$

where

- Φ = cumulative distribution of the standard normal distribution
- L = segment length
- r = average migration velocity through the segment (developed in Active Migration Equation section below).

The probability of a fish leaving a segment between time t and $t + \Delta t$ is:

$$\Delta P(t_j|t_i) = P(t_j|t_i) - P(t_{j-1}|t_i)\,. \tag{46}$$

This is the arrival time distribution at the point L, which is generally a dam or river confluence. The number of fish exiting each river segment is defined by eq (46).

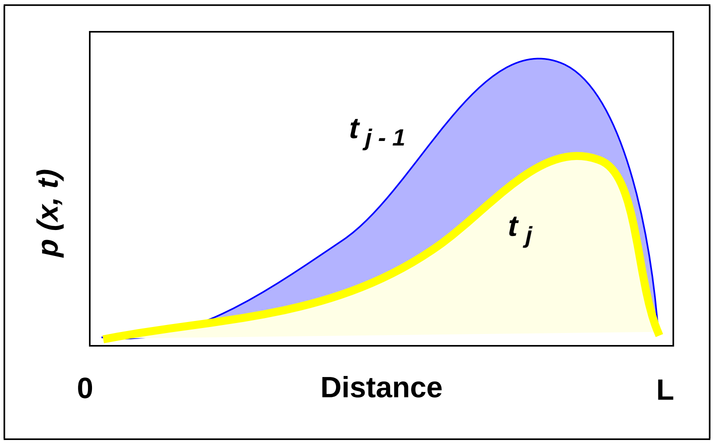

Fig. 24 Fish distribution, $p(x, t)$, at t_j and t_{j-1}. Size of the shaded area represents probability of fish leaving the segment over the interval $t_j - t_{j-1}$

II.3.2 - Migration Models

Active Migration Equation

The goal of the active migration equation is to be flexible enough to capture a variety of migratory behaviors without requiring an excessive number of parameters to fit. The equation has a term that relates migration rate to river velocity and a term that is independent of river velocity. Both terms have temporal components, with migration rate increasing with time of year.

The flow independent migration rate is driven by two parameters, β_{min} and β_{max}. β_{min} is the flow independent migration rate at the time of release (T_{RLS}), and β_{max} is the maximum flow independent migration rate. In eq (47) below, it is easier to express the equation in terms of the regression coefficients β_0 and β_1, with the following relations:

$$\begin{aligned} \beta_{\min} &= \beta_0 + \frac{\beta_1}{2} \\ \beta_{\max} &= \beta_0 + \beta_1 \end{aligned} . \tag{47}$$

With $\beta_{\max} > \beta_{\min}$, the fish have a tendency to migrate faster the longer they have been in the river. This tendency can be "turned off" by setting $\beta_{\max} = \beta_{\min}$ (that is, $\beta_1 = 0$). Also, flow independent migration can be turned off entirely by setting $\beta_{\max} = \beta_{\min} = 0$ (that is, $\beta_0 = \beta_1 = 0$).

The magnitude of the flow dependent term is determined by β_{FLOW}. This term determines the percentage of the average river velocity that is used by the fish in downstream migration. This term has a seasonal component determined by the T_{SEASN} term, which is expressed in terms of julian date. This has the effect of the fish using less of the flow early in the season and more of the flow later in the season. Values of T_{SEASN} that are relatively early in the season mean that the fish mature relatively early. The α parameters determine how quickly the fish mature from early season behavior to later season behavior. Setting α_2 equal to 0 has the effect of "turning off" the flow/season interaction, resulting in a linear relationship between migration rate and river flow.

The full migration rate model (Zabel, Anderson and Shaw 1998) is:

$$\begin{aligned} r(t) &= \beta_0 + \beta_1\left[\frac{1}{1 + \exp(-\alpha_1(t - T_{RLS}))}\right] \\ &\quad \beta_{FLOW}\bar{V}_t\left[\frac{1}{1 + \exp(-\alpha_2(t - T_{SEASN}))}\right] \end{aligned} \tag{48}$$

where

- $r(t)$ = migration rate (miles/day)
- t = julian date
- β's = regression coefficients, described above
- $\bar{V}_t$ = average river velocity during the average migration period
- α_1 , α_2 = slope parameters
- T_{SEASN} = seasonal inflection point (in julian days)
- T_{RLS} = release date (in julian days).

Both the flow dependent and flow independent components of eq (48) use the logistic equation (term in brackets). The logistic equation is expressed in general as:

$$y = \beta_0 + \beta_1\left[\frac{1}{1 + \exp(-\alpha(t - T_0))}\right] . \tag{49}$$

This equation has a minimum value of β_0 and a maximum value of $\beta_0 + \beta_1$. T_0 determines the inflection point, and α determines the slope. Fig. 25 contains example plots of the equation and demonstrates how varying a parameter affects the shape of the curve.

The logistic equation is used instead of a linear equation because upper and lower bounds can be set. This eliminates the problem of unrealistically high or low migration rates that can occur outside observed ranges with linear equations. Also, for suitable parameter values, the logistic equation effectively mimics a linear relationship.

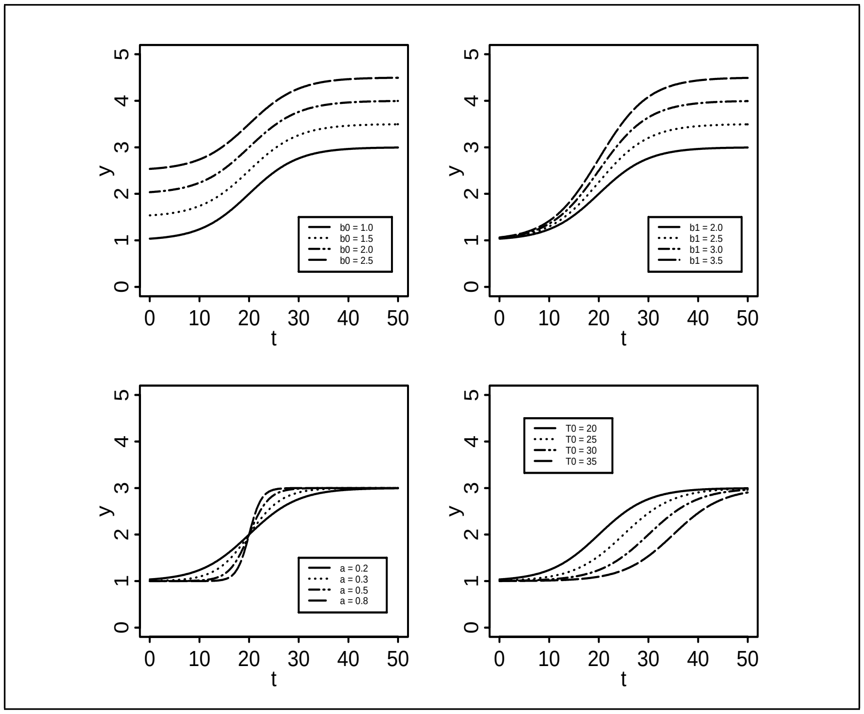

Fig. 25 Examples of the logistic equation (eq (49)) with various parameter values. In all four plots, the parameter values for the solid curves are: $\beta_0 = 1.0$, $\beta_1 = 2.0$, $\alpha = 0.2$, and $T_0 = 20$. In the upper left plot β_0 is varied, and β_1 is varied in the upper right. In the lower left plot, α is varied, and T_0 is varied in the lower right.

Other Migration Model Options

As mentioned in the previous section, simpler models are nested within the full migration model. For example, setting $\beta_1 = 0$ removes the flow-independent experience term. The resulting model:

$$r(t) = \beta_0 + \beta_{FLOW}\bar{V}_t\left[\frac{1}{1 + \exp(-\alpha_2(t - T_{SEASN}))}\right] \tag{50}$$

has only the flow-dependent experience factor, which assumes that fish migrate more rapidly later in the season by migrating in high flow regions of the river and/or by spending a greater portion of the day in the river rather than holding up along the shore.

By also setting $\alpha_2 = 0$, all experience related migration rate increases are removed. The resulting model:

$$r(t) = \beta_0 + (\beta_{FLOW}\bar{V}_t)/2 \tag{51}$$

assumes a linear relation between migration rate and river velocity. Other combinations of assumptions are also available in CRiSP.1.

Velocity Variance

The spread parameter σ sets the variability in the migration velocity. This term represents variability from all causes including water velocity and fish behavior. In CRiSP.1, $\sigma^2 = V_{var}$ which is the variance in the velocity. This can vary on a daily basis.

Variance in Migration Rate

Variance in the migration rate is applied for each release, thus randomly representing differences in the migration characteristics of each release. Although studies suggest differences in migration can partly be attributed to differences in fish condition and perhaps stock to stock variations, these factors have not been sufficiently identified so their contribution to differences in travel time is randomized. The equation is:

$$r_i(t) = r(t) \cdot V(i) \tag{52}$$

where

- $r(t)$ = determined from eq (48)
- $V(i)$ = variance factor that varies *between* releases only.

$V(i)$ is drawn from the broken-stick distribution. The mean value is set at 1, representing $r(t)$, and the upper and lower values are set with sliders in **Migration Rate Variance** window in the **Behavior** menu.

Pre-smolt Behavior

In some cases, fish are released into the river before they are ready to initiate migration. This may be the case with hatchery releases or fish that are sampled and released in their rearing grounds. The probability of moving from the release site is determined by two dates, $smolt_{start}$ and $smolt_{stop}$:

$$p = \begin{cases} 0 & for \quad (t < smolt_{start}) \\ \dfrac{(t - smolt_{start})}{(smolt_{stop} - smolt_{start})} & for \quad (smolt_{start} < t < smolt_{stop}) \\ 1 & for \quad (t > smolt_{stop}) \end{cases} . \tag{53}$$

In other words, the probability of initiating migration is 0 before $smolt_{start}$, 1 after $smolt_{stop}$, and linearly increasing with time between the two values. Fish are subjected to predation prior to the onset of smoltification. The predation activity coefficient for pre-smolt mortality uses the activity coefficient for the first day of smoltification $t = 1$.

Implementing the Travel Time Algorithm

The basic unit of the travel time algorithm is a reach of river between two nodes, where a node is a dam, confluence of two rivers, or a release point (Fig. 26). The travel time algorithm passes a group of fish from node to node and determines the distribution of travel times from an upstream node to the next downstream node.

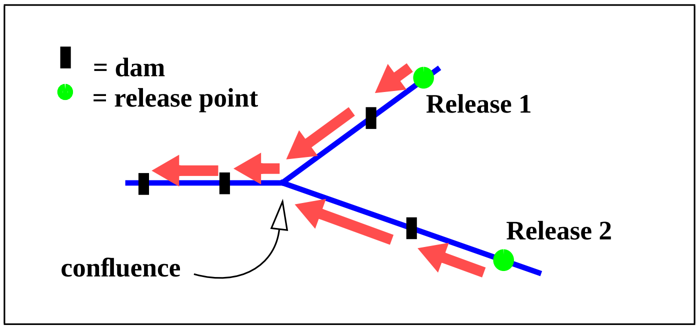

Fig. 26 Schematic diagram of a river system. Arrows represent the migration of release groups 1 and 2 through reaches. At the confluence, groups are combined for counting purposes only, i.e they still exhibit their unique migration characteristics.

CRiSP.1 groups fish according to user preference. The user defines *species* (and *stocks*, if desired) in the **columbia.desc** file[1] and associates behavioral characteristics with each species through the user interface or the yearly input data file. For instance, the user may decide that all chinook 1's should be treated identically or that wild and hatchery stocks should be treated separately. All releases that are treated similarly are referred to as a release group, except for the random selection of a migration rate variance.

During one iteration of the travel time submodel, fish from a release group pass through a reach. The input to CRiSP.1 is the number of fish from the release group that are ready to depart a node during the time interval. This input group is passed to the next node downstream with the travel time distributions determined by eq (45) and (46). Fig. 27 demonstrates a single iteration of the travel time algorithm.

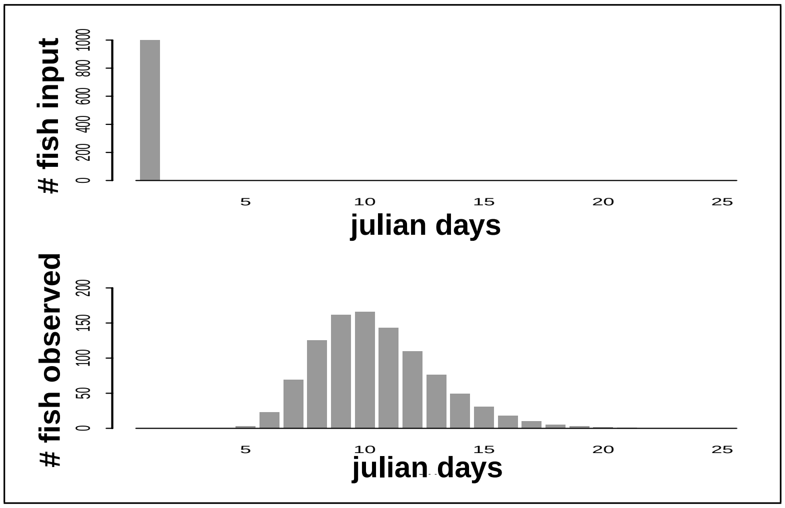

Fig. 27 Plots of a single iteration of the travel time algorithm through a single reach. 1000 fish released at the upstream node are distributed through time at the next downstream node. Parameter: $r = 10$, $\sigma = 8$, $L = 100$.

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[1] As configured, the **columbia.desc** file defines three species: chinook 1 = spring (yearling) chinook, chinook 0 = fall (subyearling) chinook, and steelhead.

II.4 - Reservoir Survival

The main component of fish mortality in the reservoirs is the predation rate. The predation rate is dependent on factors such as the number and behavior of predators, size of prey, genetic disposition of prey, disease, stress from dam passage, and degree of smoltification. The theory presented below approximates the mortality processes in the reservoirs. The CRiSP.1 model incorporates some of the details of the interactions of the various factors in mortality in further modeling the predation rate. The included factors are pictured in (Fig. 28). In the model, we further partition the reservoir into forebay, tailrace and reach (also called reservoir) segments for the purpose of travel time and mortality modeling.

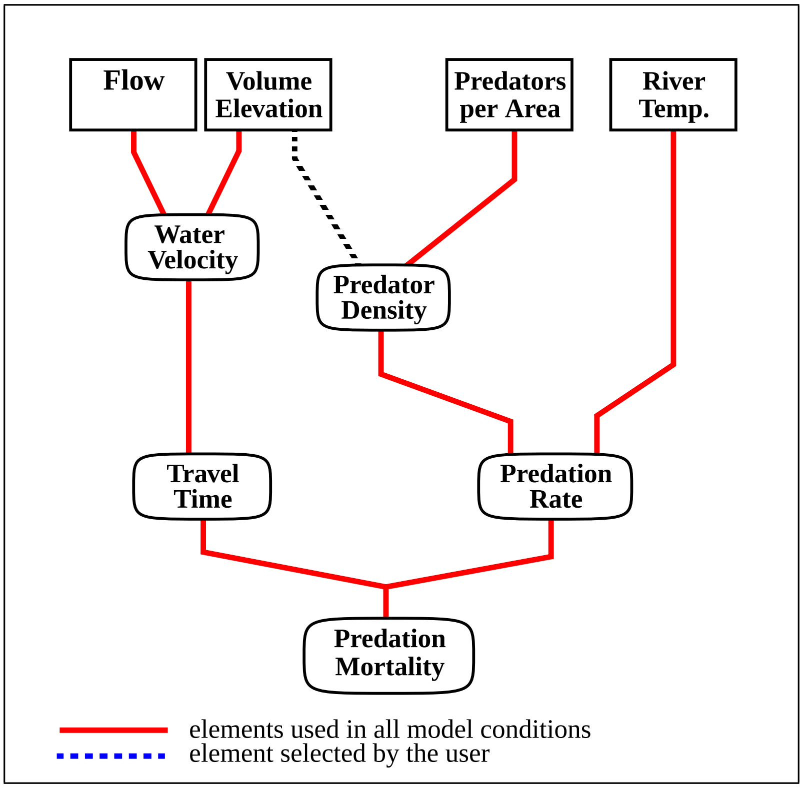

Fig. 28 Elements in reservoir mortality algorithm

II.4.1 - Theoretical Framework

The theoretical framework for describing reservoir mortality in the current model uses the time fish spend in a river segment and the rate of mortality in that segment. The basic equation describing the rate of mortality as a function of time is:

$$\frac{dS}{dt} = -\varphi S \tag{54}$$

where

- S = measure of smolt density in the river segment and can be taken as the total number in the segment
- φ = mortality rate from all causes.

In the present model, two causes of mortality are identified: predation and gas bubble disease. CRiSP.1 assumes the rates of each are independent and this is expressed by the equation:

$$\frac{dS}{dt} = -\varphi S = -(M_p + M_{tdg})S \tag{55}$$

where

- M_p = mortality rate from predation with units of time^{-1}
- M_{tdg} = mortality rate from total dissolved gas supersaturation with units of time^{-1}
- S = number of smolts leaving reservoir per day (smolts reservoir $^{-1}$)
- φ = combined mortality rate as used in eq (54).

Fish enter and leave river segments every day and spend differing amounts of time in a segment as described by the migration equations. Thus, on a given day the group of fish leaving a segment may have entered on different days and thus have different residence time in the segment. To describe the number of fish that survive a river segment on a daily basis CRiSP.1 solves eq (54) for each group, identified by when they entered the segment and when they exited. The solution is:

$$S(t_j|t_i) = S_0(t_j|t_i) \cdot exp\left(-\int_{t_i}^{t_j} \varphi(t)dt\right) \tag{56}$$

where

- S_0 (t_j | t_i) = potential number of fish that enter the segment on day t_i and survive to leave the segment on day t_j
- S (t_j | t_i) = actual number of fish that enter the segment on day t_i and leave on day t_j.

Applying an elementary property of integrals, the integral is expressed:

$$\int_{t_i}^{t_j} \varphi(t)dt = \int_{0}^{t_j} \varphi(t)dt - \int_{0}^{t_i} \varphi(t)dt\,. \tag{57}$$

In general, the numerical form of the integral is:

$$\int_{0}^{t_j} \varphi(t)dt = \sum_{k=0}^{j} \varphi(t)(t_k)\Delta t \tag{58}$$

where

- Δt = reservoir computational time increment.

The resulting equation for the number of fish passing through each river segment as a function of when it entered the segment is expressed:

$$S(t_j|t_i) = S_0(t_j|t_i) \cdot exp\left(-\sum_{k=0}^{j} \varphi(t_k)\Delta t + \sum_{k=0}^{i} \varphi(t_k)\Delta t\right). \tag{59}$$

The input term S_0 (t_j | t_i) expressing the potential number that exit on day t_j given then entered the segment on day t_i can be expressed:

$$S_0(t_j|t_i) = N(t_i) \cdot \Delta P(t_j|t_i) \tag{60}$$

where

- N (t_i) = number of fish that enter the river segment on day t_i
- ΔP (t_j | t_i) = probability that a fish entering on day t_i survives to exit on day t_j (defined by eq (46) on page 38).

II.4.2 - Predation Mortality

Predation mortality rate in CRiSP.1 is dependent on predator abundance (density), predator temperature response, and a predator activity coefficient. These factors combine to determine a predation rate *r* which is applied to the smolt population in each time step to determine predation mortality.

Predation occurs in three reservoir zones: forebay, tailrace, and mid-reservoir. Each zone has its own predator abundances, which vary from project to project, and predator activity coefficients, which are set system-wide via the calibration process. The predation mortality is then a function of predation rate and exposure time.

Predator abundances may vary yearly and are based on predator index studies (Beamesderfer and Rieman 1988; Rieman et al. 1991; Ward et al. 1995). The major predator is the northern pikeminnow[1] (*Ptychocheilus oregonensis*), which accounts for approximately 78 percent of the predation mortality (Rieman et al. 1991). The abundances of other major predators—walleye and smallmouth bass—are converted into northern pikeminnow equivalents via their consumption rates. The effects of the predator removal program on pikeminnow populations have been accounted for from 1991 on.

The *predator temperature response function* determines maximum consumption rates as a function of temperature and is based on laboratory experiments by Vigg and Burley (1991). The parameters in the temperature response function are set during the calibration process (calibration of CRiSP.1 to NMFS survival estimates). Thus, the predator temperature response may account also for response of the prey species in the model to variation in temperature.

The *predator activity coefficient* scales the maximal consumption rate to represent *in situ* conditions where predator-prey encounters may be less frequent, alternative prey may exist, and predators may not be feeding to satiation. As stated above, this coefficient varies by reservoir zone to account for the differences in predator-prey behavior in each zone.

General Model

The predation rate is assumed to be proportional to predator abundance and consumption rate. Consumption rate is scaled by the temperature response function, with consumption increasing with higher water temperature. The general form of the predation rate in the ***i***th zone (forebay, tailrace, or reach) for the ***j***th project is:

$$r_{ij}(T) = \alpha_i \cdot P_{ij} \cdot f(T) \tag{61}$$

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[1] Northern pikeminnow were formerly known as northern squawfish.

where

- T = temperature (˚C)
- P_{ij} = the predator density in the ith zone (forebay, tailrace, or reach) for the jth project
- a_i = the predator activity coefficient in the ith reservoir zone
- $f(T)$ = the temperature response equation.

The predation survival is determined from the predation rate in each time step as follows:

$$S_{ij} = e^{-r_{ij}t} \tag{62}$$

where t is time (in days).

For the temperature response function, the sigmoidal form (reparameterized) from Vigg and Burley (1991) is employed:

$$f(T) = C_{MAX}/(1 + \exp(-\alpha_T(T - T_{INF}))) \tag{63}$$

where

- C_{MAX} = the maximum consumption rate
- α_T = a slope parameter
- T_{INF} = the inflection point of the curve.

With this equation, predation rate approaches its maximal rate at higher temperatures. An example of equation (63) fit to data from Vigg and Burley (1991) is shown in Fig. 29.

Table 11 Summary of the forms of the predation mortality rate equation

Reservoir zone	α	applied
forebay, mid-reservoir	α_f, α_r	per time step
tailrace	α_t	per tailrace

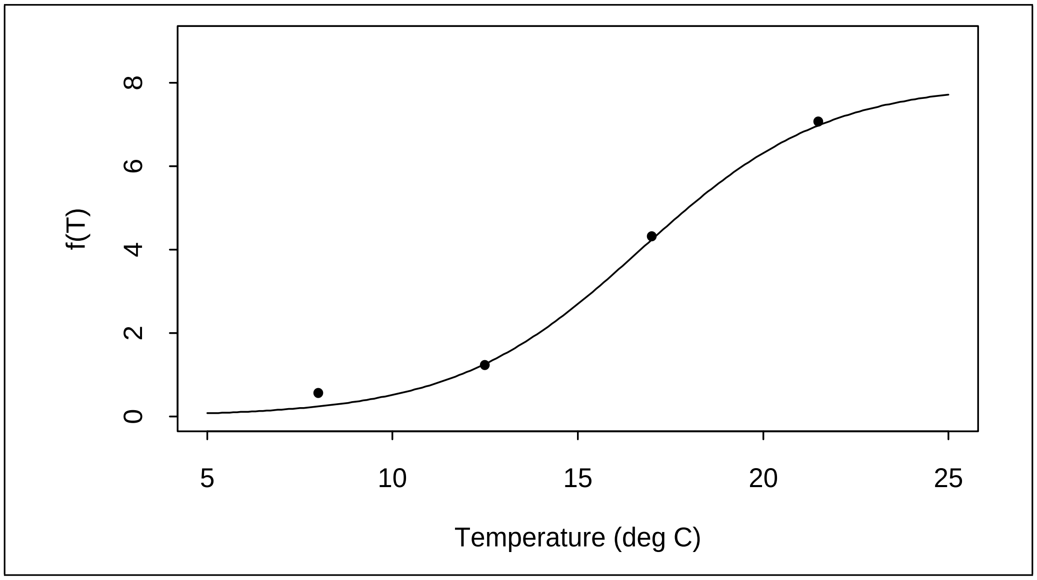

Fig. 29 Equation (63) fit to data from Vigg and Burley (1991) with C_{MAX} = 8.0, α_T = 0.40, and T_{INF} = 16.7. Note that each point represents the mean from 11 to 22 replicates.

The old (exponential) form of the temperature response function is also available, but it is no longer supported in the calibration. The exponential form is:

$$f(T) = ae^{bT} \quad . \tag{64}$$

This form may be reasonable for the spring migration period where higher temperatures are not encountered.

As formulated in equation (61), predation rate is dependent on predator abundance but not on smolt abundance. Thus with a given predator density and temperature, mean predator consumption rate is linearly related to smolt abundance. This is consistent with data provided by Vigg (1988) except at extremely high smolt abundances, which represent only a few points out of hundreds. The Vigg (1988) study was conducted in the tailrace.

Note also that the CRiSP.1 predation algorithm is very similar to the RESPRED model as described by Beamesderfer et al. (1990). One difference is that RESPRED has a type III functional response of predators on prey, i.e., consumption rate tails off at high prey abundances. Also, RESPRED uses a gamma distribution for the temperature response function instead of the sigmoidal one utilized by CRiSP.1.

Zone Specific Formulations of the Predation Model

As noted above, the predation equation (61) varies according to reservoir zone (forebay, tailrace or mid-reservoir). The forebay and mid-reservoir predation models are based on exposure time as calculated from the migration submodel. Tailrace residence times tend to be very short, so we have assumed one time step residence and have calibrated the model with that in mind.

Another type of model would incorporate exposure (travel) distance as well as exposure time. The tailrace predation model can be thought of as a travel distance based predation model.

Predator Abundance

Predator abundances (as relative predator densities) are needed for each zone of each reservoir. These abundances are based on the predator index studies performed by the Oregon Department of Fish and Wildlife and the Washington Department of Fish and Wildlife (Ward et al. 1995; Zimmerman and Parker 1995). The major piscivorous predators on juvenile salmonids are northern pikeminnow (*Ptychocheilus oregonensis*) formerly known as northern squawfish, smallmouth bass (*Micropterus dolomieu*), and walleye (*Stizostedion vitreum*). Abundances for these predators were based on mark-recapture studies in John Day Pool from 1983-1986 (Beamesderfer and Rieman 1991). For pikeminnow, predator index data from 1990-1991 were used as base abundances because the predator removal program had little or no effect in those years. Bass and walleye abundances were converted to *pikeminnow equivalents* based on their consumption rates relative to pikeminnow consumption rates (see Table 16) (Vigg et al. 1991).

The abundance data should be considered in a *relative* sense because abundances based on the mark-recapture studies have very broad confidence intervals (Beamesderfer and Rieman 1991), and the predator index are not intended to provide *absolute* abundances (Ward et al. 1995; Zimmerman and Parker 1995). The purpose of the predator index studies was to gauge relative differences in predator abundances among reservoirs and within reservoir zones. This is how this information is utilized in CRiSP.1.

In CRiSP.1, the temperature response function parameter C_{MAX} has the effect of scaling predation rate up or down such that model-predicted survivals are consistent with observed survivals (NMFS survival estimates). See Section III.3 Predation Rate Parameter Calibration on page 142 for the full explanation. This can be thought of as a scaling of the relative predator abundances to reflect the actual predator abundances.

Outline of Calculations for Predator Abundance

Outline of steps:

1. Compute densities in John Day Pool based on 1984-1986 mark-recapture data and relative abundances in different reservoir zones (for each species).
2. Calculate CPUE[1] -> density conversion factors.
3. Estimate densities in other reservoirs/zones based on CPUE data. For some zones, pikeminnow abundance indices must be converted to CPUE based on linear regression of CPUE vs. indices in cases where both are available.
4. Convert smallmouth bass and walleye to “pikeminnow equivalents” based on relative consumption rates. These densities are different for spring and fall migrations due to seasonal differences in consumption rates by the predators. The CPUE is then multiplied by 1080 to convert to density (based on John Day population estimates).

Mean population abundances (1984-1986) in John Day Pool for the three predator species are provided in Table 12. Information and interim calculations are provided in Tables 13 - 21. Table 22 gives the resulting densities for spring and fall migrations. It also gives the pikeminnow percentage, which is needed when accounting for results of the pikeminnow removal program.

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[1] Catch per unit effort

Table 12 Population abundance estimates for John Day Pool, 1984-1986 (Beamesderfer and Rieman 1991); the 95% confidence intervals are in parentheses.

N. Pikeminnow (>250 mm)	Smallmouth Bass (>200 mm)	Walleye (>250 mm)
85,316 (65,693-106,645)	34,954 (35,166-44,741)	15,168 (6,067-32,914)

Table 13 Northern pikeminnow density and distribution in John Day Pool, based on 1990-1991 CPUE data, assuming total abundance the same as 1984-1986.[a]

Pikeminnow	Reservoir Zone				Total
	John Day Forebay	Mid-Reservoir	McNary Tailrace	McNary Tailrace BRZ[b]	
CPUE	0.69	0.25	0.76	16.33	
Area	10.74	186.7	9.7	1.07	208.2
rel. abundance	0.094	0.592	0.093	0.221	1.0
abundance	8019.7	50507.1	7934.4	18854.8	85316
density	746.7	270.5	818.0	17621.3	
comb. density	746.7	297.6		17621.3	

a. CPUE mult factor = density/CPUE = 1080.
b. Boat restricted zone.

Table 14 Walleye density and distribution in John Day Pool, 1984-1986; relative densities are mean for 1984-1986 from Beamesderfer and Rieman (1988).

Walleye	Reservoir Zone					Total
	John Day Forebay	Arlington	Irrigon	McNary Tailrace	McNary Tailrace BRZ	
relative density	0.002	0.114	0.305	0.58	0.000	1.0
Area	10.74	117.1	69.6	9.7	1.07	208.2
abundance						15,168
comb. density	0.0	77.2				

Table 15 Smallmouth bass density and distribution in John Day Pool, 1984-1986; relative densities are mean for 1984-1986 from Beamesderfer and Rieman (1988).[a]

Smallmouth Bass	Reservoir Zone					Total
	John Day Forebay	Arlington	Irrigon	McNary Tailrace	McNary Tailrace BRZ	
relative density	0.374	0.289	0.277	0.060	0.0	1.0
Area	10.74	117.1	69.6	9.7	1.07	208.2
rel. abundance	0.070	0.586	0.334	0.010		1.0
abundance	2446.8	20483.1	11674.6	349.5	0.0	34,954
comb. density	227.8	165.5				

[a] For final calculation, forebay and mid-reservoir were averaged (weighted by area) to give a density of 168.8.

Table 16 Mean daily salmonid consumption estimates for the major predators (salmonids predator^{-1} day^{-1}) from Vigg et al. (1991); walleye and smallmouth bass estimates are for the reservoir only.

Month	N. Pikeminnow			Walleye	Smallmouth Bass
	Tailrace	Mid-Reservoir	Forebay		
April	0.123	0.043	0.053	0.021	0.003
May	0.416	0.251	0.280	0.113	0.009
June	0.318	0.086	0.136	0.118	0.019
July	1.950	0.154	0.270	0.447	0.118
August	0.350	0.094	0.130	0.232	0.070

Table 17 Consumption rates for N. Pikeminnow, Walleye and Smallmouth Bass in John Day Pool, 1984-1986, from Vigg et al. (1991); mean for April-June.

Species	Reservoir Zone		
	Forebay	Mid-Reservoir	Tailrace BRZ
N. Pikeminnow	0.156[a]	0.127	0.330
Walleye	–	0.08	–
Smallmouth Bass	0.010[b]	0.010	–

[a] Mean from Table 16 for April - June.
[b] Assumed to be same as reservoir consumption rate.

Table 18 Consumption rates for N. Pikeminnow, Walleye and Smallmouth Bass in John Day Pool, 1984-1986, from Vigg et al. (1991); mean for July-August.

Species	Reservoir Zone		
	Forebay	Mid-Reservoir	Tailrace BRZ
N. Pikeminnow	0.20[a]	0.124	1.21
Walleye	–	0.34	–
Smallmouth Bass	0.094[b]	0.094	–

[a] Mean from Table 16 for July - August.
[b] Assumed to be same as reservoir consumption rate.

Table 19 Pikeminnow density indices (CPUE) in all reservoir zones, 1990-1991

Reservoir Zone		CPUE	Ref
Bonneville	tailrace	6.30	c
	tailrace BRZ	16.35	c
	forebay	5.71	a
	mid-reservoir	2.102	a
The Dalles	tailrace	0.512	a
	tailrace BRZ	5.47	a
	forebay	1.104	a
	mid-reservoir	1.61	d
John Day	tailrace	2.75	a
	tailrace BRZ	21.54	a
	forebay	0.69	c
	mid-reservoir	0.25	c
McNary	tailrace	0.76	c
	tailrace BRZ	16.33	c
	forebay	0.17	c
	mid-reservoir	0.51	d
	upper reservoir	0.89	d
Ice Harbor	tailrace	0.45	d
	tailrace BRZ	8.42	d
	forebay	0.08	e
	mid-reservoir	0.30	e

Table 19 Pikeminnow density indices (CPUE) in all reservoir zones, 1990-1991

Reservoir Zone		CPUE	Ref
Lower Monumental	tailrace	0.76	e
	tailrace BRZ	1.30	e
	forebay	0.67	e
	mid-reservoir	0.83	e
Little Goose	tailrace	1.52	b
	tailrace BRZ	16.31	b
	forebay	0.64	e
	mid-reservoir	0.39	e
Lower Granite	tailrace	1.63	b
	tailrace BRZ	28.29	b
	forebay	0.48	e
	mid-reservoir	0.17	e
	upper reservoir	1.86	b
Hanford Reach	(Priest Rapids) tailrace	2.85	f
Priest Rapids	tailrace BRZ	6.28	g
	forebay	1.62	g
	mid-reservoir	0.97	f
Wanapum	tailrace BRZ	11.33	g
	forebay	1.32	g
	mid-reservoir	2.82	f
Rock Island	tailrace BRZ	20.20	g
	forebay	.66	g
	mid-reservoir	2.27	f
Rocky Reach	tailrace BRZ	1.62	g
	forebay	9.0	g
	mid-reservoir	2.38	f
Wells	tailrace BRZ	1.50	g
	forebay	1.50	g
	mid-reservoir	1.26	f

Table 19 Pikeminnow density indices (CPUE) in all reservoir zones, 1990-1991

Reservoir Zone		CPUE	Ref
Chief Joseph	tailrace BRZ	1.47	g

a. 1990 CPUE data (Zimmerman et al. 1997)
b. 1991 CPUE data (Zimmerman et al. 1997)
c. mean 1990 and 1991 CPUE data (Zimmerman et al. 1997)
d. CPUE estimated from 1990 density index (Ward et al. 1993)
e. CPUE estimated from 1991 density index (Ward et al. 1993)
Linear regressions for estimating CPUE's from density index based on reciprocal square root zero catches: $R^2 = 0.818$ (intercept = -3.11, slope = 3.13, $p < 0.001$) for index < 1.6; $R^2 = 0.711$ (intercept = -7.64, slope = 7.44, $p < 0.01$) for index > 1.6.
f. 1993 CPUE (Loch et al. 1994)
g. CPUE estimated from 1993 density index (Loch et al. 1994) using linear regression.

Table 20 Relative CPUEs for smallmouth bass and walleye in the Snake and Columbia rivers (standardized to John Day Pool) based on the abundances from Zimmerman and Parker (1995). Raw data from N. Bouwes, ODFW, pers. com. Also given are CPUEs for the upper Columbia (not standardized to John Day Pool) from Loch et al. (1994).

Reservoir	Smallmouth Bass	Walleye
Bonneville	0.69	6.39
The Dalles	0.83	2.88
John Day	1.00	1.00
McNary	0.89	1.11
Ice Harbor	3.93	0.00
L. Monumental	3.87	0.00
Little Goose	4.92	0.00
Lower Granite	11.72	0.00
Hanford Reach (Priest Rapids Tailrace)	0.00	0.21
Priest Rapids	0.45	0.02
Wanapum	0.02	0.06
Rock Island	0.02	0.01
Rocky Reach	0.19	0.13
Wells	0.06	0.05

Table 21 River dimensions for the Snake and Columbia rivers (Ward et al. 1995) and for the upper Columbia River (Loch et al. 1994). Tailrace (at the head of the reservoir) is assumed to be 0.6 km in length; forebay is assumed to be 6.0 km in length.

	length (km)	avg. width (km)	total S.A. (km^2)	S.A. tailrace (km^2)	S.A. forebay (km^2)	S.A. reservoir
Bonneville	74.3	1.37	101.79	0.82	8.22	92.75
The Dalles	38.5	1.42	54.67	0.85	8.52	45.30
John Day	122.9	1.79	219.99	1.07	10.74	208.18
McNary	52.0	1.58	82.16	0.95	9.48	71.73
Snake R. below Ice Harbor	16.0	0.61	9.76	0.37		9.76
Ice Harbor	51.3	0.61	31.29	0.37	3.66	27.26
L. Monumental	46.2	0.58	26.80	0.35	3.48	22.97
Little Goose	59.9	0.51	30.55	0.31	3.06	27.18
Lower Granite	85.3	0.64	54.59	–	3.84	50.37

Table 21 River dimensions for the Snake and Columbia rivers (Ward et al. 1995) and for the upper Columbia River (Loch et al. 1994). Tailrace (at the head of the reservoir) is assumed to be 0.6 km in length; forebay is assumed to be 6.0 km in length.

	length (km)	avg. width (km)	total S.A. (km^2)	S.A. tailrace (km^2)	S.A. forebay (km^2)	S.A. reservoir
Columbia R. below P.R. Dam	46.2	0.87	40.19	0.95		39.67
Priest Rapids	29.0	0.87	25.23	0.52	5.22	19.49
Wanapum	61.1	0.96	58.66	0.58	5.76	52.32
Rock Island	33.8	0.46	15.55	0.28	2.76	12.51
Rocky Reach	67.3	0.55	37.01	0.33	3.30	33.39
Wells	47.0	0.56	26.32	0.34	3.36	22.62

The predator abundance calculations above arrive at the predator densities shown in Table 22. As stated earlier, the densities are considered to be *relative*, that is they provide a relationship between densities from one zone to the next. They are not intended to be absolute predator densities.

The difference between spring and fall densities stems from the differences in per predator consumption rates in those periods (see Tables 17 and 18). These densities are the *base* densities for 1990 and prior years. For subsequent years, adjustments are made as a result of the pikeminnow removal program.

Table 22 1990 predator densities for spring (SP) and fall (FA) migrations, by reach and zone. Pikeminnow fraction (% PM) are given for Snake and lower Columbia reaches that are subjected to the pikeminnow removal program.

Reach	Zone	Density (SP)	% PM (SP)	Density (FA)	% PM (FA)
Estuary	mid-res.	2137.73	0.853	3314.1	0.551
Jones Beach	mid-res.	2008.13	0.844	3184.5	0.532
Columbia Gorge	mid-res.	1835.33	0.829	3011.7	0.506
Bonneville Tailrace	mid-res.	7123.91	0.955	8244.91	0.825
Bonneville Dam	tailrace	17658.0	1.0	17658.0	1.0
Bonneville Dam	forebay	6173.27	0.998	6221.54	0.991
Bonneville Pool	mid-res.	2458.31	0.869	3579.31	0.597
The Dalles Dam	tailrace	5907.6	1.0	5907.6	1.0
The Dalles Dam	forebay	1195.78	0.993	1253.84	0.947
The Dalles Pool	mid-res.	2105.88	0.928	2670.63	0.731
Deschutes Confluence	mid-res.	2105.88	0.928	2670.63	0.731

Table 22 1990 predator densities for spring (SP) and fall (FA) migrations, by reach and zone. Pikeminnow fraction (% PM) are given for Snake and lower Columbia reaches that are subjected to the pikeminnow removal program.

Reach	Zone	Density (SP)	% PM (SP)	Density (FA)	% PM (FA)
John Day Dam	tailrace	23263.2	1.0	23263.2	1.0
John Day Dam	forebay	754.57	0.987	824.53	0.903
John Day Pool	mid-res.	353.52	0.824	631.23	0.461
McNary Dam	tailrace	17636.4	1.0	17636.4	1
McNary Dam	forebay	191.94	0.956	254.20	0.722
McNary Pool	mid-res.	616.60	0.893	899.64	0.612
Lower Snake River	mid-res.	894.63	0.941	1345.28	0.626
Ice Harbor Dam	tailrace	9093.6	1.0	9093.6	1
Ice Harbor Dam	forebay	123.25	0.701	398.19	0.216
Ice Harbor Pool	mid-res.	430.23	0.878	880.88	0.429
Lower Monumental Dam	tailrace	1404.0	1.0	1404.0	1
Lower Monumental Dam	forebay	759.89	0.952	1030.63	0.702
Lower Monumental Pool	mid-res.	1034.23	0.950	1478.01	0.664
Little Goose Dam	tailrace	17614.8	1.0	17614.8	1
Little Goose Dam	forebay	737.33	0.937	1081.53	0.639
Little Goose Pool	mid-res.	605.39	0.891	1169.56	0.461
Lower Granite Dam	tailrace	30553.2	1.0	30553.2	1
Lower Granite Dam	forebay	628.30	0.825	1448.21	0.357
Lower Granite Pool	mid-res.	1246.57	0.875	2590.50	0.421
Columbia above confluence	mid-res.	607.8		890.8	
Hanford Reach	mid-res.	3078.0		3078.0	
Priest Rapids Dam	tailrace	6782.6		6782.6	
Priest Rapids Dam	forebay	1779.6		2121.7	
Priest Rapids Pool	mid-res.	1099.6		1335.2	
Wanapum Dam	tailrace	12238.6		12238.6	
Wanapum Dam	forebay	1422.9		1437.5	
Wanapum Pool	mid-res.	3088.1		3233.3	
Rock Island Dam	tailrace	21816.5		21816.5	
Rock Island Dam	forebay	719.2		734.4	
Rock Island Pool	mid-res.	2460.1		2491.3	

Table 22 1990 predator densities for spring (SP) and fall (FA) migrations, by reach and zone. Pikeminnow fraction (% PM) are given for Snake and lower Columbia reaches that are subjected to the pikeminnow removal program.

Reach	Zone	Density (SP)	% PM (SP)	Density (FA)	% PM (FA)
Rocky Reach Dam	tailrace	1752.4		1752.4	
Rocky Reach Dam	forebay	9727.0		9871.5	
Rocky Reach Pool	mid-res.	2675.1		3051.5	
Wells Dam	tailrace	1617.1		1617.1	
Wells Dam	forebay	1620.8		1666.4	
Wells Pool	mid-res.	1399.9		1539.2	
Chief Joseph Dam	tailrace	1590.1		1590.1	

For reservoir zones in the model for which no CPUE or predator index information was available, the following assumptions were made about predator density:

- All Clearwater, Salmon, and Snake River reaches above Lower Granite Pool were assumed to have the same density as Lower Granite Pool.
- Deschutes River reaches were assumed to have the same density as The Dalles Pool.
- Reach Wenatchee-Columbia was assumed to have the same density as Rock Island Pool.
- The reaches Wenatchee River, Methow River, Methow Confluence, and Okanogan Confluence were assumed to have the same density as Wells Pool.
- Hells Canyon and Dworshak dams were assumed to have the same forebay and tailrace densities as Lower Granite Dam.
- Chief Joseph Dam tailrace was assumed to have the same density as Wells Dam tailrace.

Predator Removal Adjustments

The predator density estimates in Table 22 are for the years up to and including 1990. For subsequent years, the densities must be adjusted for the predator (pikeminnow) removal program. Table 23 shows the percent reduction in predation due to pikeminnows at each project for each year. Note, this does not directly give the reduction in predator numbers.

To calculate the change in predator numbers due to the estimated change in predation, we use the fact that $e^{-x} \approx 1 - x$ when $x \ll 1$. Recall from equation eq (62) on page 46 that survival in a specific reservoir zone is given by:

$$S = e^{-rt}$$

and that predator density P is a factor in r. Since rt is on the order of 0.05 and predation $Pred = 1 - S$, the percent change in predation is approximately equal to the percent change in predator density:

$$Pred = 1 - e^{-rt} \approx rt \ . \qquad (65)$$

So, to calculate adjusted predator densities, reduce the pikeminnow portion of the predator density from Table 22 by the amount of predation reduction shown in Table 23.

Table 23 Pikeminnow reduction program on the Snake and lower Columbia rivers. Percent reduction in predation due to pikeminnows as a result of the pikeminnow removal program at each reservoir for each year (Peters et al. 1999, 113). Estimates of predation reduction for 2001-2006 are included in Peters et al. (1999, 113).

Reach	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Estuary	0.000	0.029	0.076	0.078	0.120	0.155	0.160	0.141	0.129	0.136
Jones Beach	0.000	0.029	0.076	0.078	0.120	0.155	0.160	0.141	0.129	0.136
Columbia Gorge	0.000	0.029	0.076	0.078	0.120	0.155	0.160	0.141	0.129	0.136
Bonneville Tailrace	0.006	0.029	0.076	0.078	0.120	0.155	0.160	0.141	0.129	0.136
Bonneville Pool	0.006	0.100	0.271	0.185	0.173	0.154	0.148	0.149	0.152	0.151
The Dalles Pool	0.065	0.272	0.274	0.274	0.283	0.309	0.329	0.298	0.305	0.306
Deschutes Confluence	0.065	0.272	0.274	0.274	0.283	0.309	0.329	0.298	0.305	0.306
John Day Pool	0.009	0.125	0.181	0.198	0.186	0.140	0.136	0.099	0.068	0.074
McNary Pool	0.000	0.020	0.016	0.013	0.009	0.007	0.004	0.003	0.001	0.001
Lower Snake	0.000	0.020	0.016	0.013	0.009	0.007	0.004	0.003	0.001	0.001
Ice Harbor Pool	0.000	0.137	0.107	0.080	0.058	0.041	0.027	0.017	0.009	0.004
Lower Mon. Pool	0.000	0.083	0.105	0.099	0.084	0.078	0.054	0.036	0.023	0.031
Little Goose Pool	0.000	0.057	0.129	0.122	0.128	0.115	0.124	0.088	0.061	0.064
Lower Granite Pool	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Predator Density / Reservoir Volume Interaction

Predators may become concentrated in the forebay or tailrace when the depth of the region is decreased by lowering the reservoir. It is possible that concentrating predators increases the encounter rate between predators and prey, and thus effectively increases the mortality rate in the forebay and tailrace.

This mortality increase can be included in CRiSP.1 runs by selecting **predator density/ volume interaction** in the **Runtime Settings** window opened from the **Run** menu. When selected, predator density is a function of pool elevation for reservoir, forebay and tailrace regions. Predator density adjustments to the forebay and tailrace (Fig. 30) are given by[1]:

$$\begin{aligned} P(h) &= P\frac{H}{h} \qquad \text{if} \qquad \frac{h}{H} > 0.05 \\ P(h) &= 20P \qquad \text{if} \qquad \frac{h}{H} \le 0.05 \end{aligned} \tag{66}$$

where

- H = forebay (tailrace) depth at full pool
- h = forebay (tailrace) depth at a lowered pool
- P = predator density at full pool for the forebay (tailrace).

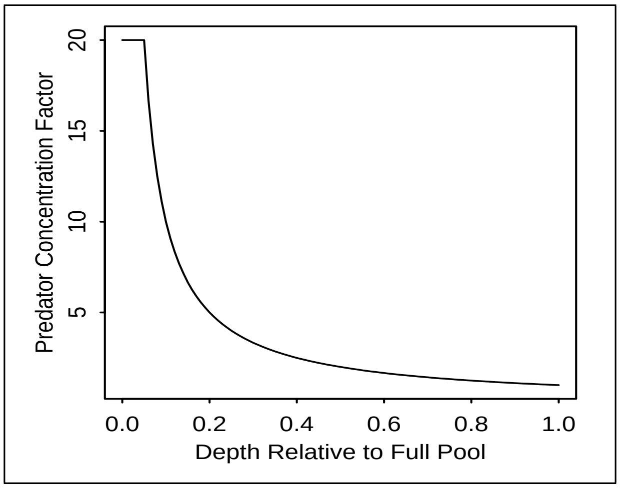

Fig. 30 Predator concentration function at dam

II.4.3 - Supersaturation Mortality

High levels of total dissolved gas in the river lead to the development of gas bubble disease (GBD) in smolts, as well as other aquatic life. This condition involves the formation of bubbles in the organs, tissues, and vascular system of the fish. GBD is also suspected of compromising the fish's vitality by increasing its susceptibility to predators, bacteria, and disease (U.S. Army Corps of Engineers 1994a). Because of the varied symptoms and effects of total dissolved gas, GBD will be considered an independent force of mortality.

There is uncertainty as to the significance of GBD-induced mortality at low levels of supersaturation (<110%); however, it is clear in all studies that as the amount of supersaturation increases (>110%) the rate of mortality increases significantly. The transition between low levels of generally sublethal effects to the higher level lethal condition involves a shift in the bubble-related mechanisms that lead to death. Specifically, at levels of supersaturation below the threshold fish are more susceptible to death related to infection and stress while above the threshold fish experience death from large intravascular bubbles (White et al. 1991).

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[1] The limit $h/H < 0.05$ is arbitrary and required to prevent divide by zero errors. The limit equates to a river depth just over the head of most managers.

Theory

In CRiSP.1, the level of total dissolved gas (TDG) is represented by percent of total dissolved gas saturated in the water above equilibrium (100%). TDG is generated by spill at the dams and then dissipated as the water moves downstream. In the model, the effects of both lethal and sublethal levels of TDG are considered as well as the changes in the effective TDG concentration resulting from depth and distance downstream.

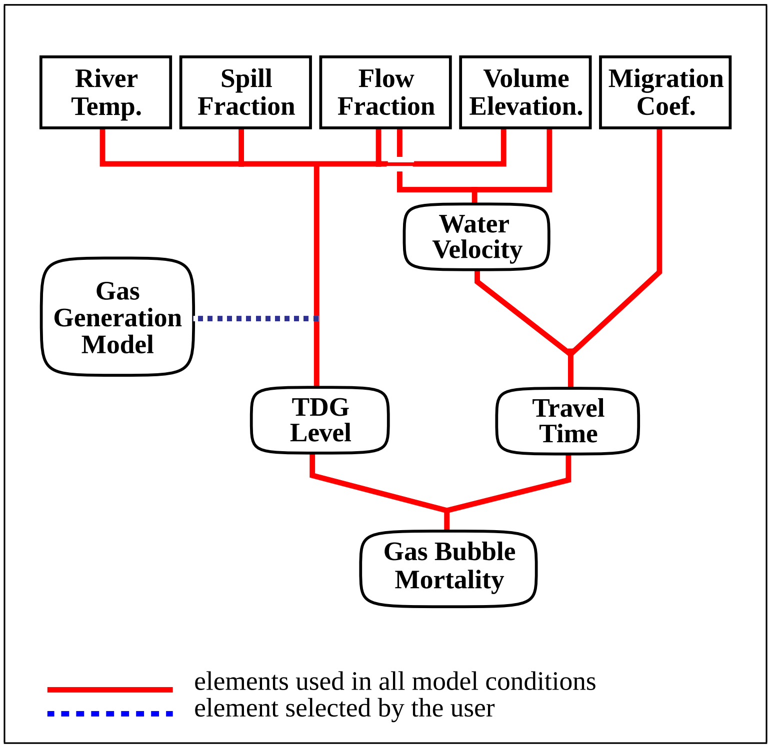

Fig. 31 Factors in gas bubble disease model

The relationship between migration factors and gas bubble disease is illustrated in Fig. 31. TDG supersaturation can be defined with any of the submodels selected from the **TDG Saturation Equations** windows opened from the **Dam** menu.

Gas Mortality Equation

To incorporate both the lethal and sublethal effects of gas bubble disease, the model uses a piecewise linear function that expresses the rate of mortality M_{tdg} as a function of G_s, the level of total dissolved gas above equilibrium (see Fig. 32). This piecewise linear characteristic is accomplished by using the Heaviside function H(), which switches from 0 to 1 as its argument changes from negative to positive. This allows the model to assume a moderate linear increase in mortality (slope a) at low levels of dissolved gas supersaturation. When the lethal threshold of saturation G_c is reached, the Heaviside function turns on and the mortality curve increases linearly with a higher rate (slope $a + b$). Using the work of Dawley et al. (1976), the empirical gas mortality rate equation is:

$$M_{tdg} = a \cdot G_s + b(G_s - G_c) \cdot H(G_s - G_c) \tag{67}$$

where

- G_s = percent TDG above 100% as measured at the surface
- G_c = threshold above 100% at which the gas bubble disease mortality rate is observed to change more rapidly towards more lethal levels
- a = species-specific gas mortality rate coefficient with units of G^{-1} day^{-1} determining the initial rate of increase of mortality per %-increase in TDG
- b = species-specific gas mortality rate coefficient with units of G^{-1} day^{-1}, determining the change in mortality rate at G_c
- H() = Heaviside function, also known as the unit step function; equal to zero when its argument is negative, and equal to one when its argument is positive.

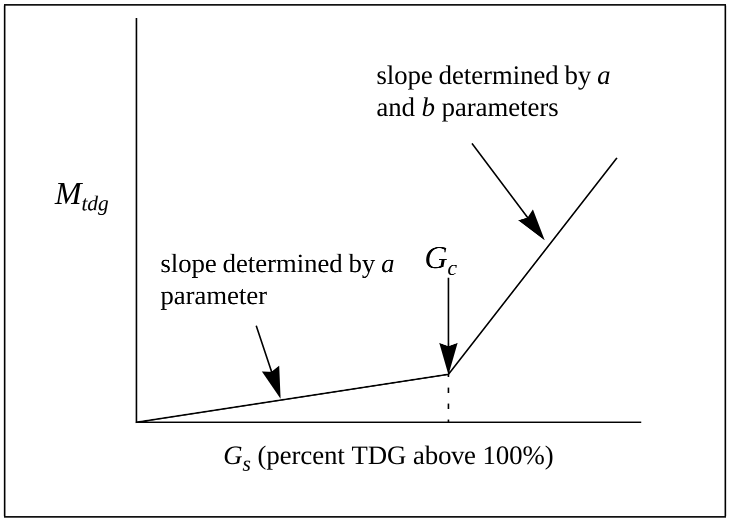

Fig. 32 Illustration of eq (81), the dissolved gas mortality equation

Vertical Distribution

A population of fish from a given species will spread out vertically. A number of distribution functions have been hypothesized (Zabel 1994). For simplicity, CRiSP.1 uses an isosceles triangular distribution given by:

$$\begin{aligned} Dist(z) = H(z_D - z)[m_0 z \cdot H(z) + (m_1 - m_0)(z - z_m) \\ H(z - z_m) - m_1(z - z_b)H(z - z_b)] \end{aligned} \qquad (68)$$

where

- z_D = depth of the reservoir
- z_b = maximum depth of fish distribution
- z_m = mode of fish distribution
- m_0 = slope of distribution function above mode
- m_1 = slope of distribution function below mode.

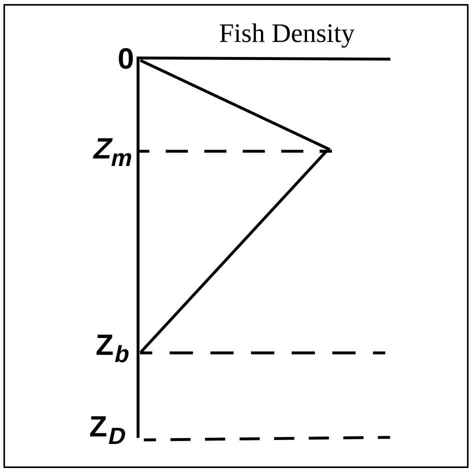

Fig. 33 Illustration of fish depth distribution of fish

The work of Zabel (1994) shows that fish of a given species tend to seek specific depths that are correlated to the level of illumination.

Size / Mortality Relationship

Although no mechanism has been developed justifying a linear relationship, qualitatively the ability of a fish to establish gas equilibrium within its environment should be related to its volume to surface area ratio, which is proportional to fish length. Thus on physical principles of gas exchange, a length relationship should be involved with TDG supersaturation mortality. For a first order estimate of the length relationship to mortality, the regression (illustrated in Fig. 36) is forced through the intercept:

$$M_{tdg}(L) = aL \tag{69}$$

where

- $M_{tdg}(L)$ = TDG mortality rate as a function of fish length
- L = fish length in mm
- a = 0.000472 mm^{-1}, length coefficient for TDG mortality rate (regression of all data from the 112% shallow tank experiments conducted by Dawley et al. (1976))

From eq (69), the TDG mortality rate can be corrected for fish length using:

$$M_{tdg}(L) = M_{tdg}(L_e)\frac{L}{L_e} \tag{70}$$

where

- L = length of fish in environment
- L_e = length of fish in TDG mortality experiments.

Downstream Dissipation

As fish move downstream in a reservoir their mortality rate due to TDG supersaturation generally decreases because dissolved gas levels are highest at the upstream end and dissipate as the water moves downstream. Using the reservoir gas distribution model (see Section II.5

Total Dissolved Gas on page 73), the saturation level is expressed differently for each side of the river:

$$G_{right} = [G_{mix} - E + G_{dif} \cdot (1 - S_{fr}) \cdot e^{-\theta x}] \cdot e^{-k \cdot \frac{x}{v}} + E \tag{71}$$

$$G_{left} = [G_{mix} - E - G_{dif} \cdot S_{fr} \cdot e^{-\theta x}] \cdot e^{-k \cdot \frac{x}{v}} + E \tag{72}$$

where

- G_{right} , G_{left} = percent TDG in the flow entering the reach on the respective sides
- S_{fr} = percent of river in the right-bank flow
- G_{mix} = flow weighted average of the TDG values in each flow
- G_{dif} = difference between the original concentrations of the two flows
- E = percent TDG in water at equilibrium, 100% saturation or 0% supersaturation
- θ = diffusion rate constant in units of $(\text{mile})^{-1}$, a model parameter set for each reach.

The dissipation parameter k is defined with respect to time. To express this time-dependent process in spatial coordinates, the time coordinate was transformed to distance downstream using the average velocity in the pool:

$$t = \frac{x}{v} \tag{73}$$

where

- v = average water velocity through the river segment
- x = distance downstream
- t = average water travel-time.

Transforming time to downstream distance using eq (73) defines a new dissipation parameter:

$$l = k/v\,. \tag{74}$$

The surface supersaturation for each side of the river takes on the general form:

$$G_s(x) = [c_1 + c_2 \cdot e^{-\theta x}] \cdot e^{-lx} + E \tag{75}$$

which leads to:

$$G_s(x) = c_1 \cdot e^{-lx} + c_2 \cdot e^{-(\theta + l)x} + E \tag{76}$$

where

- x = distance downstream and $0 \le x \le L$, where L is the pool length (miles)
- $c_1 = G_{mix} - E$
- $c_2 = G_{dif} \cdot (1-S_{fr})$ for the right-bank flow
- $c_2 = -G_{dif} \cdot S_{fr}$ for the left-bank flow (see eq (103) and eq (104) on page 88)

- θ = reservoir mixing coefficient in (miles)$^{-1}$
- E = equilibrium value (0% supersaturation).

Based on work by Fidler and Miller (1994) demonstrating that the critical supersaturation concentration G_c is depth dependent, with G_c increasing as depth increases; CRiSP.1 utilizes a linear relationship $G_c = mz + g_c$ to relate G_c to fish depth. Then the rate of mortality as a function of fish depth and distance downstream can be expressed as:

$$\begin{aligned} M_{n,i} &= a \cdot G_{s,i}(x) \\ &\quad + b \cdot (G_{s,i}(x) - mz - g_c) \cdot H(G_{s,i}(x) - mz - g_c) \end{aligned} \tag{77}$$

where

- z = fish depth
- m = a slope parameter
- g_c = critical gas supersaturation at the surface where GBD mortality rate changes more rapidly towards more lethal levels
- n = indexes the julian day
- i = indexes the side of the river.

Thus, there is a different mortality rate on each side of the river.

Integrate for Average Rate through Pool

For each side of the river the mortality rate is first averaged over the depth and length of the pool, and then an average mortality rate per day for the pool is created by calculating the flow weighted average over the two sides of the river. Thus, the average mortality rate for a fish while it is in a pool is given by the equation:

$$\overline{M} = S_{fr} \cdot \overline{M}_1 + (1 - S_{fr}) \cdot \overline{M}_2 \tag{78}$$

where

$$\begin{aligned} \overline{M}_i &= \frac{1}{L}\int_0^{z_D}\int_0^L Dist(z) \cdot \\ &\quad (aG_{s,i}(x) + b[G_{s,i}(x) - m_c z - g_c] \cdot H[G_{s,i}(x) - m_c z - g_c])dxdz \end{aligned} \tag{79}$$

and

- $\overline{M_i}$ = the mortality rate due to gas bubble disease averaged throughout the length and depth of the pool on side i
- i = indexes the side of the river and hence the level of TDG on that side of the river; 1 indexes the right-bank and 2 indexes the left-bank.

Parameter Determination

Gas Mortality Equation

Recall from equation (67), there are two gas mortality rate coefficients:

- a = species-specific gas mortality rate coefficient with units of G^{-1} day^{-1} determining the initial rate of increase of mortality per %-increase in TDG

- b = species-specific gas mortality rate coefficient with units of G^{-1} day^{-1}, determining the change in mortality rate above G_c.

Determination of the gas mortality equation parameters begins with fitting mortality rates of fish exposed to various TDG levels for various lengths of time. The TDG mortality rate equation is given by setting the predator mortality to zero in eq (55) on page 44. The resulting survival equation is:

$$\log S = -M_{tdg} t \tag{80}$$

where

- S = cumulative survival
- M_{tdg} = TDG mortality rate at a specific level of supersaturation
- t = exposure time.

Then the rate of mortality due to supersaturation as a function of time and TDG level can be expressed as:

$$M_{tdg} = -\frac{\log S}{t} . \tag{81}$$

The survival curves provided by Dawley et al. (1976) yielded pairs of (t,S) for varying levels of dissolved gas. Pairs of (G,M_{tdg}) were obtained using each of the data points determined from the graphs. This data and the mortality rate M_{tdg} calculated from (81) are shown in Table 24 and Table 25.

When the mortality rates are known, the a and b parameters follow from simple linear regressions of the mortality rate on the dissolved gas level, allowing for different slopes between the a and b values.

Table 24 Chinook mortality rates based on survival data from Dawley et al. (1976) shallow (0.25m) and deep (2.5m) tank experiments.

%TDG	Days (t)	Chinook 0.25 meters		Chinook 2.5 meters	
		Survival (S)	Mortality rate (M_{tdg})	Survival (S)	Mortality rate (M_{tdg})
105	20	0.99	0.0005	1	0
	40	0.98	0.00051	1	0
	60	0.97	0.00051	0.99	0.00017
	80	0.9	0.0013	0.97	0.00038
	100	0.88	0.0013	0.97	0.0003
	120	0.87	0.0012	0.96	0.00034
110	20	0.97	0.0015	1	0
	40	0.95	0.0013	1	0
	60	0.84	0.0029	0.99	0.00017
	80	0.63	0.0058	0.97	0.00038
	100	0.52	0.0065	0.95	0.00051
	120			0.9	0.00088

Table 24 Chinook mortality rates based on survival data from Dawley et al. (1976) shallow (0.25m) and deep (2.5m) tank experiments.

%TDG	Days (t)	Chinook 0.25 meters		Chinook 2.5 meters	
		Survival (S)	Mortality rate (M_{tdg})	Survival (S)	Mortality rate (M_{tdg})
115	10	0.95	0.0051		
	20	0.84	0.0087	1	0
	30	0.72	0.011		
	40	0.62	0.012	1	0
	50	0.49	0.014		
	60	0.22	0.025	0.97	0.00051
	70	0.12	0.03		
	80	0.08	0.032	0.88	0.0016
	100	0.05	0.03	0.83	0.0019
	120			0.78	0.0021
120	10	0.77	0.026		
	20	0.57	0.028	1	0
	30	0.32	0.038		
	40	0.22	0.038	1	0
	50	0.1	0.046		
	60	0.03	0.058	0.95	0.00085
	70	0.02	0.056		
	80	0.01	0.058	0.71	0.0043
	100			0.64	0.0045
	120			0.58	0.0045
127	10			0.97	0.003
	20			0.88	0.0064
	30			0.7	0.012
	40			0.52	0.016
	60			0.38	0.016
	80			0.1	0.029
	100			0.07	0.027

Table 25 Steelhead mortality rates based on survival data and mortality rates from Dawley et al. (1976) shallow (0.25m) and deep (2.5m) tank experiments.

%TDG	Days (t)	Steelhead 0.25m		Steelhead 2.5m	
		Survival (S)	Mortality rate (M_{tdg})	Survival (S)	Mortality rate (M_{tdg})
105	1	1	0	1	0
	2	1	0	1	0
	3			1	0
	4			1	0
	5	0.96	0.0082	1	0
	6			1	0
	7	0.95	0.0073		
110	1	1	0	1	0
	2	1	0	1	0
	7	0.97	0.0044	0.99	0.0014

Table 25 Steelhead mortality rates based on survival data and mortality rates from Dawley et al. (1976) shallow (0.25m) and deep (2.5m) tank experiments.

%TDG	Days (t)	Steelhead 0.25m		Steelhead 2.5m	
		Survival (S)	Mortality rate (M_{tdg})	Survival (S)	Mortality rate (M_{tdg})
115	1	1	0	1	0
	2	0.95	0.026		
	3	0.7	0.12	1	0
	4	0.58	0.14		
	5	0.48	0.15		
	6	0.41	0.15		
	7	0.37	0.14	0.97	0.0044
120	0.8	0.76	0.34		
	1	0.67	0.4		
	1.2	0.42	0.72		
	1.9	0.060	1.5		
	2			0.99	0.005
	3			0.96	0.014
	7			0.94	0.0088
127	2			0.92	0.042
	3			0.87	0.046
	4			0.82	0.05
	5			0.8	0.045
	6			0.77	0.044
	7			0.75	0.041

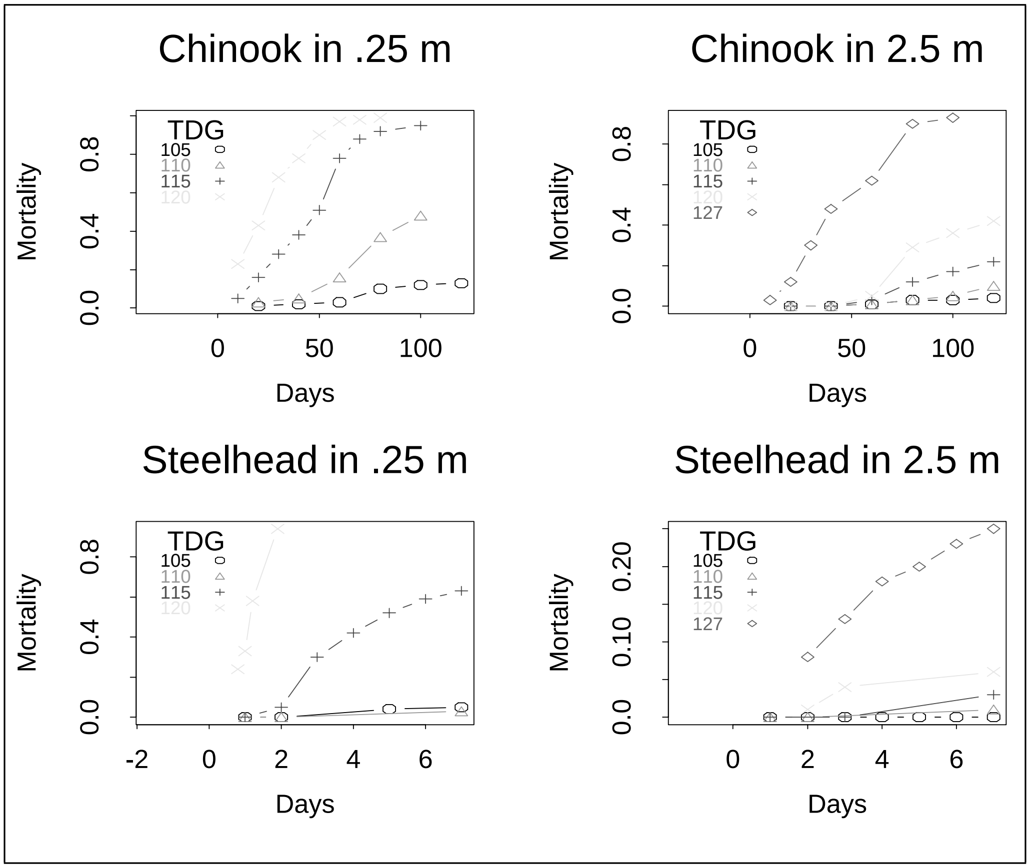

Fig. 34 Chinook and steelhead cumulative mortality from gas bubble disease at different levels of TDG supersaturation. Data points from Dawley et al. (1976).

Depth Dependent Critical Values

Fidler and Miller (1994) and Dawley et al. (1976) demonstrated that the critical supersaturation concentration is depth dependent and increases as depth increases. In other words, fish at lower depths are less susceptible to dissolved gas supersaturation. Based on the mechanisms controlling partial pressures of gas bubbles, the partial pressure increases approximately 10% per meter below the surface (Richards 1965). Fidler and Miller noticed a linear change in the threshold depth for gas bubble trauma symptoms. The slope of this linear relationship is 73.89 mmHg m^{-1}, and given the relationship of TDG to pressure (.1316 %/ mmHg), this equivalent to 9.72 m^{-1} or 2.96 ft^{-1}.

CRiSP.1 utilizes a linear relationship to relate G_{eff} (the effective gas concentration) to fish depth:

$$G_{eff} = G_s - g_{correction} \tag{82}$$

where

- G_s = TDG at the surface
- $g_{correction}$ = TDG experienced by the fish

$$g_{correction} = m \cdot z \tag{83}$$

- z = fish depth
- m = a slope parameter.

When the model is run to obtain a G_{eff} for a stock, eq (82) is multiplied by fish density as a function of depth, and then this term is integrated over the reservoir depth. Effective gas pressures used for the regressions to determine a and b (see eq (67)) were therefore corrected for the depth of the fish in the experimental tanks.

Table 26 Depths of fish in the deep water tanks and $g_{correction}$ used to determine mortality rate coefficients

species	Depth	$g_{correction}$
chinook	1.0m	9.7
steelhead	1.5m	14.6

Size-Mortality Relationship

Experiments conducted by Dawley et al. (1976) demonstrated that large fish have higher levels of mortality. The experiments exposed fall chinook of various sizes to 112% supersaturation in shallow tanks; they determined cumulative mortality curves were significantly different (Dawley et al. 1976, Fig. 10). These data can be used to infer the effect of fish length on TDG mortality in reservoirs since the study also demonstrated that shallow tank mortality curves had the same pattern as deep tank mortalities with higher TDG supersaturation levels. The experiments indicated that mortality curves in shallow tanks at 112% saturation were equivalent to mortality curves in a deep tank with 122% supersaturation.

The resulting mortality-length relationship can be used to extrapolate experimental results to field conditions where the fish are larger. The first step is to determine an empirical relationship relating TDG supersaturation mortality to fish length. This is done by regressing the mortality rates against fish length for the fish in the 112% TDG experiments. Given this relationship, the results of the Dawley fall chinook experiments are extrapolated to fall and spring chinook in the Lower Granite reservoir using different average fish lengths for each stock. The steelhead in the Lower Granite reservoir are treated similarly.

To determine the relationship between fish size and TDG supersaturation mortality, the mortality rate is estimated by fitting eq (69) to cumulative mortality vs. exposure time for different sized fall chinook (Fig. 35). The estimated rates are given in Table 27.

Table 27 Total dissolved gas mortality rates and fish length in shallow tank experiments (Dawley et al. 1976). Plotting symbols refer to Fig. 35.

Species	Plotting Symbols	Length (mm)	Average Mortality Rate
fall chinook	∆	40	0.00364
	+	53	0.0327
	○	67	0.0374

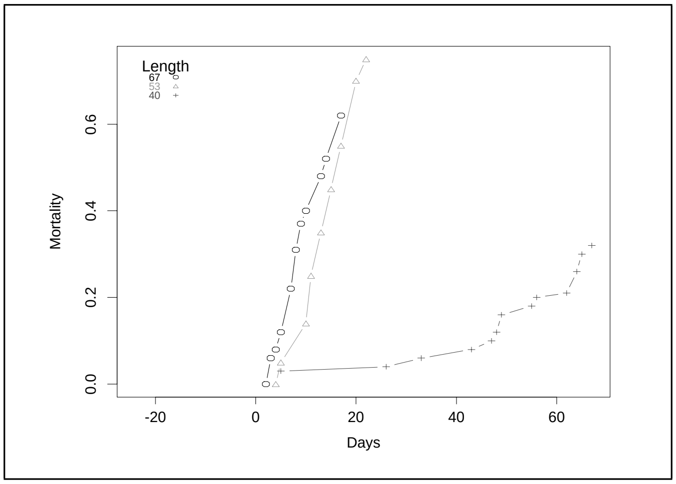

Fig. 35 Cumulative mortality vs. exposure time to TDG supersaturation for different fish lengths.

The resulting mean mortality rates are plotted against fish length in Fig. 36. The slope of the line relating mean mortality rate to length is 0.00126. The regression was not confined to go through zero because Dawley et al. (1976) and Jensen (1986) both report that there is a sensitivity threshold for size.

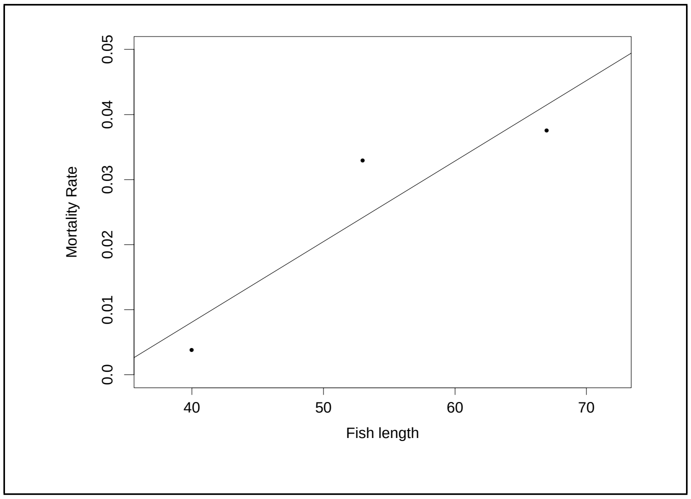

Fig. 36 Mean mortality rate due to TDG supersaturation vs. fish length

Exposure Time Limits

In addition to a threshold for size, there appears to be a threshold for time as well. This suggests that compensatory mechanisms are functional for a period of time and then begin to break down. As a result, fish exposed to high levels of dissolved gas (for up to 2 months or more as in the Dawley experiments) are susceptible to mortality at a higher rate than fish exposed for a short period of time. We restrict the mortality rate data to fish exposed for 40 days or less, on the order of time that the fish are exposed in the river system. This subset of the mortality data is used to determine the TDG mortality coefficients.

Vertical Distribution

The gas bubble disease rate depends on fish depth which is characterized by a mode depth and bottom depth. Fish depths vary continuously over day and night, fish age, and position in the river. For the current model a representative depth is required for each species. The species-specific depth values were selected after reviewing the data on fish vertical distributions. The essential elements and references are given in Table 28.

Table 28 Fish vertical distributions and references

Species	Location	Time	Mode depth	Reference	CRiSP.1 values
spring chinook	Forebay	Day	39 ft 5 ft	Johnson et al. 1985 Ebel and Raymond 1976	mode=12 maximum = 36
	Reservoir	Day	12-24 ft 27-36 ft	Smith 1974 Dauble et al. 1989	
		Night	0-12 ft 27-36 ft	Smith 1974 Dauble et al. 1989	
fall chinook	Forebay	Day			mode=12 maximum = 36
	Reservoir	Day	12-20 ft	Dauble et al. 1989	
		Night	12-20 ft	Dauble et al. 1989	
steelhead	Forebay	Day	13 ft 4 ft	Johnson et al. 1985 Ebel and Raymond 1976	mode=12 maximum = 36
		Night			
	Reservoir	Day	0-12 ft	Smith 1974	
		Night	12-24 ft	Smith 1974	

Mortality Coefficients

Using eq (67) and the Dawley survival data for fish exposed under 40 days (Table 24); the parameters a and b were fit using linear regression. Regression results are summarized in Table 29 and shown in Fig. 37.

Table 29 TDG mortality coefficients

Parameter	Fall Chinook	Spring Chinook	Steelhead
a	0.000018	0.000021	0.000594
b	0.005150	0.005980	0.004820
g_c	10.9	10.9	12.7

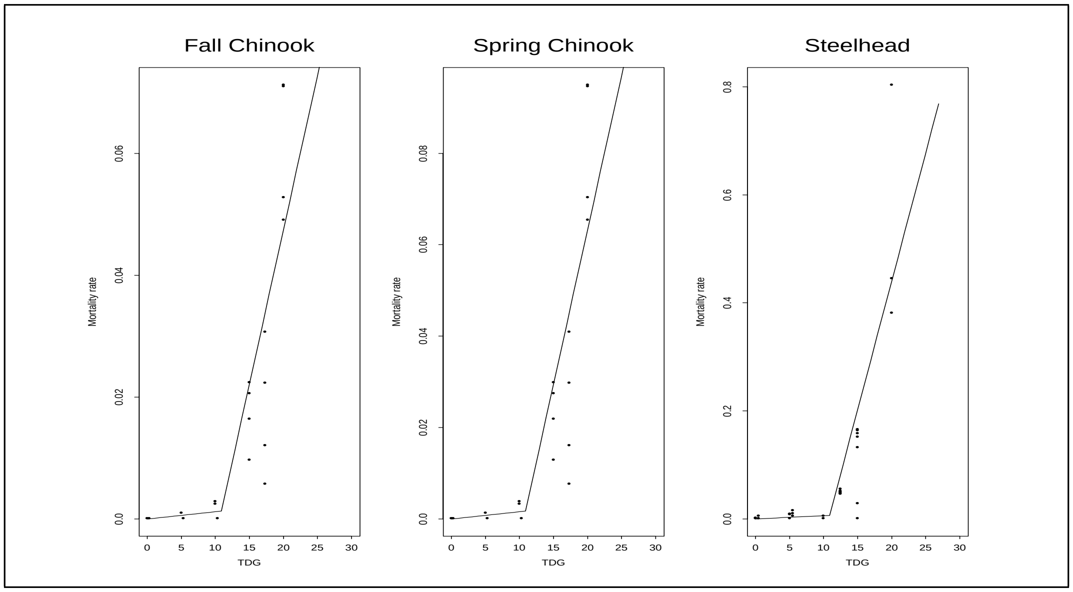

Fig. 37 Fits of mortality rate parameters to mortality rate data corrected for depth and fish length. Data points from Dawley et al. (1976); curve from fit of eq (67). There are extreme points not shown on the steelhead graph.

II.4.4 - Simple Mortality

A number of simple hydrosystem reservoir mortality functions can be selected to represent the equations used the FLUSH spring chinook smolt passage model as part of the Plan for Analyzing and Testing Hypotheses (PATH) (Marmorek et al. 1996). Four models are provided for spring chinook reservoir survival through the hydrosystem.

Simple Mortality

Used in FLUSH up through 1996 for model smolt reservoir survival, which excludes dam passage survival. The model was calibrated with survival studies from Little Goose Dam to The Dalles Dam over the years 1970 and 1973 through 1980. To estimate reservoir survival the dam passage survival was removed by assuming turbine mortality was 15% and bypass and spill mortalities were 2% at all projects. Spill efficiency was assumed to be 1:1 at all projects except at The Dalles Dam where it was 2:1. The equation is:

$$S(t) = \frac{(1+A)\exp(-Bt)}{1+A\exp(-Bt)} \tag{84}$$

where

- $S(t)$ = reservoir survival after t days of migration
- A = 14.07
- B = 0.1822.

Simple TURBx Mortality

The FLUSH spring chinook smolt reservoir survival was changed for PATH analysis from 1997 through 2000. Three different forms of the model were developed depending on assumptions on dam passage mortality in the 1970 through 1980 period. These were designated

TURB1, TURB 4, and TURB5 (Marmorek and Peters 1998). The model calibration is undocumented, but the model equation and parameters were provided by H. Schaller (pers. com.). The equation is:

$$S(t) = \frac{1}{t^{B}(\exp((At) - 1)) + 1} \tag{85}$$

where

- $S(t)$ = reservoir survival after t days of migration
- A = 6.73 e-06 (TURB1)
  = 8.623 e-04 (TURB4)
  = 8.87 e-06 (TURB5)
- B = 3.16 (TURB1)
  = 1.43 (TURB4)
  = 3.02 (TURB5).

Note: Recent PIT tag survival studies have invalidated these FLUSH reservoir mortality equations and we recommend against using them for model analysis. They are presented to document use in the FLUSH model in PATH.

II.5 - Total Dissolved Gas

II.5.1 - Introduction

In a riverine environment, total dissolved gas at equilibrium should be in relative balance with the atmospheric pressure. Natural sources, such as waterfalls or organic inputs, can cause the level of gas to rise above the equilibrium level. The primary source of dissolved gas supersaturation in the Columbia and Snake rivers is spill from hydroelectric dams. As water flows over the spillway, air becomes entrained by the spill flow. As a result, the river becomes supersaturated in total dissolved gas. Sinks of dissolved gas are relatively insignificant for the Snake and Columbia rivers; therefore, in CRiSP.1, the river never falls below the equilibrium level.

In the model, dissolved gas can enter the system in two ways: 1) at a headwater, representing the amount of gas coming from upstream sources or 2) at a dam, resulting from spill. Headwater input is read into the model from data files. Dissolved gas production at a dam is calculated by the model based on the level of spill. Then dissolved gas is propagated downstream with the water according to a system of reach dynamics (see Section II.5.4 Reservoir Dissolved Gas Distributions on page 87).

II.5.2 - Gas Production Equations

Theory

For CRiSP.1 version 6, new equations have been implemented for gas production from spill. As a part of the Dissolved Gas Abatement Study conducted by the U.S. Army Corps of Engineers, Waterways Experiment Station (WES) developed these new equations as an improvement over GASSPILL, the previously predominant model for gas production.

The new equations are an empirical fit of spill data and monitoring data collected by the U.S. Army Corps of Engineers. The percent of total dissolved gas (TDG) exiting the tailrace of a dam is predicted as a function of the amount of discharge in kcfs. This level of TDG is not necessarily the highest level of gas reached, but rather the level of gas in the spill water after some of the more turbulent processes have stabilized. The calibration for each dam was fit to the nearest downstream gas monitoring station, which is typically about a mile downstream of the dam.

For the eight lower Snake and lower Columbia dams that were studied by WES, the gas production equations take one of three forms: linear function of total spill, a bounded exponential function of total spill, or a bounded exponential function of the spill on a per spillbay basis. These equations were adopted for all dams in CRiSP.1. See Section III.2 Total Dissolved Gas Calibration on page 135 for more details.

Equations for TDG supersaturation are of two types. One type constitutes empirical equations with no underlying theory, but the equations provide a general fit to observed supersaturation data as a function of spill. The other type constitutes mechanistic equations which define TDG levels in terms of physical processes producing spill. CRiSP.1 contains four empirical models and two mechanistic models. In general, we recommend using the calibrated values for TDG.

TDG Empirical Models

WES Linear Equation

The gas production equation as a linear function of total spill is:

$$G = m \cdot Q_s + b \tag{86}$$

where

- G = percent total dissolved gas saturation above equilibrium (100%)
- Q_s = total amount of spill in kcfs
- m, b = empirically fit slope and intercept parameters.

WES Exponential Equations

The gas production equation as a bounded exponential function of total spill is:

$$G = \mathrm{a} + \mathrm{b} \cdot \exp(c \cdot Q_s) \tag{87}$$

or as a bounded exponential function of the spill on a per spillbay basis is:

$$G = \mathrm{a} + \mathrm{b} \cdot \exp(c \cdot q_s) \tag{88}$$

where

- G = percent total dissolved gas saturation above equilibrium (100%)
- Q_s = total amount of spill in kcfs
- q_s = amount of spill through an individual spillbay
- a,b,c = empirically fit model parameters.

Different day and night spill patterns for adult and juvenile fish passage at the Snake River dams require different production equations. CRiSP.1 is currently configured so that a separate spill pattern, and thus a separate gas production function, for night and for day can be set for each dam. A spill pattern specifies which spill bays are used to discharge flow both in number and position. Once the number of spill gates n for a particular pattern is set, eq (88) is then converted into eq (87) by the relation $q_s = Q_s/n$. This conversion formula assumes that the amount of spill is uniformly distributed among the open spill gates. The model parameters for the day and night gas production can be different for a given dam, reflecting a change in the position or number of gates and hence in the dynamics of gas production.

Empirical Exponential Equation

An empirical TDG supersaturation equation based on an exponential relationship between spill flow and supersaturation in the spilled water can be expressed:

$$G = bQ_s + a(1 - \exp(-kQ_s)) \tag{89}$$

where

- G = percent total dissolved gas saturation above equilibrium (100%)
- Q_s = total amount of spill in kcfs
- a, b and k = coefficients specific to each dam derived from TDG rating curves provided by the Bolyvong Tanovan of the U.S. Army Corps of Engineers.

This alternative exponential equation was first developed and used in CRiSP.1 version 3, and it was retained in version 4 for backward compatibility of models. It is currently used as the backup model when spill exceeds a certain value for certain dams in certain years.

Empirical Hyperbolic Equation

The TDG supersaturation equation data can also be fit with a hyperbolic relationship between spill flow and supersaturation. The relationship is:

$$G = bQ_s + \frac{aQ_s}{h + Q_s} \tag{90}$$

where

- G = percent total dissolved gas saturation above equilibrium (100%)
- Q_s = total amount of spill in kcfs
- a, b and h = coefficients specific to each dam and can be derived from TDG rating curves available from the U.S. Army Corps of Engineers.

Although this submodel can produce a degree of supersaturation at zero spill flow (when h = 0), this does not contribute to supersaturation in the tailrace water since the contribution of spill water to the tailrace is zero with zero spill as is defined in eq (109) on page 90.

TDG Mechanistic Models

The TDG mechanistic models based on the physical process on spilling water and dissolving excess TDG in the tailrace water was developed by Water Resource Engineers, Inc. (Roesner and Norton 1971) for the U.S Army Corps of Engineers. Relevant parameters in the mechanistic submodels are illustrated in Fig. 38.

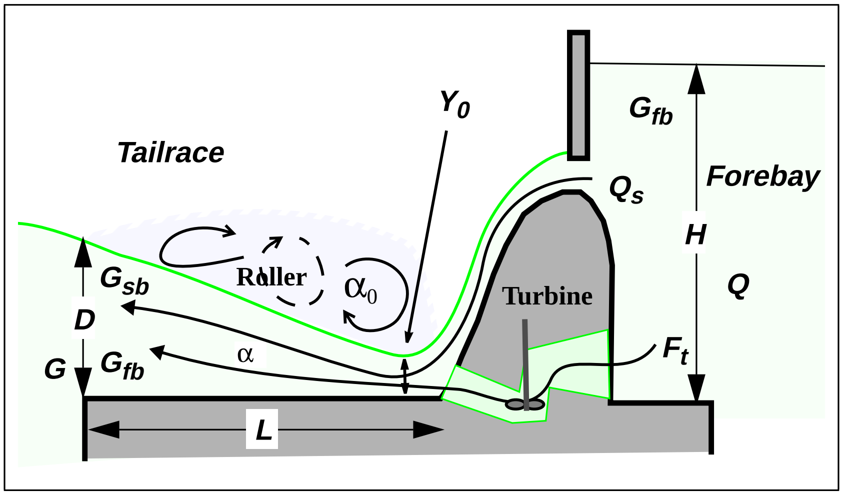

Fig. 38 Representation of spillway and stilling basin.

The mechanistic model begins with an equation for TDG concentration as:

$$G_{sb} = G_{eq} \cdot \bar{P} - (G_{eq} \cdot \bar{P} - G_{fb}) \cdot \exp\left(-\frac{K_e}{Q_s} W L \Delta\right) \qquad (91)$$

where

- Q = total flow in kcfs
- Q_s = spillway flow in kcfs
- G_{sb} = TDG concentration exiting the stilling basin in mg/l
- G_{fb} = TDG concentration in the forebay in mg/l
- G_{eq} = TDG equilibrium concentration as a function of temperature (˚C) at one atmosphere of pressure (mgl^{-1} atm^{-1})

  This is approximated by:

$$G_{eq} = 21.1 - 0.3125 \cdot T \qquad (92)$$

- L = length of the stilling basin in feet
- $\bar{P}$ = average hydrostatic pressure in the main flow of the stilling basin in atmospheres

  This is defined

$$\bar{P} = P_0 + \frac{\alpha_0}{2}(D - Y_0) + \frac{\alpha}{4}(D + Y_0) \qquad (93)$$

- P_0 = barometric pressure in atmospheres (assume P_0 is 1)
- α = density of water (0.0295 atm/ft)
- α_0 = specific gravity of the roller at the base of the spill

  This depends on the degree of aeration of the roller.
- W = spillway width
- D = water depth at the end of the stilling basin
- Y_0 = thickness of the spill at the stilling basin entrance, where

$$Y_0 = \frac{Q_s}{W\sqrt{2gH}} \tag{94}$$

- H = hydraulic head expressing the forebay elevation minus the elevation of the spilling basin floor (H is in ft and gravity constant g is 32 ft s^{-2})
- Δ = differential pressure factor defined

$$\Delta = \left(\bar{P} + \frac{\alpha}{4}(D + Y_0)\right)^{1/3} - \left(\bar{P} - \frac{\alpha}{4}(D + Y_0)\right)^{1/3} \tag{95}$$

- K_e = bubble entrainment coefficient with units of ft s^{-1}atm$^{-1/3}$ and is defined

$$K_e = K_{20}(1.028)^{(T-20)} \tag{96}$$

- T = temperature (˚C)
- K_{20} = temperature compensated entrainment coefficient.

The coefficients are estimated using different relationships depending upon the dam. These are known as GasSpill 1 and GasSpill 2 and are detailed as follows.

GasSpill 1

GasSpill 1 is a three-parameter *multiplicative* model previously used by the U.S. Army Corps of Engineers at Bonneville Dam only. The equation is:

$$K_{20} = 10^a \cdot E^b \cdot p^c . \tag{97}$$

With $c = 0$, this model is identical to the two-parameter multiplicative model developed by Water Resources Engineers (WRE), Inc. (Roesner and Norton 1971).

GasSpill 2

GasSpill 2 is a three-parameter *additive* model previously used by the U.S. Army Corps of Engineers at all other dams. It is defined:

$$K_{20} = a + b \cdot E + c \cdot P \tag{98}$$

where

- E = energy loss rate expressed as total headloss divided by residence time of water in the stilling basin:

$$E = \frac{Q_s}{LWD}(H - D) - \left(\frac{Q_s}{D}\right)^3 \frac{1}{2gL} \tag{99}$$

- P = forebay percent saturation
- a, b, and c = dam dependent empirical coefficients.

II.5.3 - Tailrace Dynamics

Introduction

Extensive field studies led by the U.S. Army Corps of Engineers have provided insights into how dissolved gas exits the dams and is transported downstream. CRiSP.1 now allows for different scenarios on how the spill and powerhouse flows exit a dam.

Flow enters a dam containing a certain amount of dissolved gas (forebay gas level). This flow is routed in part through the powerhouse and the rest through the spillway. Spill produces gas in the tailrace flow that generally exceeds incoming levels, whereas the flow exiting through the powerhouse retains the forebay gas level. The interaction between these two flows in the tailrace is dynamic. Currents can dilute the supersaturated spill by inducing mixing with the less-gassed powerhouse flow or the powerhouse flow can be *entrained* into the spill flow and also become gassed as a result. Varying flow and spill conditions can change the level of entrainment and mixing, as well as the amount of dissolved gas being produced.

In CRiSP.1, both tailrace mixing and entrainment can be specified at a dam. It is likely that some dilution is represented by these coefficients because most of the data used to calibrate the gas production equations came from gas monitoring stations downstream of the spillway. In addition, there is very little data from the powerhouse flow after it exits the dam, so it is also difficult to measure entrainment directly. To avoid over-determination due to too many parameters and too little data, this calibration was kept simple by using an all or nothing approach to mixing in the tailrace based on observations from field studies rather than a statistical fit of the tailrace mixing parameter.

The final measure of CRiSP.1's calibration is the accuracy of the modeled forebay levels. If the amount of gas in the downstream forebay was underestimated then the entrainment function was used to adequately adjust the total amount of gas being added to the system. This was done using the procedure described in Entrainment section on page 81.

Separate Flows

For the majority of dams on the Columbia and Snake rivers, the flows exit the dams as *separate* flows. The spill flow will exit the dam with a dissolved gas value produced from spill. The powerhouse flow will often contain a lower gas level, typically closer to the level of gas in the forebay. This motivated a two-flow model for the river. The two flows are denoted (looking downstream) as "left flow" and "right flow." Currently, only the amount of flow and the dissolved gas level vary between the left and right flows in a reach or at a dam.

For each dam a `spill_side` token and value is designated in the **columbia.desc** file. For example, looking downstream at Ice Harbor Dam, the spillway is on the right side of the dam, so the `spill_side` value is right, and consequently the spill flow is the right flow and the powerhouse flow is the left flow. For some projects, this is a simplified view. In these cases, if a bias in the spill flow exists as it exits the dam then that side was chosen as the `spill_side`. CRiSP.1 assigns `spill_side` to right if the `spill_side` is not designated in the river description file. Table 30 contains the `spill_side` values used by the model.

It should be noted that for some of these dams, there is essentially complete mixing in the tailrace of the two flows and hence both flows will exit the dam with the same dissolved gas level. The `spill_side` in this case will have no real impact. The next section discusses mixing in more detail.

Table 30 Spill side tokens for each dam

Dam	spill side	Dam	spill side	Dam	spill side
Chief Joseph	right	Dworshak	left	McNary	right
Wells	left	Hells Canyon	right	John Day	right
Rocky Reach	left	Lower Granite	right	The Dalles	right
Rock Island	right	Little Goose	right	Bonneville	right
Wanapum	right	Lower Monumental	left		
Priest Rapids	right	Ice Harbor	right		

The spill fraction determines the amount of flow which is attributed to the `spill_side` flow of the river. The amount of dissolved gas in each of the flows depends on several factors: the amount of gas in the forebay of the dam, the amount of gas produced by the spill flow, and the amount of mixing and/or entrainment in the tailrace. Mixing and entrainment are both adjustable by dam and are explained in the following sections. Once mixing and entrainment are applied, a dissolved gas value is determined for each flow and passed as input gas values to the next reach.

Mixing

Theory

In CRiSP.1, for dams where there is a significant amount of mixing in the tailrace, the flows from spill and the powerhouse are averaged according to their flow fractions. The mixed TDG value is contained in both flows upon exiting the tailrace. This has the effect of diluting the spill flow and raising the level of dissolved gas in the powerhouse flow.

To allow for all possibilities between the extremes of separate flows and full mixing, CRiSP.1 includes a mixing coefficient for the dam which determines the amount of mixing to occur between the powerhouse and spill flows before exiting the tailrace of the dam.

Let $G_{dif} = G_{spill} - G_{phouse}$ and $G_{mix} = S_{fr} \cdot G_{spill} + (1 - S_{fr}) \cdot G_{phouse}$, where S_{fr} is the percent of the river in the spill side flow. Then mixing in the tailrace can be expressed by a decay process which decreases the difference between the two gas levels as a function of the mixing parameter set for each dam. At the dam, the spill flow gets the gas level G_{spill} and the powerhouse flow has the gas level of the forebay. Before exiting the tailrace, the difference in gas level between the two flows is decayed. This is represented by replacing G_{dif} with the expression $G_{dif} \cdot \exp(-\theta)$.

After applying the mixing in the tailrace and solving for G_{spill} and G_{phouse}, the exiting gas levels are:

$$G_{spill} = G_{mix} + (1 - S_{fr}) \cdot G_{dif} \cdot \exp(-\theta) \tag{100}$$

$$G_{phouse} = G_{mix} - S_{fr} \cdot G_{dif} \cdot \exp(-\theta) . \quad (101)$$

where

- G_{spill} = percent TDG in the spill side flow exiting the tailrace
- G_{phouse} = percent TDG in the powerhouse side flow exiting the tailrace
- S_{fr} = percent of river in the spill side flow
- G_{mix} = flow weighted average of two gas levels
- G_{dif} = difference between the original concentrations of the two flows.

Given these expressions for mixing, a value of $\theta = 0$ leads to no mixing and the spill flow exits with the gas value generated by the gas production equations and the powerhouse flow retains the forebay gas value. For a value of $\theta = 10$, complete mixing is attained and both flows leave the dam with a gas level of G_{mix}, the flow weighted average of the two gas levels.

Parameter Determination

In the gas production field studies led by the Waterways Experiment Station (1996; 1997a), a significant amount of mixing was observed in the tailraces of The Dalles Dam and Bonneville Dam. For these dams, the gas production equations represent well-mixed powerhouse and spillway flows in the tailrace (U.S. Army Corps of Engineers 1996b). As a result, complete mixing was assumed in CRiSP.1 by setting $\theta = 10$. For the remaining dams on the mainstem Columbia River and lower Snake River, WES's work supported separate spill and powerhouse flows. This is represented by a zero mixing coefficient, $\theta = 0$. For these dams, their gas production equations represent the amount of gas in the spill flow.

On the upper Columbia River according to a field study for Chief Joseph Dam prepared by the Seattle District, U.S. Army Corps of Engineers, the spill and powerhouse flows exit Chief Joseph Dam as separate flows (U.S. Army Corps of Engineers 1998b). Separate flows were assumed for the remaining upper Columbia dams. This is represented by a zero mixing coefficient, $\theta = 0$.

Complete mixing at Dworshak Dam was also assumed based on the steep structure of the dam and its narrow tailrace. This is represented by setting $\theta = 10$.

Table 31 Tailrace Mixing coefficients

Dam	θ	Dam	θ	Dam	θ
CHJ	0	HCY	0	MCN	0
WEL	0	DWR	10	JDA	0
RRH	0	LWG	0	TDA	10
RIS	0	LGS	0	BON	10
WAN	0	LMN	0		
PRD	0	IHR	0		

Entrainment

Theory

Entrainment refers to the phenomena that the powerhouse flow actually becomes entrained by the spill flow and is gassed as a result. In this scenario, the spill TDG levels are not diluted but rather more TDG is added to the system via the powerhouse flow. The entrainment function is an empirical relationship between the total amount of gas added to the powerhouse flow and the amount of flow going over the spillway. The higher the spill the more gas that is added to the powerhouse, with the level of TDG in the exiting powerhouse flow ranging from the forebay TDG level to the TDG level in the spill flow. This relationship was motivated by the heuristic that the greater the amount of spill, the greater the “plunging” force and hence the greater amount of energy in the spill flow. The relationship can be expressed:

$$G_{phouse} = G_{forebay} + (G_{spill} - G_{forebay}) \cdot \exp(-k\_entrain \cdot Q_s) \tag{102}$$

where

- G_{spill} = percent TDG in the spill side flow exiting the tailrace
- G_{phouse} = percent TDG in the powerhouse side flow exiting the tailrace
- $G_{forebay}$ = percent TDG in the forebay
- Q_s = total amount of spill flow.

Parameter Determination

The values for `k_entrain` are estimated annually and represent annual averages. They can be expected to vary from year to year as details of the annual spill patterns and other conditions vary.

Table 32 Estimations of `k_entrain` from CRiSP.1 runs using filtered Columbia River Data Access in Real Time (DART) data (observed and modeled TDG > 100%).

Location	1994	1995	1996	1997	1998	1999
CHJ						0.13
WEL		.143	0.00	.94	1	0.25
RRH		.001	.005	0.00	.002	0.00
RIS		.143	.004	.018	.014	0.00
WAN	.052	.029	0.00	.054	.013	0.13
PRD		0.00	0.22	0.00	0.04	0.00
LWG		.009	.009	.012	.017	0.025
LGS		.143	.96	.555	.802	0.325
LMN		0.00	0.00	0.00	0.00	0.05
IHR		0.00	0.22	0.00	0.004	0.05
MCN		0.00	0.00	0.00	0.00	0.00

Table 32 Estimations of `k_entrain` from CRiSP.1 runs using filtered Columbia River Data Access in Real Time (DART) data (observed and modeled TDG > 100%).

Location	1994	1995	1996	1997	1998	1999
JDA		0.00	0.00	0.00	0.00	0.00
TDA	0.00	0.00	0.00	0.00	0.00	0.00

Modeled forebay levels at Little Goose, Lower Monumental, Wanapum and Priest Rapids dams with and without the entrainment coefficient at the previous dam are shown versus the observed forebay values in Fig. 40-Fig. 42.

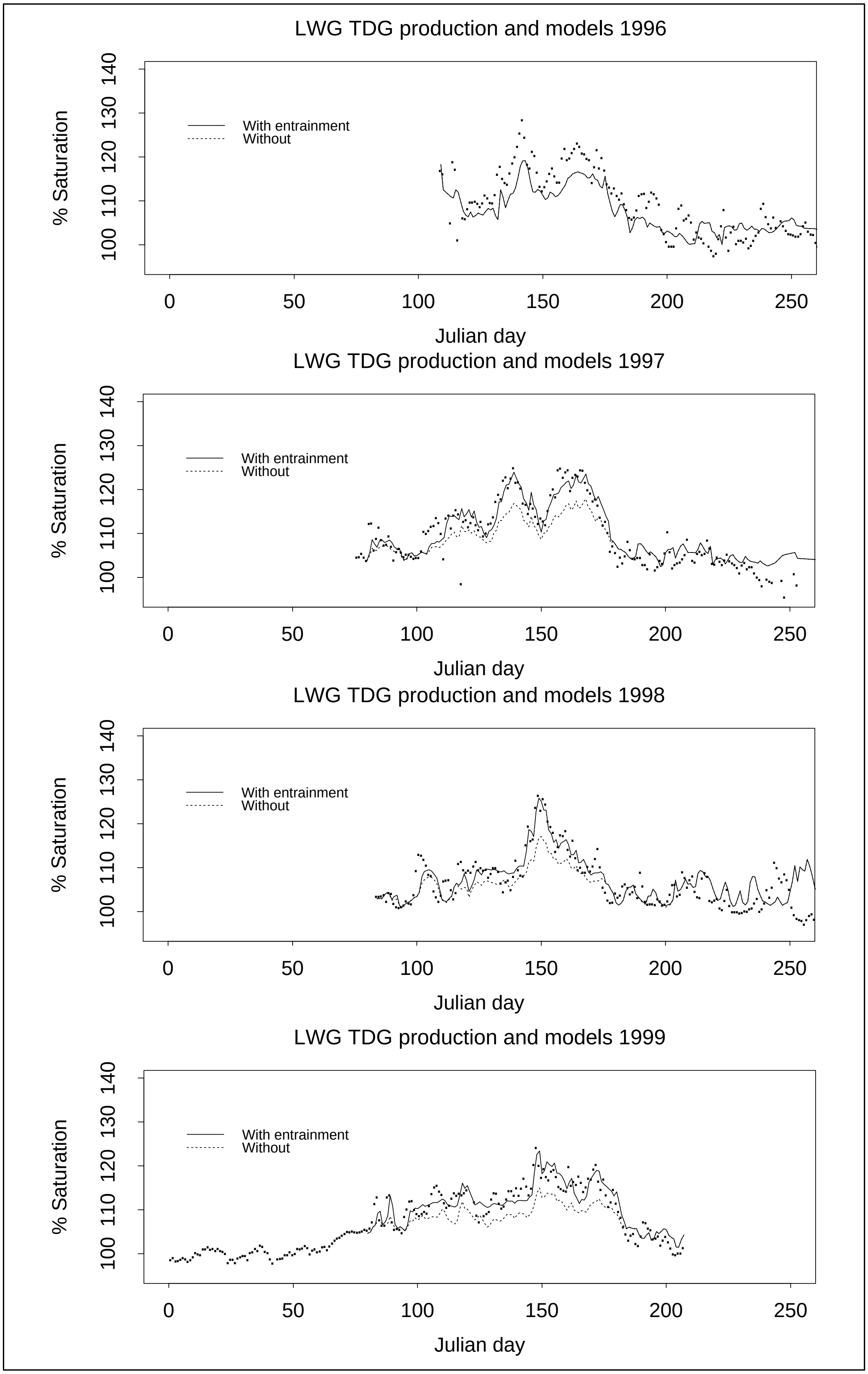

Fig. 39 Lower Granite (LWG) production values with and without entrainment and observed data (points) at Little Goose Forebay.

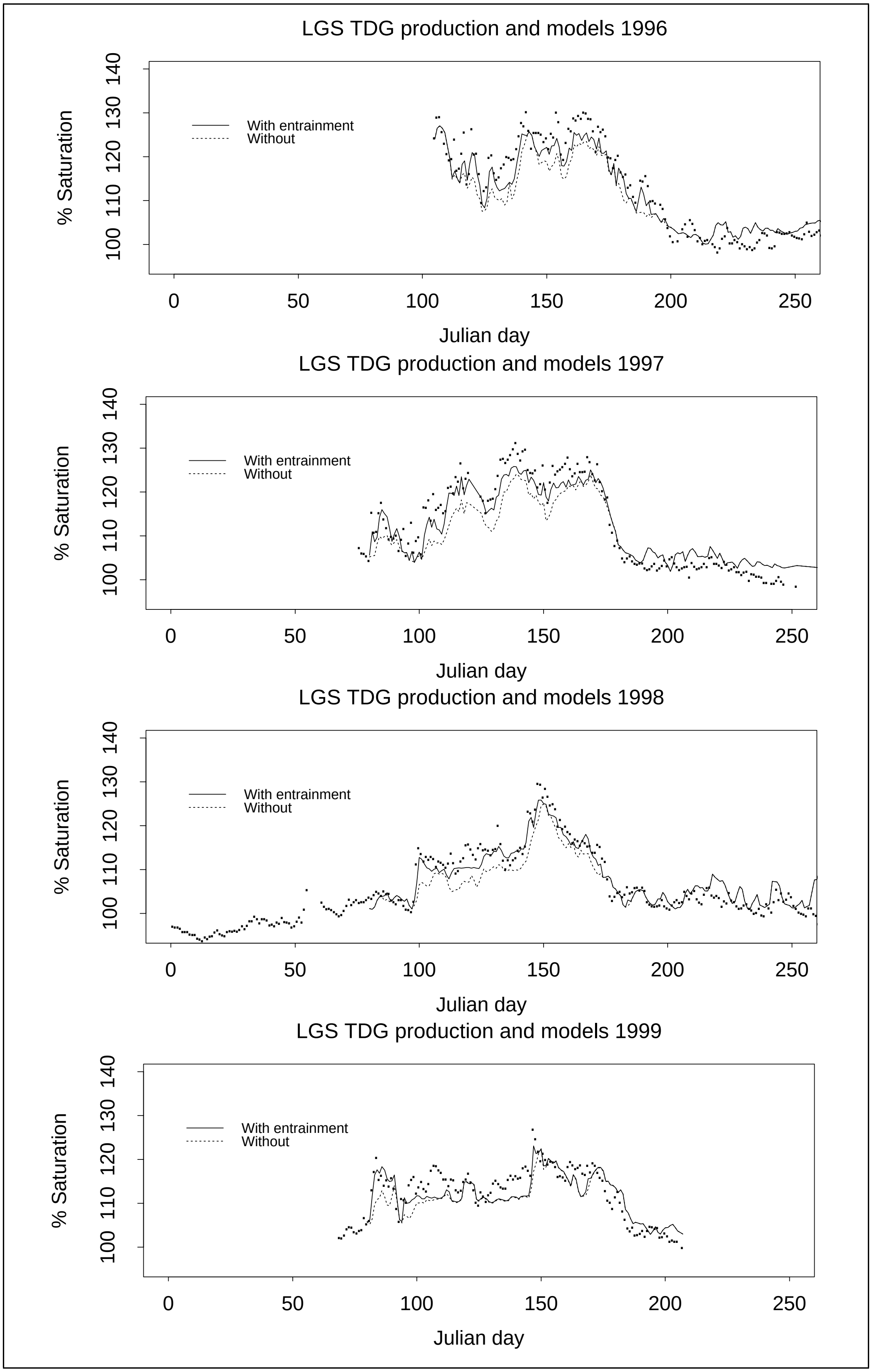

Fig. 40 Little Goose (LGS) production values with and without entrainment and observed data (points) at Lower Monumental Forebay.

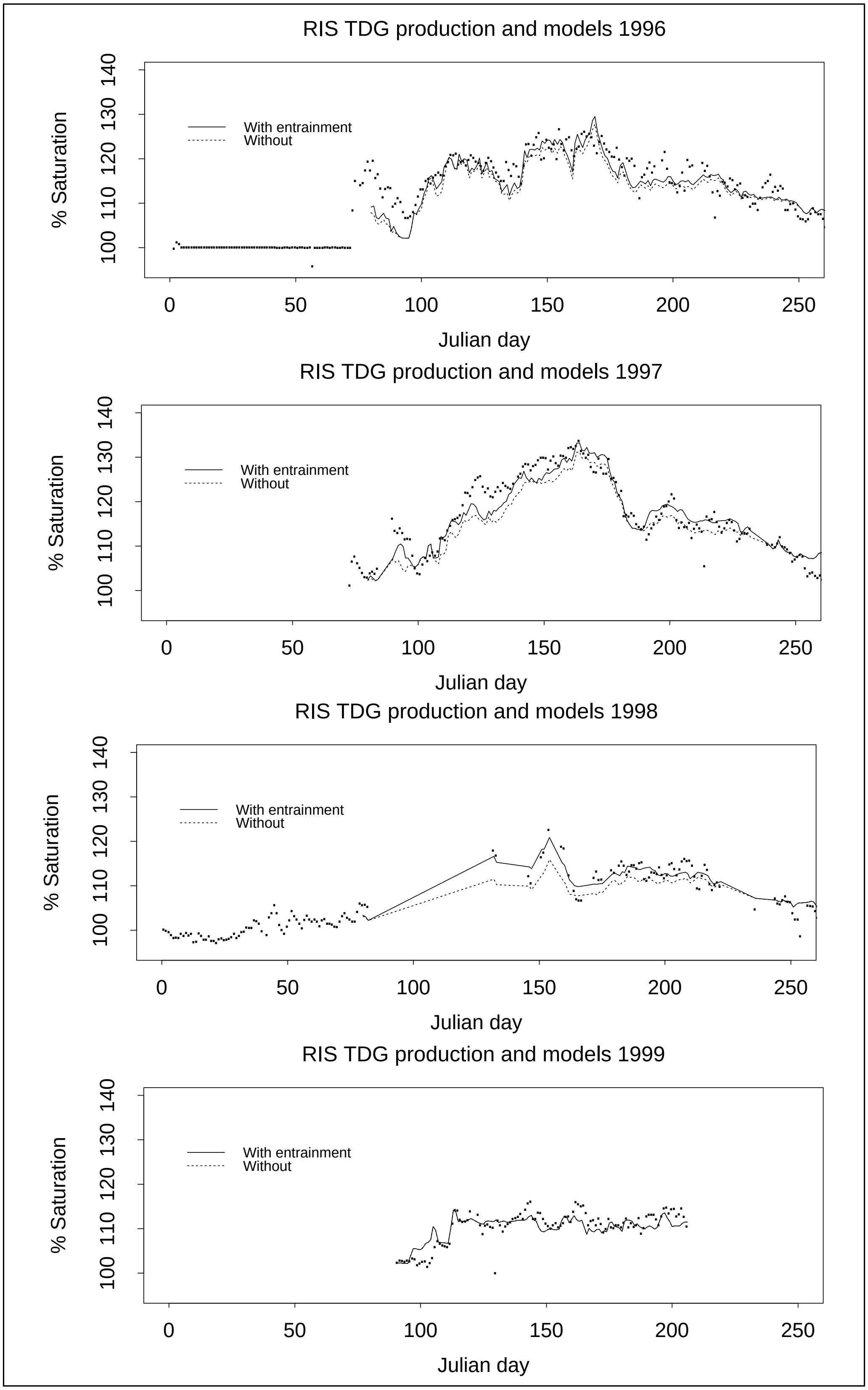

Fig. 41 Rock Island (RIS) production values with and without entrainment and observed data (points) at Wanapum Forebay.

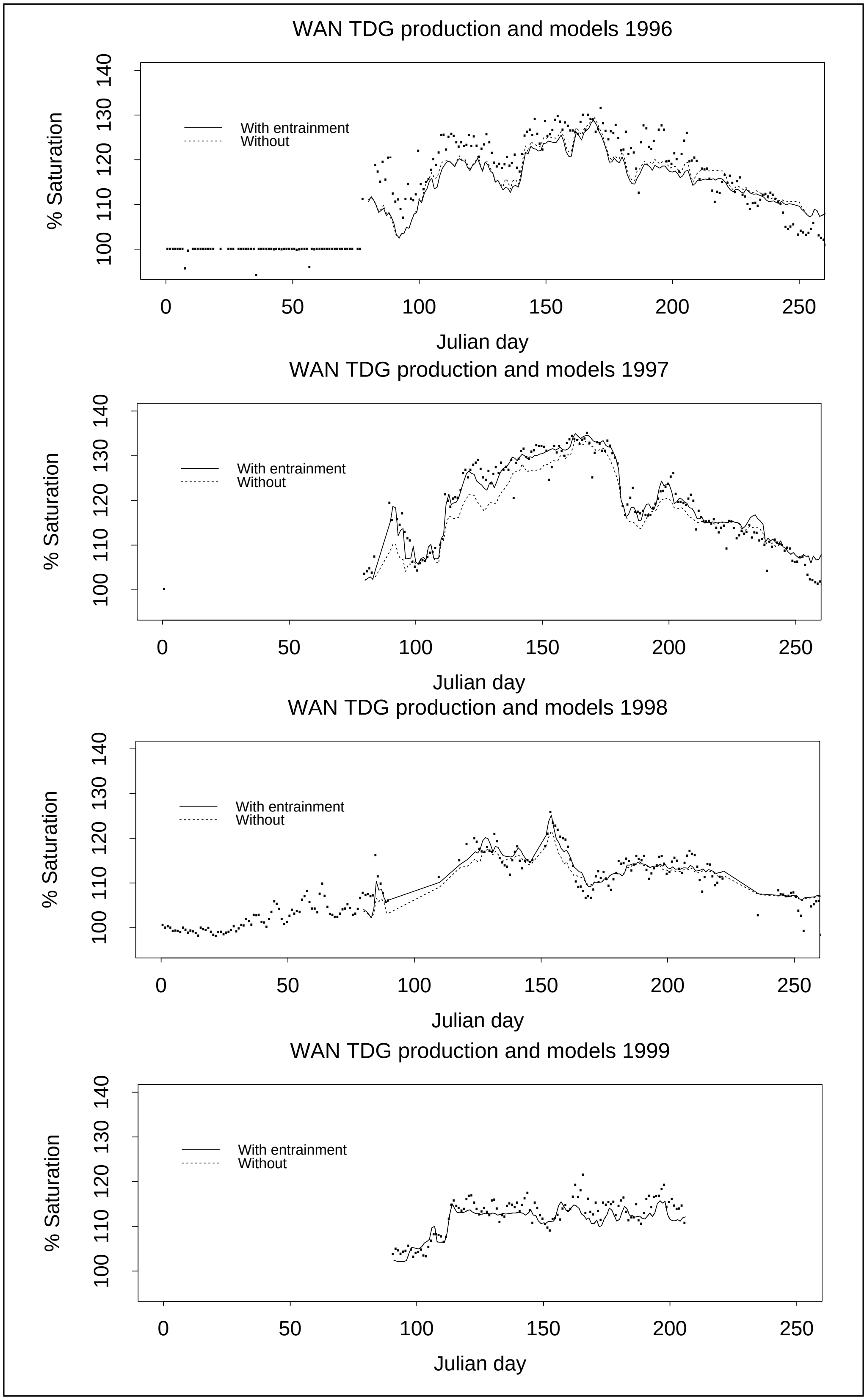

Fig. 42 Wanapum (WAN) production values with and without entrainment and observed data (points) at Priest Rapids Forebay.

II.5.4 - Reservoir Dissolved Gas Distributions

Theory

The CRiSP.1 reservoir gas model has been reworked to model the movement and mixing of parcels of water distinguished by different levels of total dissolved gas. A quasi-2D river model describes the river as two flows, with each flow having its own TDG level. Looking downstream, there is the right-bank and the left-bank flow (see Fig. 43).

At a dam, the river is divided according to the proportion of spill from the nearest upstream dam. At a confluence, the river is divided according to the proportion of flow from the two converging rivers. At a reach where there has been no spill or upstream confluences, the gas levels on either side of the river are simply set to be equal and there is essentially one flow in the reservoir. Fig. 44 represents the case downstream of a dam. The right-bank flow in this case is just the spill flow, and the fraction of flow in the right-bank flow is simply the spill fraction.

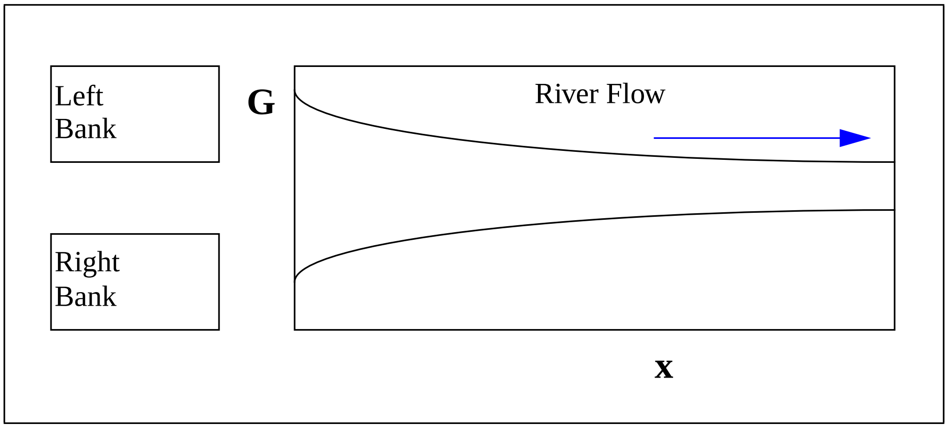

Fig. 43 A Divided Reservoir

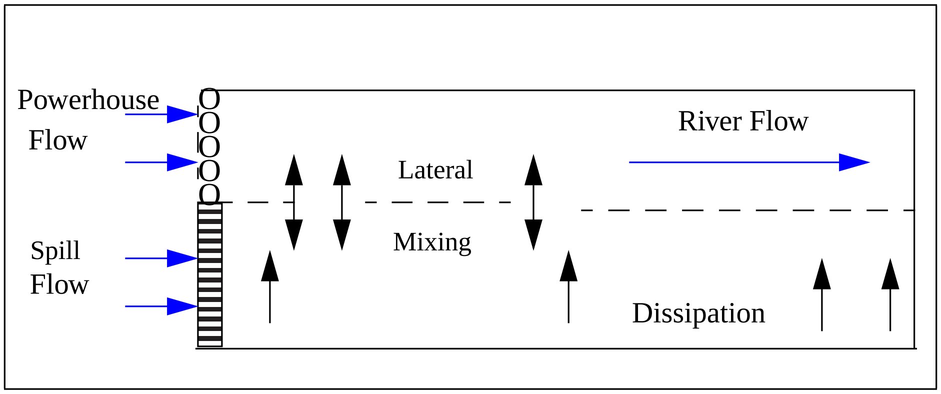

Fig. 44 Reservoir Gas Dynamics

TDG is mixed between the two flows and simultaneously dissipated as the water moves downstream, with the river velocity being estimated from the flow and reservoir geometry. In this manner, the model captures heterogeneous levels of gas. Fig. 44 also illustrates the gas dynamics modeled in the reservoir.

Each of the flows has an initial level of TDG which is then diffused through the boundary between them and also dissipated into the air. Simple exponential functions were used to achieve these processes in the model. These exponential functions were chosen for their simplicity; the sparseness of data and the added complexity discouraged the use of a full two-dimensional advection-diffusion model. Exponential functions were also used because the rate of change of an exponential variable is proportional to its value; this is representative of many decaying substances in nature.

The 2-flow model is shown in eq (103) and (104):

$$G_{right} = [G_{mix} - E + G_{dif} \cdot (1 - S_{fr}) e^{-\theta x}] \cdot e^{-k \cdot \frac{x}{v}} + E \tag{103}$$

$$G_{left} = [G_{mix} - E - G_{dif} \cdot S_{fr} \cdot e^{-\theta x}] \cdot e^{-k \cdot \frac{x}{v}} + E \tag{104}$$

where

- G_{right} , G_{left} = percent TDG in the flow entering the reach on the respective sides
- S_{fr} = percent of river in the right-bank flow
- G_{mix} = flow weighted average of the TDG values in each flow

$$G_{mix} = S_{fr} \cdot G_{right} + (1 - S_{fr}) \cdot G_{left} \tag{105}$$

- G_{dif} = difference between the original concentrations of the two flows at the head of the reach

$$G_{dif} = G_{right} - G_{left} \tag{106}$$

- E = percent TDG in water at equilibrium, 100% saturation or 0% supersaturation
- θ = diffusion rate constant in units of $(\text{mile})^{-1}$, a model parameter set for each reach
- k = dissipation rate constant in units of $(\text{day})^{-1}$, a model parameter calculated for each reach based on the river depth, velocity and a diffusion constant (see eq (107))
- x = longitudinal distance, where x is in miles
- v = river velocity, in miles per day.

Using eq (103) and (104), we get:

$$G_{right} - G_{left} = G_{dif} \cdot e^{-\theta x} \cdot e^{-k \cdot \frac{x}{v}} . \tag{107}$$

In other words, the difference between the two concentrations is decaying to zero due the diffusion factor $e^{-\theta x}$ and the dissipation factor $e^{-k \cdot \frac{x}{v}}$. Similarly, with a little algebra, the total mass in the system can be shown to be:

$$S_{fr} \cdot G_{right} + (1 - S_{fr}) \cdot G_{left} = (G_{mis} - E) \cdot e^{-k \cdot \frac{x}{v}} + E\,. \tag{108}$$

Thus the total mass (without the dissipation factor $e^{-k \cdot \frac{x}{v}}$ it remains at G_{mix}) is decaying to equilibrium level E. Hence the physical properties are captured with these two equations. G_{right} and G_{left} are computationally inexpensive and their simplicity results in an easy fitting and integration.

A given reservoir can have “slugs” of water which entered the reach under different initial conditions. Typically, these slugs are caused by varying spill conditions at an upstream dam. Conditions at a dam can vary on a dam time step (six hour) basis. Thus all water leaving the reach in a given dam time step is assumed to have the same initial conditions. At any given point in the reach, daily river velocities and the distance downstream in the reach are used to calculate the length of time the water has been in the reach. These travel times are used to capture the correct initial conditions and the amount of mixing and dissipation that have occurred in this slug of water. At any given point in the reach, the dissolved gas level is calculated by knowing the initial conditions for G_{right} and G_{left}, and S_{fr} along with x (distance downstream).

Parameter Determination

In transect studies completed by the U.S. Army Corps of Engineers, gas data from lateral cross sections of the Snake and Columbia rivers were sampled to gather information on mixing characteristics in each of the reservoirs from Lower Granite to Bonneville. These pools were sampled under high and low flow conditions and showed that while the dam introduced a heterogeneous flow, the reservoirs were well-mixed by the next downstream forebay.

Because mixing rates vary according to dam operations, river velocity, and other conditions such as wind, a conservative estimate for mixing was fixed for all reaches. A value of 0.075 was used to fix the mixing rate so that the flows were 95% mixed in 40 miles. The transect data from the 1996 and 1997 studies showed that the difference between the left-bank and right-bank flows rarely differed by more than this in the downstream forebay (Waterways Experiment Station 1996, 1997a).

II.5.5 - Other Gas Inputs

In the last several years, more and more dissolved gas data has become available from the U.S. Army Corps of Engineers. Nearly every pool has at least 2 gas monitoring stations (Fig. 45), one in the forebay of the dam and one in the tailrace of the previous dam. For this reason, an input feature was added to CRiSP.1 to allow the direct input of dissolved gas data at any reach or dam in the model. This is achieved through the `output_gas` token in the yearly input data file. By default this feature is turned off, but if the line `output_gas on` appears in a reach or dam profile, then a vector of dissolved gas data of length `num_days * num_dam_slices` (currently 366*4) should be supplied.

The intention of this feature was to allow total dissolved gas to enter the system above the dams. In most data files, a vector of data is provided at two locations: Chief Joseph Pool for gas entering from the Columbia headwaters, and Lower Granite Pool for the gas entering from the upper Snake and Clearwater. For a more accurate description of dissolved gas, historic data could be used for all reaches where it is available, but generally this is turned off since gas production and distribution is well modeled.

The `output_gas` token has the effect of setting gas values that exit the reach on both sides of the river to the same value.

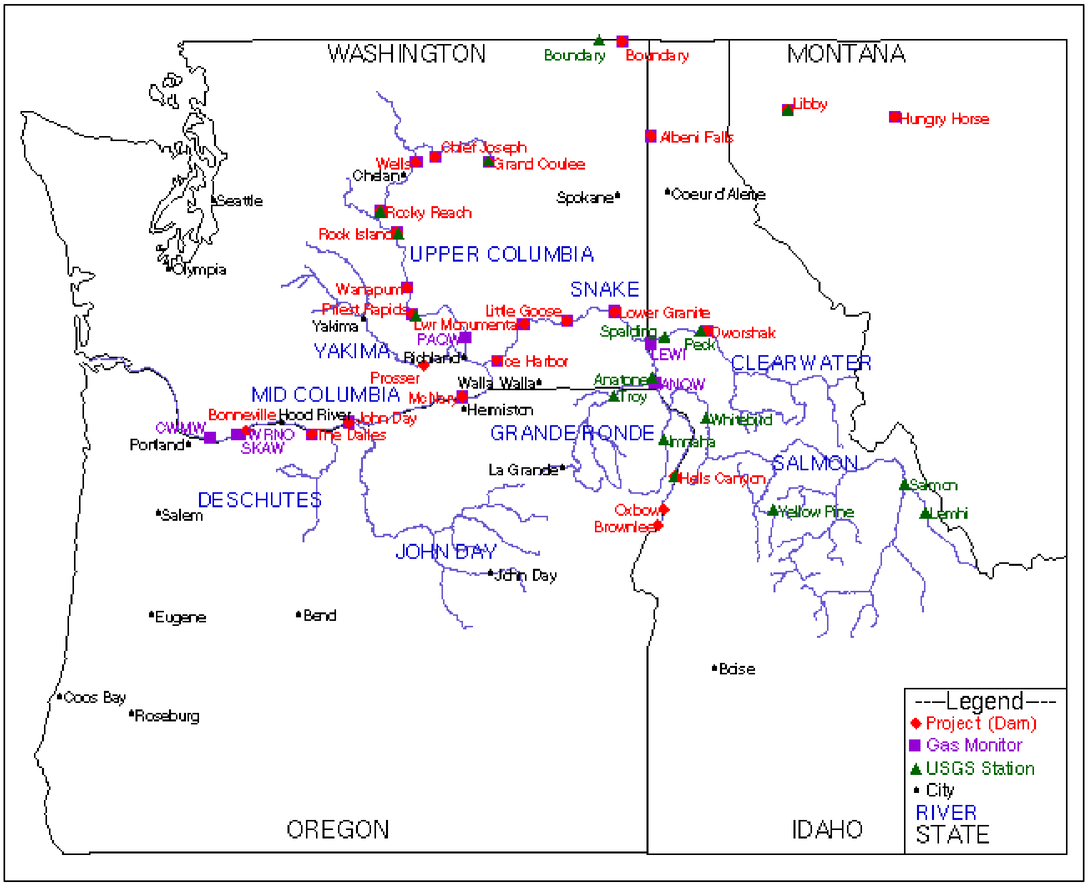

Fig. 45 Map of Columbia Basin showing dams, USACE Gas Monitor Stations, and USGS Streamflow Gaging Stations

Total Dissolved Gas in the Tailrace

Total dissolved gas supersaturation in the tailrace results from mixing spill water with water passing through turbines (Fig. 38 on page 76). The equation is:

$$G = G_{fb} + \frac{Q_s}{Q}(G_{sf} - G_{fb}) \tag{109}$$

where

- Q = total flow through the dam in kcfs
- Q_s = spill flow in kcfs
- G = tailrace TDG supersaturation (in percent)
- G_{fb} = forebay TDG supersaturation (in percent)
- G_{sf} = spill water TDG in percent saturation as defined by an empirical or mechanistic saturation equation.

Total Dissolved Gas at a Confluence

The TDG at a confluence is determined by the addition of two flows with different TDG levels. The equation is:

$$G = \frac{Q_1 G_1 + Q_2 G_2}{Q_1 + Q_2} \tag{110}$$

where

- Q_i = flow in kcfs in segment i
- G_i = TDG in percent supersaturation in segment i of the confluences.

Total Dissolved Gas Dissipation

Total dissolved gas levels above the saturation level are lost from the river as a first order process. WRE (Roesner and Norton 1971) defined this by a total flux equation for a segment as:

$$\Phi = AK_d(G_{eq} - G) \tag{111}$$

where

- Φ = flux of TDG across the air/water interface
- G = TDG supersaturation concentration in the segment
- G_{eq} = TDG equilibrium concentration
- A = surface area of the segment
- K_d = transfer coefficient defined

$$K_d = \left(\frac{D_m U}{D}\right)^{0.5} \tag{112}$$

where

- D_m = molecular diffusion coefficient of TDG
- U = hydraulic stream velocity
- D = depth of the segment.

To express the loss in terms of concentration, we divided eq (111) by *AD* to give:

$$\frac{dG}{dt} = \frac{\Phi}{AD} = (G_{eq} - G)\sqrt{\frac{D_m U}{D^3}}\,. \tag{113}$$

Note that one mile = 16.0934 x 10^4 cm = 5280 ft, and one day = 8.64 x10^4 seconds. To put the calculation in units of miles and days, we express *U* in miles/day and *D* in feet and D_m in cm^2/s. Thus the diffusion coefficient per unit square mile of river is:

$$\frac{dG}{dt} = k(G_{eq} - G) \tag{114}$$

where the coefficient *k* is expressed:

$$k = 700.75\sqrt{\frac{D_m U}{D^3}} \approx 0.085\ /\mathrm{day} \tag{115}$$

assuming:

- D_m = order of 2 x 10^{-5} cm^2s^{-1} (Richards 1965)
- U = order of 3 cm/s (20 miles/day), note this changes on a daily basis and for each reach in the model
- D = order of 900 cm, note this changes on a reach specific basis and is dependent on reservoir elevation
- the constant 700.75 gives the coefficient k in unit of day^{-1}.

TDG loss rate due to degassing can be expressed as a function of the residence time since the water entered the tailrace:

$$G(t) = G_{eq} + [G(0) - G_{eq}]e^{-kt} \tag{116}$$

where

- G_{eq} = TDG equilibrium concentration
- $G(0)$ = tailrace concentration defined by eq (109)
- k = dissipation coefficient defined by eq (115)
- t = time in a river segment.

Noting that in the models G is in terms of percent above supersaturation, we then set $G_{eq} = 0$.

Adjustments of k

The TDG dissipation coefficient depends on the average depth as defined in eq (115). The average depth is variable according to the geometry of the reservoir and the pool elevation. This depth is defined as:

$$D = \frac{Volume}{WL} \tag{117}$$

where

- *Volume* = pool volume at a specific elevation
- W = average pool width at full pool
- L = length of pool.

II.6 - Dam Passage

Fish enter the forebay of a dam from the reservoir and experience predation during transit time and during delays due to diel and flow related processes. They leave the forebay and pass the dam mainly at night through spill, bypass or turbine routes, or are diverted to barges or trucks for transportation. Each route leaving the forebay has an associated mortality, and fish returning to the river are exposed to predators in the tailrace before they enter the next reservoir. The details of passage through the regions of the dam are illustrated schematically in Fig. 46.

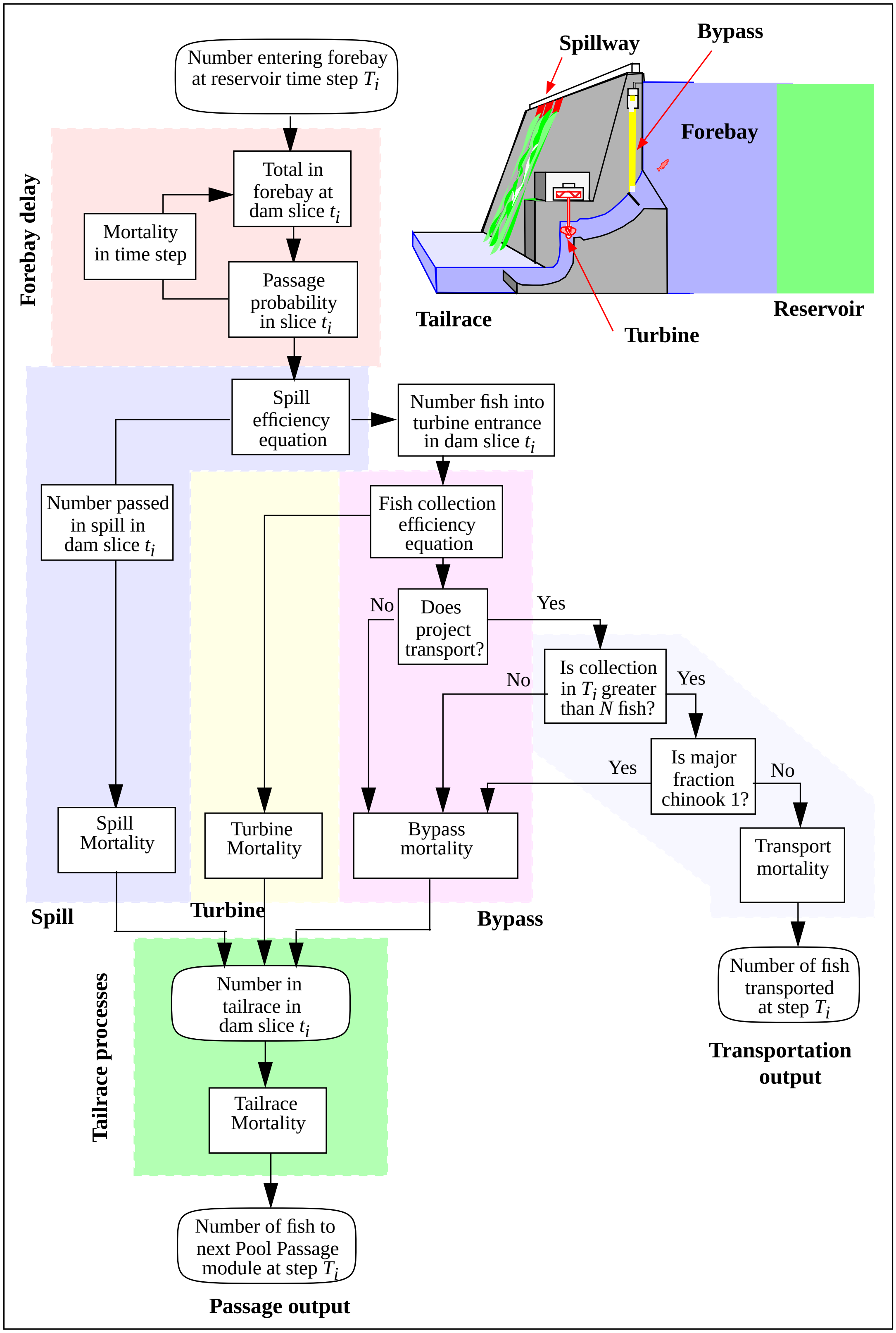

Fig. 46 Dam processes showing passage routes and mortality. Forebay delay is further illuminated in Fig. 47.

The movement and allocation of fish through the forebay is illustrated in Fig. 47. Fish exiting the reservoir in each reservoir time slice, currently two slices per day, are evenly allocated as input to the forebay across the dam time slices, currently four slices per day. Fish entering from the reservoir are subjected to possible predation for the duration of the forebay transit. The forebay transit only affects mortality modeling, not travel time. Next, fish are either passed (through dam or spillway) to the tailrace or are delayed for one dam time slice in the forebay. Delayed fish are combined in the next dam time slice with fish completing the forebay transit. These fish are passed or are delayed and the cycle repeats.

Output from the forebay in each dam time slice depends on flow and diel illumination. Allocation to the passage routes depends on spill schedules and passage efficiencies through the routes.

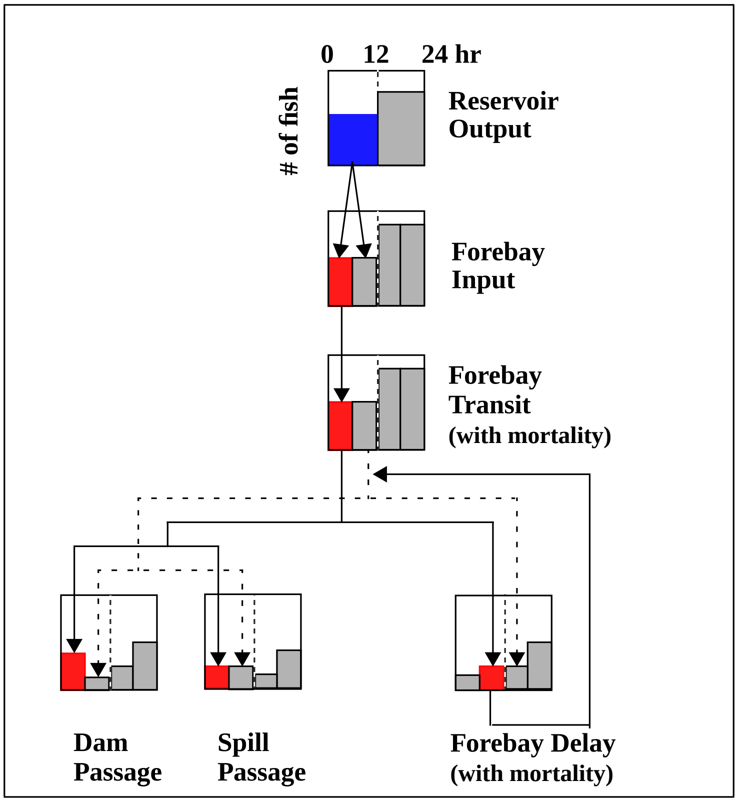

Fig. 47 Transfer of fish from reservoir to forebay to dam. Diagram shows allocation of fish from a reservoir time slice of 12 hours to dam time slices of 6 hours each. Mortality is associated with dam and spill passage as well as forebay transit and delay.

II.6.1 - Forebay Delay

Studies of the timing of fish passage at dams indicate that passage occurs mostly at night, with fish delaying passage during daylight hours. This delay process is represented in CRiSP.1 as a simple input-output submodel. Fish enter the forebay at a rate determined by reservoir passage factors. Fish are assumed to be more susceptible to being drawn into turbine intakes or spill at night than during the day. Susceptibility is also determined by flow, spill, and julian date; expressing the propensity of the fish to pass dams as the season progresses.

Dam Delay Model

$$\lambda_t = p \cdot \alpha_{day} + (1-p) \cdot \alpha_{night} + \beta_1 \cdot V_t + \beta_2 \cdot SP_t + \beta_3 \cdot D_t \qquad (118)$$

where

- λ_t = instantaneous probability of passage
- p = proportion of time step during day
- (1-p) = proportion of time step during night
- V_t = upstream river velocity in mi/day
- SP_t = proportion of river spilled
- D_t = julian date
- α's and β's = parameters that vary by dam and species.

The probability of remaining during a single time step is:

$$P_1 = e^{-(\lambda_t \cdot \Delta t)}. \qquad (119)$$

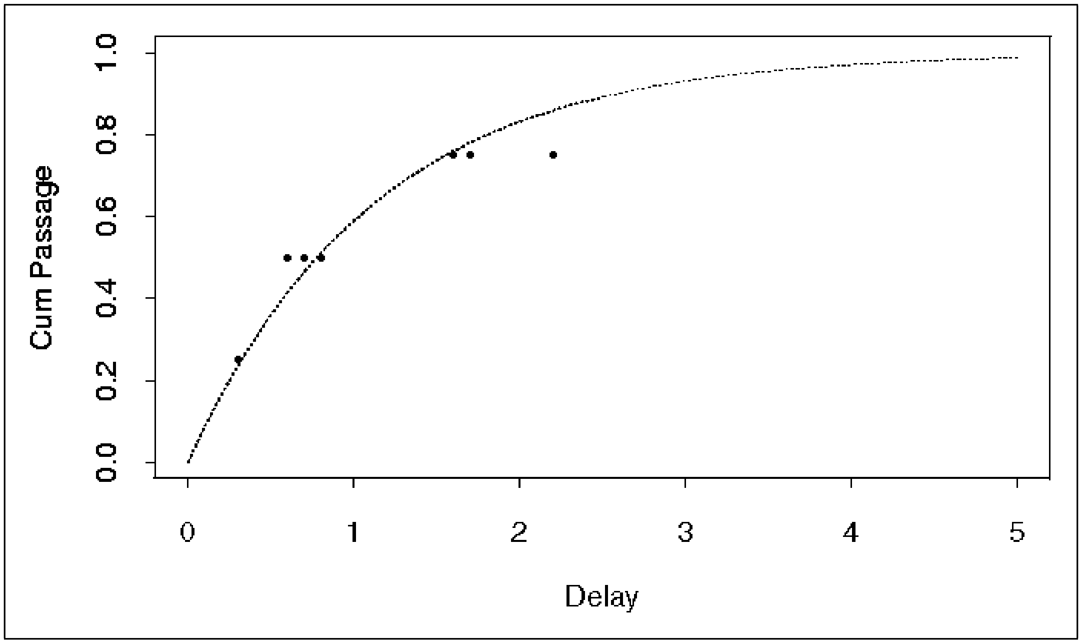

Fig. 48 Cumulative passage versus dam delay in days at Little Goose Dam

II.6.2 - Spill

The spill algorithm represents allocations of spill from hydroregulation models (HYDROSIM or HYSSR) through flow archive files or the **Spill Schedule** window under the **Dam** menu.

Flow Archive Spill

When spill is allocated from flow archive files, it is identified as a percent of daily averaged flow over multi-day periods. Consequently, for use in CRiSP.1, archive derived spill must be allocated to specific days and hours of the day. CRiSP.1 considers three types of spill: Planned Fish Spill, Overgeneration Spill, and Forced Spill.

- **Planned Fish Spill** is requested by the fisheries agencies. The schedule for this can be obtained from the Flow Archive files or can be set in the **Spill Schedule** window.
- **Overgeneration Spill** occurs when electrical generation demand is less than that available in flow. This is obtained from the flow archive file only.
- **Forced Spill** occurs when river flow exceeds powerhouse capacity. This is calculated by CRiSP.1.

CRiSP.1 allocates spill flows in the following order.

⇒First, **Planned Fish Spill** is allocated. For each period, planned spill is distributed over scheduled spill days and fish spill hours (within those days) using the following steps.

1. Total modulated flow in the period that occurs in fish spill hours on planned spill days is calculated and designated

   `flow_available` (in kcfs)

2. The requested spill in a period is designated

   `spill_request` (in kcfs)

3. Percent spill during **Fish Hours** is calculated as

   `spill_daily_percent` = `spill_request/flow_available`

4. If `spill_daily_percent` > 100%

   then `spill_daily_percent` = 100% of the flow available in the request periods and the rest is discarded and a warning message is generated.

⇒Second, **Overgeneration Spill** identified in the hydroregulation models for 2 or 4 week periods is evenly distributed over all days in the periods. The following calculations are made on a daily basis.

1. Overgeneration spill is added to **Planned Fish Spill** in **Fish Hours** every day in a period to yield total spill.
2. If total spill in **Fish Hours** is now greater than the total flow over the hours then the excess is distributed over the rest of the day.
3. If total spill for the entire day is greater than the total daily modulated flow then the spill is set to the total daily modulated flow.

⇒Third, **Forced Spill** occurs when river flow exceeds powerhouse capacity. Forced Spill is calculated on the dam time slice periods. This is typically a 6 hour interval. CRiSP.1 uses the following steps.

1. Calculate the quantity

   flow - powerhouse capacity/flow = possible forced spill

2. Then, if possible forced spill > total fish & overgeneration spill

   assign total spill = possible forced spill

3. Otherwise, the forced spill is assimilated into fish and overgeneration spills.

Spill from Spill Schedule Tool

Planned spill can be set by specifying spill information with the **Spill Schedule** window. The following information is entered:

- fraction of flow spilled
- days over which the spill fraction applies

- days in which actual spill occurs, i.e. the planned spill
- hours of planned spill for the indicated days.

Overgeneration spill is only applied if Monte Carlo Mode is used. Forced spill is calculated as described above and is applied in both Scenario and Monte Carlo Modes.

Spill Caps

The maximum allowable planned spill is set by the spill capacity (cap) at each dam. If planned spill exceeds the cap then spill is limited to spill cap. Forced spill can exceed the spill cap.

Spill Efficiency

The fraction of fish passed with spilled water is defined by one of nine possible empirical equations that can be selected by the user. The following are the spill efficiency equations:

$$\begin{aligned}
Y &= a + b \cdot X + e \\
Y &= a + b \cdot X + X \cdot e \\
Y &= b \cdot exp(a \cdot X + e) \\
Y &= b \cdot exp(a \cdot X) + X \cdot e \\
Y &= b \cdot X^{a + e} \\
Y &= b \cdot (X / 100)^{a} + X \cdot e \\
Y &= a + b \cdot \ln X + e \\
Y &= a \cdot X + b \cdot X^{2} + c \cdot X^{3} + e \\
Y &= a \cdot (X / 100) + b \cdot (X / 100)^{2} + c \cdot (X / 100)^{3} + e
\end{aligned} \tag{120}$$

where

- Y = fraction of total fish passed in spill
- X = fraction of water spilled
- a and b = regression coefficients
- e = error term (var) selected from random distribution.

The equations and parameters defining spill efficiency (often called “effectiveness” in the literature) are indicated in Table 33. These values were used beginning with the SOR (System Operation Review) screening runs of CRiSP.1.

Table 33 Spill efficiency (% fish passed in spillway /% flow passed in spillway).

Dam	Spill equation	Reference
Wells	zero[a]	Erho et al. 1988; Kudera et al. 1991
Rocky Reach	% pass = 0.65 * (% spill)	Raemhild et al. 1984b
Rock Island	% pass = 0.94 * (% spill) + 11.3	Ransom et al. 1988
Wanapum	% pass = 15.42 * ln (% spill)	Dawson et al. 1983
Priest Rapids	% pass = (% spill) ^ 0.82	

Table 33 Spill efficiency (% fish passed in spillway /% flow passed in spillway).

Dam	Spill equation	Reference
L. Monumental	% pass = 1.2 * (% spill)	Johnson et al. 1985; Ransom and Sullivan 1989
The Dalles	% pass = 2 * (% spill)	Parametrix, Inc. 1987
all other dams	% pass = (% spill)	-

a. Wells Dam is designed to pass smolts preferentially through the spillway system: about 96% of all smolts pass via the spillway. This is modeled by assigning an FGE value of 96% (range 95-97%) at Wells with a zero spill efficiency for years 1991 on, except as specified in Table 34.

II.6.3 - Fish Guidance Efficiency (FGE)

Guidance of fish into the bypass systems of dams is achieved by diverting fish into a bypass slot. Individual FGEs are specified for day and night at each dam and for each species. In addition, CRiSP.1 can treat FGE as constant over time or vary FGE with the age of the fish relative to the onset of smoltification.

Constant FGE

When **age dependent fge** is turned off, the model will use the constant FGE condition. Day and night fish guidance efficiency then vary randomly on each dam time step according to a fixed probability distribution, i.e. the distribution has no seasonal trend. FGE is specific to a given dam and species and its random variations occur for each dam time step (6 hours).

The probability distribution of constant FGE is defined by a piecewise linear distribution within the range identified by the low and high values. When the low and high values are set to zero, or when the low and high are set to the mean value, CRiSP.1 uses the mean value at all times (the term becomes deterministic). When the low and high values are not equal, CRiSP.1 uses the mean, low and high values to randomly generate a value when executed with **variance suppression** turned off. With **variance suppression** turned on, CRiSP.1 uses the mean value and ignores the high and low values. In either case, the mean value must lie within the central two quartiles of the distribution (i.e., the middle 50%).

Age Dependent FGE

Studies on fish guidance at several dams in the Columbia system indicate that FGE varies with seasons from a number of factors including the water quality and the degree of smolt development in the fish, which changes with age. When the model is run under this condition (**age dependent fge** turned on), day and night FGE change randomly for each dam time step (6 hours) according to probability distributions that change with fish age and reservoir elevation. Variations in FGE from the initial condition depends on julian day, the day since the onset of smoltification, and reservoir elevation for each day. If the age dependent option is selected, fish depth in the forebay varies with age, which in turn alters the FGE. The algorithm assumes that fish above some critical depth z enter the bypass system and fish below z enter the turbine (Fig. 49). Thus, to define age dependent FGE, fish depth in the forebay is defined as a function of age. If the surface drops below the level of the bypass orifice, then fish bypass goes to zero.

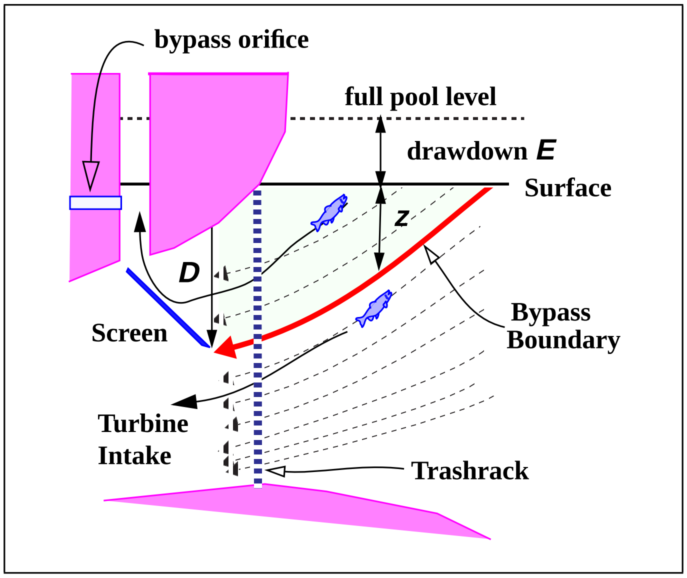

Fig. 49 Critical parameters in fish guidance are fish forebay depth *z*, screen depth *D* and elevation drop *E*. Only fish above *z* are bypassed. Bypass stops when the surface is below the bypass orifice depth.

The FGE submodel is based on the FGE model of Anderson (1991). Behavioral and hydraulic factors affecting FGE are combined into a calibration factor D_c. In addition, the affect of drawdown on FGE can be expressed in terms of screen depth relative to the surface. The modified equation is:

$$fge = 1 - \exp\left(\frac{-0.693}{z}(D - D_c - E)\right) \tag{121}$$

where

- fge = fish guidance efficiency
- z = median depth of fish in the forebay at a distance from the dam where fish are susceptible to being drawn into the intake
- D = screen depth relative to full pool forebay elevation
- D_c = FGE calibration parameter
- E = amount the pool is lowered below full pool elevation.

Thus, changes in FGE result from changes in fish depth and changes in reservoir elevation. The parameter D_c depends on physical and hydraulic properties of a dam, and behavioral properties of fish. As such, the term is specific to both a given species and a given dam. In addition, separate coefficients are defined for day and night dam passage.

Changes in FGE with fish age are represented by changes in fish forebay depth which is described by a linear equation:

$$\begin{array}{ll} t < t_0 & z(t) = z_0 \\ t_0 < t < t_0 + \Delta t & z(t) = z_0 + (z_1 - z_0)\left(\dfrac{t - t_0}{\Delta t}\right). \\ t > t_0 + \Delta t & z(t) = z_1 \end{array} \tag{122}$$

To implement the FGE equation, we define the calibration coefficient:

$$K = \frac{\log(1 - fge_0)}{-0.693} = \frac{D - D_c}{z_0}. \tag{123}$$

Combining equations (121), (122) and (123), the final FGE equation is:

$$fge(t) = 1 - \exp\left(-\frac{0.693}{z(t)}(z_0 K - E(t))\right) \tag{124}$$

where

- t = fish age since the onset of smoltification
- t_0 = onset of change in FGE relative to the onset of smoltification, set in the **Release** window
- Δt = increment of time over which FGE changes
- z_0 = initial mean fish depth (at age t equals 0) in the forebay
- z_1= final mean fish depth (at age t equals $t_0 + \Delta t$) in the forebay
- fge_0 = FGE at onset of smoltification
- $E(t)$ = elevation drop.

The resulting FGE and depth are illustrated in Fig. 50.

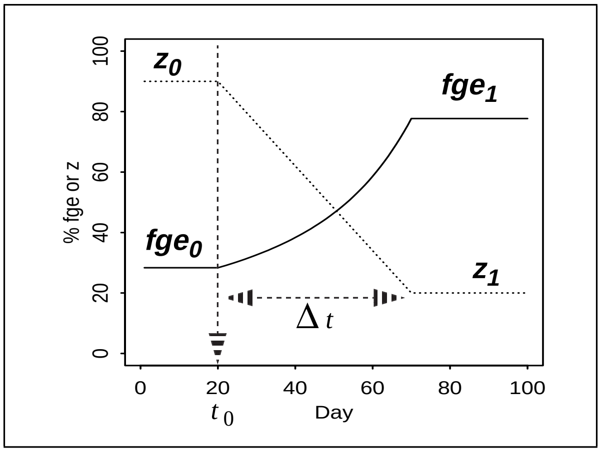

Fig. 50 FGE and fish depth over fish age

Parameter Determination

Nearly all federal projects on the Columbia and Snake rivers have undergone considerable change since their initial construction. Most have added bypass systems or other mechanisms to provide improved juvenile passage; consequently, FGE has improved over time. We use current estimates of FGE as determined by the PATH process (L.D. Krasnow, National Marine

Fisheries Service, NWFSC, pers. com., 2000). These FGE values are adjusted for sensitivity #1 analysis, where the effectiveness of extended-length submersible-bar screen is assumed to be better than standard screens. Estimated historical FGE values for CRiSP.1 for all species are given in Table 34.

Table 34 Historical FGE values for each dam, by species as determined by PATH and used for CRiSP.1 (L.D. Krasnow, National Marine Fisheries Service, NWFSC, pers. com., 2000).

Dam	Year	yearling chinook	subyearling chinook	steelhead
Bonneville 1	1971-1983	40.0%	40.0%	40.0%
	1984-1987	75.0%	56.0%	82.0%
	1988-1998	38.0%	16.0%	41.0%
Bonneville 2	1982-1988	24.0%	35.0%	41.0%
	1989-1992	32.0%	10.0%	38.0%
	1993-1998	44.0%	18.0%	48.0%
The Dalles	1957-1974	2.0%	2.0%	2.0%
	1975-1998	46.0%	46.0%	40.0%
John Day	1968-1984	2.0%	2.0%	2.0%
	1985	36.0%	19.1%	47.8%
	1986	48.0%	25.5%	63.8%
	1987-1998	64.0%	34.0%	85.0%
McNary	1979	11.4%	5.4%	5.3%
	1980	9.4%	34.3%	9.6%
	1981	58.9%	21.4%	59.8%
	1982	61.3%	22.3%	62.2%
	1983-1989	66.0%	24.0%	67.0%
	1990	69.9%	27.4%	67.0%
	1991-1992	66.0%	24.0%	67.0%
	1993	69.9%	27.4%	67.0%
	1994	68.1%	25.9%	68.1%
	1995	66.0%	24.0%	81.0%
	1996	77.6%	34.3%	69.6%
	1997-1998	95.0%	62.0%	89.0%
Wells[a]	1991-1992	96.0%	96.0%	96.0%
	1993-1999	89.0%	96.0%	96.0%
Rocky Reach[a]	1993-1998	30.8%	21.9%	40.2%
Rock Island 1[a]	1994-1998	85.7%	spring migrants 29.6% summer migrants 63.7%	60.9%
Ice Harbor	1967-1979	3.0%	3.0%	3.0%
	1980-1982	30.0%	20.0%	30.0%
	1983-1992	61.0%	40.0%	61.0%
	1993-1995	70.0%	46.0%	86.0%
	1996-1998	71.0%	46.0%	93.0%
Lower Monumental	1969-1991	2.0%	2.0%	2.0%
	1992-1999	61.0%	49.0%	82.0%

Table 34 Historical FGE values for each dam, by species as determined by PATH and used for CRiSP.1 (L.D. Krasnow, National Marine Fisheries Service, NWFSC, pers. com., 2000).

Dam	Year	yearling chinook	subyearling chinook	steelhead
Little Goose	1970	2.0%	2.0%	2.0%
	1971-1972	19%	12.3%	24.7%
	1973-1975	57.0%	37.0%	74.0%
	1976	38.0%	37.0%	74.0%
	1977	57.0%	12.7%	49.3%
	1978-1987	57.0%	37.0%	74.0%
	1988-1992	69.0%	48.0%	76.0%
	1993-1994	70.0%	47.0%	81.0%
	1995	67.0%	47.5%	81.0%
	1996	64.0%	48.0%	81.0%
	1997-1999	82.0%	53.0%	81.0%
Lower Granite	1975-1976	13.7%	9.0%	24.7%
	1977-1990	41.0%	27.0%	74.0%
	1991-1994	55.0%	49.0%	81.0%
	1995	58.3%	49.7%	81.0%
	1996-1999	78.0%	53.0%	81.0%

a. Whitney et al. 1997.

Time Variable FGE

The calibration of time varying FGE is not available for CRiSP1.6.

Bypass Orifice and FGE

Fish guidance goes to zero when the surface elevation drops below the bypass orifice elevation (Fig. 49 on page 99). This parameter, designated `bypass_elevation`, is set in the **columbia.desc** file. If `bypass_elevation` is not specified, then the bypass elevation is set to the pool `floor_elevation` and bypass will occur for all reservoir elevations. This function applies with or without selection of age dependent FGE.

Bypass Elevations

The bypass elevations and forebay elevations in feet above sea level (obtained from the U.S. Army Corps of Engineers) are set in the **columbia.desc** file for each dam where a bypass system exists.

Table 35 Bypass and forebay elevations of dams with bypass systems

Dam	Bypass elevation (ft)	Forebay elevation (ft)
Bonneville 1 and 2	65.5	77
The Dalles	149	160
John Day	250.5	269
McNary	330	340

Table 35 Bypass and forebay elevations of dams with bypass systems

Dam	Bypass elevation (ft)	Forebay elevation (ft)
Wells	716	781
Ice Harbor	431.5	440
Lower Monumental	531.5	540
Little Goose	628.9	638
Lower Granite	729	738

Multiple Powerhouses

Bonneville Dam and Rock Island Dam each have two powerhouses that can be operated independently to optimize survival during the fish passage season since each project has a single spillway. Multiple powerhouse dams can be represented schematically as shown in Fig. 51.

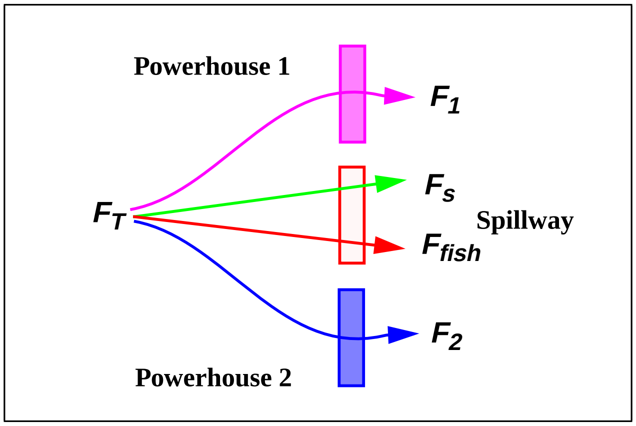

Fig. 51 Multiple powerhouse configuration showing allocation of spill and powerhouse flows.

For multiple powerhouse dams, flow is allocated fractionally as follows:

1. Flows are first allocated to planned spill in fish passage hours.
2. Remaining flow is partitioned between the primary and secondary powerhouses and additional spill as follows:
    - operate highest priority powerhouse up to its hydraulic capacity
    - spill water up to another level called the spill threshold
    - above the threshold, use the second powerhouse
    - over the second powerhouse hydraulic capacity, spill extra flow.

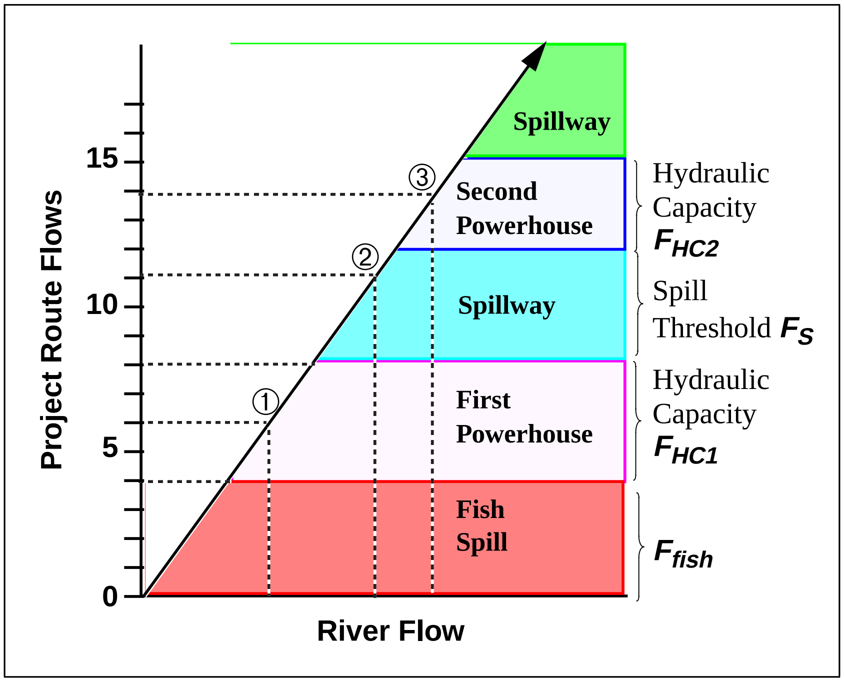

Fig. 52 Flow allocation through two powerhouse projects.

An example of flow allocations is described as follows (Fig. 52):

- At level ①: 4 units of flow are put to **Fish Spill** and 2 units are put through the First Powerhouse.
- At level ②: **Fish Spill** has four units of flow, the First Powerhouse is run at its hydraulic capacity, which is 4 flow units, and the spillway has 3 units of additional spill.
- At level ③: the First Powerhouse is at hydraulic capacity, spill flow includes **Fish Spill** and additional spill up to the spill threshold, and 2 units of flow pass the Second Powerhouse.

Fish Passage Efficiency (FPE)

Fish passage efficiency (FPE) is the percent of fish that pass a project by non-turbine routes (spill, bypass, and sluiceway passage). FPE considers that fish pass mostly during the night, and spill generally occurs at night. The simple fish routing is illustrated in Fig. 53. A fraction of the fish are first diverted in to spill water. The fish that remain are diverted into the turbine intake and a fraction of this flux is diverted into the fish bypass system.

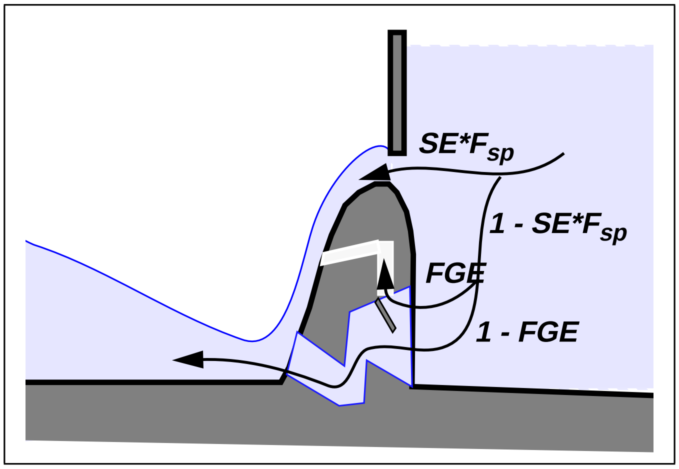

Fig. 53 Routing of fish for calculation of FPE

The formula expressing FPE considers these independent diversions and accounts for the fact that fish may be attracted to spill flow over flows into the turbine. The simplified formula for FPE which considers spill occurs at night and most of the fish pass at night can be expressed:

$$FPE = \{D \cdot F_{sp} \cdot SE + D \cdot FGE \cdot (1 - F_{sp} SE) + (1 - D) \cdot FGE\} \cdot 100 \tag{125}$$

where

- D = fraction of fish that pass dam during spill hours
- F_{sp} = fraction of daily flow that passes in spill
- SE = fraction of fish that pass in spill relative to the fraction of flow passing in spill
- FGE = fraction of fish passing into turbine intake that are bypassed.

The spill flow, in percent of the total flow, required to generate a given FPE can be expressed by arranging eq (125) to give:

$$F_{sp} = \frac{FPE - FGE}{D \cdot SE \cdot (1 - FGE)} . \tag{126}$$

Dam Passage Survival

Fish passing through the dams can take several routes (depicted in Fig. 46 on page 93). Equations describing the number of fish that pass through each route in terms of the number that enter the dam from the forebay in a particular dam time step are given in the following sections. In each case, the mortality and passage efficiencies have deterministic and stochastic parts.

For mortalities and FGE, the random elements are represented by additive deterministic and stochastic parts in:

$$x = \bar{x} + x' \tag{127}$$

where

- $\bar{x}$ = deterministic part of the random parameter fixed for each species and dam
- x' = stochastic part of the parameter taken from a broken-stick distribution (see Section II.7.1 Stochastic Parameter Probability Density on page 127) over each dam time slice.

For spill efficiency, each equation contains a random term. A typical equation is:

$$y = a + bx + e \tag{128}$$

where

- y = spill efficiency
- x = percent flow
- a and b = deterministic parameters
- e = stochastic parameter selected from a normal distribution.

Turbine Survival

The equation for turbine survival can be expressed:

$$N_{tu} = N_{fo} \cdot p \cdot (1 - Y) \cdot (1 - m_{fo}) \cdot (1 - m_{tu}) \cdot (1 - fge) \tag{129}$$

where

- N_{tu} = number of fish passing in a time increment (6 hours)
- N_{fo} = number of fish in forebay ready to pass in the increment
- p = probability of passing during the increment (1 - P_1 from eq (119) on page 95)
- m_{fo} = mortality in forebay (see Section II.4.2 Predation Mortality on page 45)
- m_{tu} = mortality in turbine passage
- fge = fish guidance efficiency for a day or night period
- Y = proportion of fish passage in spill defined by spill efficiency equation (see eq (120) on page 97).

Bypass Survival

The equation for bypass survival is:

$$N_{by} = N_{fo} \cdot p \cdot (1 - Y) \cdot (1 - m_{fo}) \cdot (1 - m_{by}) \cdot fge \tag{130}$$

where

- m_{by} = mortality in the bypass.

Transport Survival

The equation for transport survival with fixed transport mortality is:

$$N_{tr} = N_{fo} \cdot p \cdot (1 - Y) \cdot (1 - m_{fo}) \cdot (1 - m_{by}) \cdot fge \cdot m_{tr} \tag{131}$$

where

- m_{tr} = mortality in the transport.

Spill Survival

The equation for spill survival is:

$$N_{sp} = N_{fo} \cdot p \cdot (1 - m_{sp}) \cdot Y \tag{132}$$

where

- m_{sp} = mortality in the spill passage.

Parameter Determination for Passage Mortality

Turbine mortalities are based on the following studies:

Direct measure estimates
  Oligher and Donaldson 1966
  Weber 1954
Indirect measure estimates
  Holmes 1952
  Schoeneman et al. 1961
  Long 1968
  Long et al. 1975
  Raymond 1979
  Raymond and Sims 1980
  Ledgerwood et al. 1990.

The recent measurements of turbine survival with inflated tags and PIT tags are given in Table 36.

Table 36 Recent turbine mortality estimates

Dam Species	Mortality estimate	Technique	Reference
Rocky Reach yearling fall chinook	5.6%	inflated tags	RMC Environmental Service, Inc. and J.R. Skalski 1993
Lower Granite spring yearling chinook	6.6%	inflated tags	RMC Environmental Service, Inc. and J.R. Skalski 1994
Lower Granite spring yearling chinook	17.3%	PIT tags	Iwamoto et al. 1994
Little Goose spring yearling chinook	8.0%	PIT tags	Iwamoto et al. 1994
Lower Monumental spring yearling chinook	13.5%	PIT tags	Muir et al. 1995
Lower Granite spring yearling chinook	7.3%	PIT tags	Muir et al. 1996
average	9.7%	-	-

Bypass and spill mortalities are based on the following studies:

Ceballos et al. 1991
Ledgerwood et al. 1990
Ledgerwood et al. 1991
Muir et al. 1996.

Passage mortalities used in calibration, including mean, low and high values, are given in Table 37. The mortalities are used for all species but most of the data was from studies involving spring chinook. The estimates are weighted towards the more recent studies. High estimates of dam passage mortality in 1970s are used to represent documented problems in Snake River dam passage in these years (Raymond 1979; Raymond and Sims 1980). The high mortalities were assigned to both turbine and bypass routes.

Table 37 Percent mortality at dams: m = mean, l = low, h = high. These mortality estimates are applied to spring chinook and steelhead analyses. High estimates of bypass and turbine mortalities are from Marmorek and Peters (1998).

Dam	Year	Spillway			Bypass			Turbine		
		m	l	h	m	l	h	m	l	h
All dams and years except where noted		2	0	7	2	0	8	7	1	10
Lower Monumental	1972				50			50		
	1973				49			49		
Little Goose	1971				35			35		
	1972				42			42		
	1973				49			49		
	1974				11			11		
	1975				36			36		
	1976				32			32		
	1977				56			56		
	1978				5			50		
	1979				24			24		
	1980							7		
	1981							24		
Lower Granite	1975				36			36		
	1976				21			21		
	1977				59			59		
	1978				22			22		
	1979				16			16		

II.6.4 - Transport Parameters

The direct transport survival in barging is set at 98%. The transport effectiveness expressed by “D” is not included in the passage model.

Transportation schedule

The schedule of transporting fish from each transport dam depends on the flow, number of each species passing the dam, and the efficiency of separating fish for return back into the river. The schedules for transportation, compiled from the annual reports from various sources on the juvenile fishery operation of the Columbia Basin and transportation plans and studies, for the historical years 1975-1999 are given in Table 38.

Table 38 Historical transport operations, 1975-1999, at Lower Granite (LWG), Little Goose (LGS), Lower Monumental (LMN), and McNary (MCN) dams.

Year	Dam	Start Date	Stop Date	Ref.
1975	LGS	4/10	6/15	[a]
1976	LWG	4/15	6/15	Park et al. 1977
	LGS	4/16	6/15	
1977	LWG	4/25	6/17	Park et al. 1978
	LGS	4/29	6/16	
1978	LWG	4/4	6/21	Park et al. 1979
	LGS	4/6	6/15	
1979	LWG	4/11	7/4	Smith et al. 1980
	LGS	4/17	7/4	
	MCN	4/16	8/24	Park et al. 1980
1980	LWG	4/3	7/7	Smith et al. 1981
	LGS	4/7	7/4	
	MCN	4/9	9/5	Park et al. 1981
1981	LWG	4/2	7/30	Athearn 1985
	LGS	4/7	7/25	
	MCN	3/27	9/11	
1982	LWG	4/4	7/29	Basham et al. 1983
	LGS	4/8	7/22	
	MCN	3/30	9/24	
1983	LWG	4/2	7/30	Delarm et al. 1984
	LGS	4/4	7/8	
	MCN	4/2	9/22	
1984	LWG	4/1	7/26	Koski et al. 1985
	LGS	4/5	7/28	
	MCN	4/16	9/28	

Table 38 Historical transport operations, 1975-1999, at Lower Granite (LWG), Little Goose (LGS), Lower Monumental (LMN), and McNary (MCN) dams.

Year	Dam	Start Date	Stop Date	Ref.
1985	LWG	3/28	7/23	Koski et al. 1986
	LGS	3/30	7/23	
	MCN	4/6	9/26	
1986	LWG	3/27	7/24	Koski et al. 1987
	LGS	3/29	7/3	
	MCN	3/27	9/26	
1987	LWG	3/28	7/31	Koski et al. 1988
	LGS	4/2	7/9	
	MCN	3/27	10/29	
1988	LWG	3/25	7/31	Koski et al. 1989
	LGS	4/7	7/15	
	MCN	3/25	9/21	
1989	LWG	3/25	7/27	Koski et al. 1990
	LGS	4/4	7/11	
	MCN	3/24	9/19	
1990	LWG	3/27	7/26	Ceballos et al. 1991
	LGS	4/12	7/21	
	MCN	4/2	9/14	
1991	LWG	3/27	10/31	Ceballos et al. 1992
	LGS	4/3	8/21	
	MCN	4/2	9/14	
1992	LWG	4/1	10/31	Ceballos et al. 1993
	LGS	4/12	10/31	
	MCN	3/25	12/7	
1993	LWG	4/14	11/1	Hurson et al. 1995
	LGS	4/15	11/1	
	LMN	5/3	11/1	
	MCN	4/14	10/30	
1994	LWG	4/6	11/1	Hurson et al. 1996
	LGS	4/5	11/1	
	LMN	4/6	11/1	
	MCN	4/8	12/6	

Table 38 Historical transport operations, 1975-1999, at Lower Granite (LWG), Little Goose (LGS), Lower Monumental (LMN), and McNary (MCN) dams.

Year	Dam	Start Date	Stop Date	Ref.
1995	LWG	3/28	11/1	Baxter et al. 1996
	LGS	4/5	11/1	
	LMN	4/1	11/1	
	MCN	6/20	12/8	
1996	LWG	3/27	10/31	Spurgeon et al. 1997
	LGS	4/1	10/28	
	LMN	4/1	10/28	
	MCN	6/4	11/22	
1997	LWG	3/26	11/1	Hetherman et al. 1998
	LGS	4/1	11/1	
	LMN	4/1	11/1	
	MCN	5/30	12/14	
1998	LWG	3/26	11/1	Hurson et al. 1999
	LGS	4/1	11/1	
	LMN	4/1	11/1	
	MCN	6/1	12/15	
1999	LWG	3/25	11/10	a
	LGS	4/1	11/4	
	LMN	4/1	10/31	
	MCN	6/22	12/14	

a. Dave Hurson, U.S. Army Corps of Engineers, Walla Walla District. Telephone conversation with author, 6 July 2000.

Transportation Separation

Transportation separation criterion indicates conditions under which collected fish are separated and returned to the river. Transportation studies indicate that transportation always benefits juvenile steelhead. Many people believe that smaller migrants (chinook, coho, sockeye) benefit from transportation when flows are low, but are better off in the river when flows are higher and conditions are presumably better. If a dam has a *Separation Trigger*, when flows exceed that value, smaller fish are separated from the larger steelhead smolts and are returned to the river. This separation continues according to the criterion given in Table 40. For example, the criterion “full transport @ 80% yearlings” means that fish are separated under high flow conditions until it is estimated that 80% of yearlings have already passed the dam. After that point, all collected fish are transported regardless of flow condition.

Table 39 Smolt Index passage data[a] used to determine high flow percent `hfl_pass_perc` at McNary Dam based on the separation criterion.

Date when Chin0 > Chin1	Chinook 1 (yearling)		
	# passed by Date	total # passed	% of run passed by Date
6/17/1993	1687884	1729010	98%
6/17/1994	2511366	2572338	98%
6/02/1995	2759231	2879069	96%
5/25/1996	1059141	1240878	85%
5/20/1997	894421	1184530	76%
5/28/1998	1572715	1727071	91%
6/01/1999	3605974	3692944	98%
6/06/2000	1868078	1986380	94%

a. Columbia Basin Research, ed. *Columbia River Data Access in Real Time (DART)*. Hp. 3 Dec. 2000 [last update]. Online. Columbia Basin Research, School of Aquatic & Fishery Sciences, University of Washington. Available: http://www.cbr.washington.edu/dart/dart.html. 4 Dec. 2000.

Table 40 contains the transportation separation parameters used for the historical data files at the transportation projects. The transportation separation criterion is compiled from the annual reports from various sources on the juvenile fishery operation of the Columbia Basin and transportation plans and studies for the years 1975-1999. These criterion are used in conjunction with the transport operation dates in Table 38 to create transportation records for each transport dam in the yearly input data files (**.dat**). In CRiSP.1, `high_flow` is set to 0 when no flow criterion is specified for separation. This forces separation to occur under all flow conditions until separation is terminated by the `hfl_pass_perc` of the indicator species (always set to `Chinook_1`). When the transport operations criterion specifies *transport all* with no separation specifications, then `high_flow` is set to 1. During a model run, this forces no separation of the collected fish to occur, and as a result, all fish collected are transported.

Table 40 Transport separation parameters[a] for historical data files, 1975-1999, at Lower Granite (LWG), Little Goose (LGS), Lower Monumental (LMN), and McNary (MCN) dams.

Year	Dam	Separation @ kcfs	Criterion[b]	Ref.	`hfl_pass_perc`[c]	`high_flow`
1975	LGS		transport all	d	0	0
1976	LWG		transport to 50% of run	Park et al. 1977	1	0
	LGS		transport to 50% of run		1	0
1977	LWG		transport to 65% of run	Park et al. 1978	0	0
	LGS		transport to 65% of run		0	0

Table 40 Transport separation parameters[a] for historical data files, 1975-1999, at Lower Granite (LWG), Little Goose (LGS), Lower Monumental (LMN), and McNary (MCN) dams.

Year	Dam	Separation @ kcfs	Criterion[b]	Ref.	`hfl_pass_perc`[c]	`high_flow`
1978	LWG		transport all		0	0
	LGS		transport all		0	0
1979	LWG		transport all; control by spill	COFO 1980	0	0
	LGS		transport all; control by spill		0	0
	MCN		transport all; control by spill		0	0
1980	LWG		transport all; control by spill	COFO 1981	0	0
	LGS		transport all; control by spill		0	0
	MCN		transport all; control by spill		0	0
1981	LWG		transport all; control by spill	COFO 1982	0	0
	LGS		transport all; control by spill		0	0
	MCN		transport all; control by spill		0	0
1982	LWG		full trans @ 80% yearlings	COFO 1983	0.8	0
	LGS		full trans @ 80% yearlings		0.8	0
	MCN		transport all		0	0
1983	LWG	none sep by size	full trans @ 80% yearlings	COFO 1984	0.8	0
	LGS	none sep by size	full trans @ 80% yearlings		0.8	0
	MCN	none sep by size	full trans @ 80% yearlings		0.8	0
1984	LWG		full trans @ 80% yearlings	BPA 1984	0.8	0
	LGS		full trans @ 80% yearlings		0.8	0
	MCN		full trans @ yearlings < subyearlings		0.95	0

Table 40 Transport separation parameters[a] for historical data files, 1975-1999, at Lower Granite (LWG), Little Goose (LGS), Lower Monumental (LMN), and McNary (MCN) dams.

Year	Dam	Separation @ kcfs	Criterion[b]	Ref.	`hfl_pass_perc`[c]	`high_flow`
1985	LWG		full trans @ 80% yearlings	Karr and Mather 1985	0.8	0
	LGS		full trans @ 80% yearlings		0.8	0
	MCN		full trans @ yearlings < subyearlings		0.95	0
1986	LWG		full trans @ 80% yearlings	CBFWA 1986	0.8	0
	LGS		full trans @ 80% yearlings		0.8	0
	MCN		full trans @ yearlings < subyearlings		0.95	0
1987	LWG		full trans @ 80% yearlings	CBFWA 1987	0.8	0
	LGS	100	full trans @ 80% yearlings		0.8	100
	MCN	220	full trans @ yearlings < subyearlings		0.95	220
1988	LWG		full trans @ 80% yearlings	CBFWA 1988	0.8	0
	LGS	100	full trans @ 80% yearlings		0.8	100
	MCN	220	full trans @ yearlings < subyearlings		0.95	220
1989	LWG		transport all	USACE 1989c	0	0
	LGS	100	full trans @ 80% yearlings		0.8	100
	MCN	220	full trans @ yearlings < subyearlings		0.95	220
1990	LWG		transport all	USACE 1990	0	0
	LGS	100	full trans @ 80% yearlings		0.8	100
	MCN	220	full trans @ yearlings < subyearlings		0.95	220

Table 40 Transport separation parameters[a] for historical data files, 1975-1999, at Lower Granite (LWG), Little Goose (LGS), Lower Monumental (LMN), and McNary (MCN) dams.

Year	Dam	Separation @ kcfs	Criterion[b]	Ref.	`hfl_pass_perc`[c]	`high_flow`
1991	LWG		transport all	USACE 1991	0	0
	LGS	100	full trans @ 80% yearlings		0.8	100
	MCN	220	full trans @ yearlings < subyearlings		0.95	220
1992	LWG		transport all	USACE 1992a	0	0
	LGS	100	full trans @ 80% yearlings		0.8	100
	MCN	220	full trans @ yearlings < subyearlings		0.95	220
1993	LWG		transport all	USACE 1993	0	0
	LGS	100	full trans @ 80% yearlings		0.8	100
	LMN	100	full trans @ 80% yearlings		0.8	100
	MCN	220	full trans @ yearlings < subyearlings		0.98	220
1994	LWG		transport all	USACE 1994b	0	0
	LGS	100	full trans @ 80% yearlings		0.8	100
	LMN	100	full trans @ 80% yearlings		0.8	100
	MCN	220	full trans @ yearlings < subyearlings		0.98	0
1995	LWG		transport all	USACE 1995	0	0
	LGS	100	full trans @ 80% yearlings		0.8	100[d]
	LMN	100	full trans @ 80% yearlings		0.8	100[d]
	MCN		full trans @ yearlings < subyearlings		0.96	0

Table 40 Transport separation parameters[a] for historical data files, 1975-1999, at Lower Granite (LWG), Little Goose (LGS), Lower Monumental (LMN), and McNary (MCN) dams.

Year	Dam	Separation @ kcfs	Criterion[b]	Ref.	`hfl_pass_perc`[c]	`high_flow`
1996	LWG		transport all	d	0	0
	LGS	100	full trans @ 80% yearlings		0.8	100[d]
	LMN	100	full trans @ 80% yearlings		0.8	100[d]
	MCN		full trans @ yearlings < subyearlings		0.85	0
1997	LWG		transport all	d	0	0
	LGS	100	full trans @ 80% yearlings		0.8	100[d]
	LMN	100	full trans @ 80% yearlings		0.8	100[d]
	MCN		full trans @ yearlings < subyearlings		0.76	0
1998	LWG		transport all	d	0	0
	LGS		transport all		0	0
	LMN		transport all		0	0
	MCN		full trans @ yearlings < subyearlings		0.91	0
1999	LWG		transport all	USACE 1999a	0	0
	LGS		transport all		0	0
	LMN		transport all		0	0
	MCN		full trans @ yearlings < subyearlings		0.98	0

[a] High Flow Species (`high_flow_species`) is set to Chinook 1 for all dams for all transportation years.

[b] Criterion Definitions:
transport all: transport all fish that are collected; does not mean that all fish passing a dam are transported
full trans @ 80% yearling: transport all collected fish after a date when it is estimated that 80% of the yearling chinook run has passed the dam
full trans @ yearlings < subyearlings: transport all collected fish after a date when it is determined that the majority of the yearling chinook run has passed the dam and subyearling chinook are the dominate species in the collection
transport all; control by spill: transport all fish that are collected with collection at the dam controlled by spill

[c] High Flow Percent (`hfl_pass_perc`) at McNary Dam is set to the median value 95% from Table 39 for the years 1984-1992 for which there is no Smolt Index passage data.

[d] Dave Hurson, U.S. Army Corps of Engineers, Walla Walla District. Telephone conversation with author, 6 July 2000.

The goal of separation is to retain steelhead for transport and return the other, smaller fish to the river. The parameter separtion probability (`separation_prob`), as used in CRiSP.1, represents the percent of the collected fish that will be returned to the river. Separation probability is species-specific and set for each dam to represent the ability of the dam to separate individuals of that species during bypass. Estimates of separation probability are based on the total number of fish collected and the total number of fish transported from each transportation dam as reported in the annual transportation reports.[1] These estimates are included in Table 41.

Table 41 Separation Probability (`separation_prob`) estimates as used in CRiSP.1, based on the total number of fish collected and the total number of fish transported from each transportation dam.

Year	Dam (report comment)	Species	Total Number Collected	Total Number Transported	Separation Probability
1982 (Basham et al. 1983)	LWG (no recorded bypass)	chin1	361369	356952	0.01
		chin0	110367	110415	(0.00)
		steelhead	1458060	1373312	0.06
	LGS (no recorded bypass)	chin1	230104	224425	0.02
		chin0	121612	107864	0.11
		steelhead	908541	897460	0.01
	MCN (no recorded bypass)	chin1	822009	789918	0.04
		chin0	1696104	1600708	0.06
		steelhead	364174	353492	0.03
1983 (Delarm et al. 1984)	LWG (no recorded bypass)	chin1	900210	862160	0.04
		chin0	239904	235256	0.02
		steelhead	1326091	1265283	0.05
	LGS (no recorded bypass)	chin1	275109	166983	0.39
		chin0	27925	24960	0.11
		steelhead	689119	673646	0.02
	MCN (no recorded bypass)	chin1	720756	10710	0.99
		chin0	4389357	4222176	0.04
		steelhead	338267	55368	0.84

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[1] For early transportation years, CRiSP.1 uses the “80/20” criterion. This means that 80% of the smaller fish are successfully returned to the river and 20% of the steelhead are also returned to the river, and 80% of steelhead are successfully retained for transportation and 20% of the smaller fish are transported.

Table 41 Separation Probability (`separation_prob`) estimates as used in CRiSP.1, based on the total number of fish collected and the total number of fish transported from each transportation dam.

Year	Dam (report comment)	Species	Total Number Collected	Total Number Transported	Separation Probability
1984 (Koski et al. 1985)	LWG (no recorded bypass)	chin1	828332	824464	0.00
		chin0	97639	96925	0.01
		steelhead	1114740	1113675	1.00
	LGS	chin1	786583	488499	0.38
		chin0	243668	157596	0.35
		steelhead	1695494	1617549	0.05
	MCN	chin1	1261187	292572	0.77
		chin0	4098004	3909983	0.05
		steelhead	610511	366647	0.40
1985 (Koski et al. 1986)	LWG	chin1	1742244	1730180	0.01
		chin0	44008	42817	0.03
		steelhead	2689579	2679990	0.00
	LGS	chin1	1114640	905272	0.19
		chin0	28175	27094	0.04
		steelhead	1124082	1073809	0.04
	MCN	chin1	2952613	902123	0.69
		chin0	6562483	6411493	0.02
		steelhead	840493	547710	0.35
1986 (Koski et al. 1987)	LWG	chin1	1625352	1572408	0.03
		chin0	51628	50435	0.02
		steelhead	3089551	3052991	0.01
	LGS	chin1	722867	694044	0.04
		chin0	2644	2595	0.02
		steelhead	1365409	1353341	0.01
	MCN	chin1	2486407	289768	0.88
		chin0	6135379	5848547	0.05
		steelhead	716335	344854	0.52

Table 41 Separation Probability (`separation_prob`) estimates as used in CRiSP.1, based on the total number of fish collected and the total number of fish transported from each transportation dam.

Year	Dam (report comment)	Species	Total Number Collected	Total Number Transported	Separation Probability
1987 (Koski et al. 1988)	LWG (no juvenile bypass)	chin comb	2497635	2466595	0.01
		steelhead	3013986	3003262	0.00
	LGS	chin comb	1021760	987722	0.03
		steelhead	953917	914724	0.04
	MCN	chin1	3450113	1689419	0.51
		chin0	7029401	6665048	0.05
		steelhead	1004967	690179	0.31
1988 (Koski et al. 1989)	LWG (no juvenile bypass)	chin comb	2790395	2775282	0.01
		steelhead	4741920	4727691	0.00
	LGS (no juvenile bypass)	chin comb	828016	816661	0.01
		steelhead	896311	889348	0.01
	MCN	chin1	2971263	2852953	0.04
		chin0	6884478	6696264	0.03
		steelhead	822944	815716	0.01
1989 (Koski et al. 1990)	LWG	chin1	2585531	2320084	0.10
		chin0			
		steelhead	5246843	4447768	0.15
	LGS	chin1	1367170	1049898	0.23
		chin0			
		steelhead	1601833	1255389	0.22
	MCN	chin1	2332718	624845	0.73
		chin0	5019631	4574417	0.09
		steelhead	943347	672196	0.29

Table 41 Separation Probability (`separation_prob`) estimates as used in CRiSP.1, based on the total number of fish collected and the total number of fish transported from each transportation dam.

Year	Dam (report comment)	Species	Total Number Collected	Total Number Transported	Separation Probability
1990 (Ceballos et al. 1991)	LWG	chin1	3200401	3187485	0.00
		chin0			
		steelhead	6139402	6133053	0.00
	LGS	chin1	1379295	1362693	0.01
		chin0			
		steelhead	952899	949249	0.00
	MCN	chin1	2344063	1854828	0.21
		chin0	7099003	6997022	0.01
		steelhead	620526	546444	0.12
1991 (Baxter et al. 1996)	LWG	chin1	2295306	2270166	0.01
		chin0	15599	15196	0.03
		steelhead	6282557	6112540	0.03
	LGS	chin1	1133986	1123886	0.01
		chin0	4106	4024	0.02
		steelhead	1110651	1104467	0.01
	MCN	chin1	1870638	735990	0.61
		chin0	4017330	3673677	0.09
		steelhead	549080	326148	0.41
1992 (Baxter et al. 1996)	LWG	chin1	2496805	2465920	0.01
		chin0	6054	6011	0.01
		steelhead	4406612	4291805	0.03
	LGS	chin1	1010333	1002191	0.01
		chin0	3001	2914	0.03
		steelhead	781074	771540	0.01
	MCN	chin1	2554039	2458090	0.04
		chin0	6193658	5780411	0.07
		steelhead	557989	538008	0.04

Table 41 Separation Probability (`separation_prob`) estimates as used in CRiSP.1, based on the total number of fish collected and the total number of fish transported from each transportation dam.

Year	Dam (report comment)	Species	Total Number Collected	Total Number Transported	Separation Probability
1993 (Baxter et al. 1996)	LWG	chin1	1782168	1684228	0.05
		chin0	16469	16263	0.01
		steelhead	6223636	5864193	0.06
	LGS	chin1	842973	497114	0.41
		chin0	10042	9510	0.05
		steelhead	1157983	826265	0.29
	LMN	chin1	540277	372484	0.31
		chin0	76745	76416	0.00
		steelhead	719493	536374	0.25
	MCN	chin1	1216056	558147	0.54
		chin0	4239846	4019359	0.05
		steelhead	450863	339958	0.25
1994 (Hurson et al. 1999)	LWG	chin1	2179329	2155140	0.01
		chin0	6769	6725	0.01
		steelhead	4701402	4653482	0.01
	LGS	chin1	696298	662504	0.05
		chin0	4168	4028	0.03
		steelhead	802378	774772	0.03
	LMN	chin1	1054265	895057	0.15
		chin0	6459	5897	0.09
		steelhead	570297	536374	0.06
	MCN	chin1	2217602	1913653	0.14
		chin0	5079565	4621965	0.09
		steelhead	562268	483206	0.14

Table 41 Separation Probability (`separation_prob`) estimates as used in CRiSP.1, based on the total number of fish collected and the total number of fish transported from each transportation dam.

Year	Dam (report comment)	Species	Total Number Collected	Total Number Transported	Separation Probability
1995 (Hurson et al. 1999)	LWG	chin1	3780519	3493439	0.08
		chin0	31019	28855	0.07
		steelhead	5915634	5522860	0.07
	LGS	chin1	1839335	1486521	0.19
		chin0	19571	15345	0.22
		steelhead	1212063	897354	0.26
	LMN	chin1	1485757	930707	0.37
		chin0	12101	8750	0.28
		steelhead	1234106	716598	0.42
	MCN	chin1	1739833	19301	0.99
		chin0	6124925	5446950	0.11
		steelhead	431125	1272	1.00
1996 (Hurson et al. 1999)	LWG	chin1	589890	516539	0.12
		chin0	17346	16742	0.03
		steelhead	4586509	4551937	0.01
	LGS	chin1	332765	329401	0.01
		chin0	10008	9777	0.02
		steelhead	1536236	1530064	0.00
	LMN	chin1	350398	322974	0.08
		chin0	8755	8663	0.01
		steelhead	966165	923598	0.04
	MCN	chin1	568781	23664	0.96
		chin0	3309408	2921165	0.12
		steelhead	370239	9626	0.97

Table 41 Separation Probability (`separation_prob`) estimates as used in CRiSP.1, based on the total number of fish collected and the total number of fish transported from each transportation dam.

Year	Dam (report comment)	Species	Total Number Collected	Total Number Transported	Separation Probability
1997 (Hurson et al. 1999)	LWG	chin1	281825	278121	0.01
		chin0	90910	87012	0.04
		steelhead	4322725	4205576	0.03
	LGS	chin1	194472	87600	0.55
		chin0	60742	57011	0.06
		steelhead	1928202	459160	0.76
	LMN	chin1	234739	119954	0.49
		chin0	18848	18277	0.03
		steelhead	1672872	591396	0.65
	MCN	chin1	458705	26207	0.94
		chin0	5587014	5209575	0.07
		steelhead	481333	26417	0.95
1998 (Hurson et al. 1999)	LWG	chin1	1604689	1491722	0.07
		chin0	81806	78810	0.04
		steelhead	5085525	4956044	0.03
	LGS	chin1	900122	888412	0.01
		chin0	52896	50848	0.04
		steelhead	1505203	1500648	0.00
	LMN	chin1	492765	487277	0.01
		chin0	22953	21428	0.07
		steelhead	949322	935917	0.01
	MCN	chin1	1045547	37341	0.96
		chin0	8290717	7948235	0.04
		steelhead	327396	10960	0.97

Table 41 Separation Probability (`separation_prob`) estimates as used in CRiSP.1, based on the total number of fish collected and the total number of fish transported from each transportation dam.

Year	Dam (report comment)	Species	Total Number Collected	Total Number Transported	Separation Probability
1999[a]	LWG	chin1	2173493	2044080	0.06
		chin0	253340	250143	0.01
		steelhead	3355165	3087680	0.08
	LGS	chin1	3532362	3489662	0.01
		chin0	197307	192502	0.02
		steelhead	3135606	2974297	0.05
	LMN	chin1	1892443	1741907	0.08
		chin0	133140	132436	0.01
		steelhead	1978791	1727103	0.13
	MCN	chin1	2104596	3745	1.00
		chin0	4226607	3382015	0.20
		steelhead	537698	4883	0.99

[a] Fish Passage Center. Bi-Weekly Report #99-31. October 29, 1999.

While the goal of separation is to retain steelhead for transportation and return smaller fish to the river, it is import to note that there is great variability in the actual separator efficiencies at each dam for each year. Tables 42, 43, and 44 show the separator efficiencies as reported in the transportation program annual reports for the three separation dams: Little Goose, Lower Monumental and McNary. CRiSP.1 does not address the great variability in separator efficiencies at the dams.

Table 42 Little Goose Separator Efficiencies from the Juvenile Transportation Program annual reports (U.S. Army Corps of Engineers 1996c, 1999b).

Year	Yearling Chinook A-side		Sub-yearling Chinook A-side		Steelhead B-side		Sockeye/Kokanee A-side	
	Hatch.	Wild	Hatch.[a]	Wild	Hatch.	Wild	Hatch.[b]	Wild
1990	80.0			--	84.2	46.3		64.8
1991	65.3			22.0	81.2	53.1		37.2
1992	72.1			31.1	93	57.9		20.0
1993	75.1	70.7		20.2	86.4	54.6		12.6
1994[c]	47.6	44.1		29.2	91.4	70.8		16.0
1995	60.3	57.0		8.4	87.8	52.4		30.0
1996	70.9	74.6		34.2	69.2	50.1	21.1	44.2
1997	60.0	59.8	17.6	18.8	75.3	50.9	32.0	60.0
1998	64.8	64.5	47.1	45.3	85.2	55.3	40.0	21.8

a. Hatchery subyearling chinook without PIT tags were not present until 1997.
b. Hatchery sockeye were not present until 1995.
c. Modification to separator.

Table 43 Lower Monumental Separator Efficiencies from the Juvenile Transportation Program annual reports (U.S. Army Corps of Engineers 1999b).

Year	Yearling Chinook A-side		Subyearling Chinook A-side[a]	Steelhead B-side		Sockeye/Kokanee A-side	
	Hatch.	Wild		Hatch.	Wild	Hatch.[b]	Wild
1993	26.3	34.1	27.1	98.7	90.5		10.5
1994	65.6	57.5	31.3	65.1	40.0		24.4
1995	61.6	56.1	17.8	65.2	27.4	4.6	19.4
1996	42.2	38.7	18.8	66.2	45.8	10.8	21.9
1997	63.9	49.5	22.2	55.6	34.7	11.1	24.9
1998	50.9	39.2	15.7	72.7	50.1	15.1	7.1

a. Hatchery and wild subyearling chinook were combined in 1993, 1995, and 1997.
b. Hatchery sockeye were not present until 1995.

Table 44 McNary Separator Efficiencies from the Juvenile Transportation Program annual reports (U.S. Army Corps of Engineers 1996c, 1999b).

Year	Yearling Chinook A-side	Sub-yearling Chinook A-side	Steelhead B-side		Coho A-side	Sockeye A-side	ref.
			Hatch	Wild			
1990	84.1	92.6	60.1	36.6	81.4	84.6	b
1991	77.4	92.8	61.7	42.6	75.8	83.5	c
1992	79.9 79.7	93.9 85.4	55.8 60.2	43.8 43.5	68.9 68.4	66.3 67.0	c d
1993	67.5 70.5	79.4 80.9	65.5 63.8	47.6 45.0	66.3 66.8	69.5 70.6	c d
1994[a]	35.0 35.5	47.5 48.7	92.8 96.1	77.8 80.3	24.1 24.3	26.4 27.4	c d
1995	53.1 52.8	60.4 58.1	84.5 84.6	55.1 55.1	20.6 20.6	35.1 35.1	c d
1996	36.8	46.3	88.1	67.0	25.6	22.7	d
1997	39.3	56.9	75.5	59.1	38.1	34.5	d
1998	41.4	49.8	84.1	62.8	22.9	26.7	d

a. New facility and separator began operation.
b. Ceballos et al. 1992.
c. U.S. Army Corps of Engineers 1996c.
d. U.S. Army Corps of Engineers 1999b.

II.6.5 - Transport Merit Function

In PATH, the FLUSH model used a transport merit function to characterize the transport control ratio experiments of Snake River spring chinook smolts from the years 1971 through 1979. Four equations were developed: the FLUSH Transport Merit, the FLUSH TURB1 Transport Merit, the FLUSH TURB4 Transport Merit, the FLUSH TURB5 Transport Merit. The equations are as follows.

FLUSH Transport Merit

Source undocumented, but used in PATH prior to 1997. The equation is:

$$\frac{T}{C} = \frac{1}{V_t(1 + a\exp(-bV_n))} \tag{133}$$

where

- T/C = ratio of survival of transport fish to control fish from transport experiments
- V_n = in river survival of spring chinook smolts
- $a = 5.8259$, $b = 5.3533$, $V_t = 0.98$.

FLUSH Transport Merit TURBx

The FLUSH Tranport Merit TURBx equation are from Marmorek and Peters (1998). The equations take the form:

$$\frac{T}{C} = \frac{1}{V_n\left(1 + \exp\left(-\frac{(V_n - a)}{b}\right)\right)} \tag{134}$$

where

- T/C = ratio of survival of transport fish to control fish from transport experiments
- V_n = in river survival of spring chinook smolts
- a = 0.3281 (TURB1)
  = 0.3330 (TURB4)
  = 0.3292 (TURB5)
- b = 0.1936 (TURB1)
  = 0.1596 (TURB4)
  = 0.1868 (TURB5).

Note: Recent analysis indicated that significant numbers of control fish in the transportation experiments in the 1970s and 1980s were transported from dams below the transport experiment dams, which invalidates the transport experiments. We recommend against using the transport merit functions for analysis.

II.7 - Stochastic Processes

CRiSP.1 provides the ability to vary parameters over a run. This allows a representation of random factors. The randomness is incorporated in different ways for flow, dam passage, reservoir mortality and travel time. The approach is to describe specific parameters as having a deterministic part and a stochastic part. A deterministic part may change with the independent variables that determine the parameter but the value obtained does not change from one model run to another if all factors are the same. The stochastic part changes each time it is calculated in CRiSP.1 or between model runs. The value of the stochastic part is obtained from a random number distribution function using a broken-stick distribution function. This is described along with deterministic and stochastic parts of the parameters in the following sections.

II.7.1 - Stochastic Parameter Probability Density

Variation in many of the stochastic rate parameters is described by a broken-stick probability distribution function (pdf). This is a simple function based on a piecewise linear distribution. The probability density function and the cumulative density function are illustrated in Fig. 54. It is described using the 0, 50 and 100% cumulative probability levels.

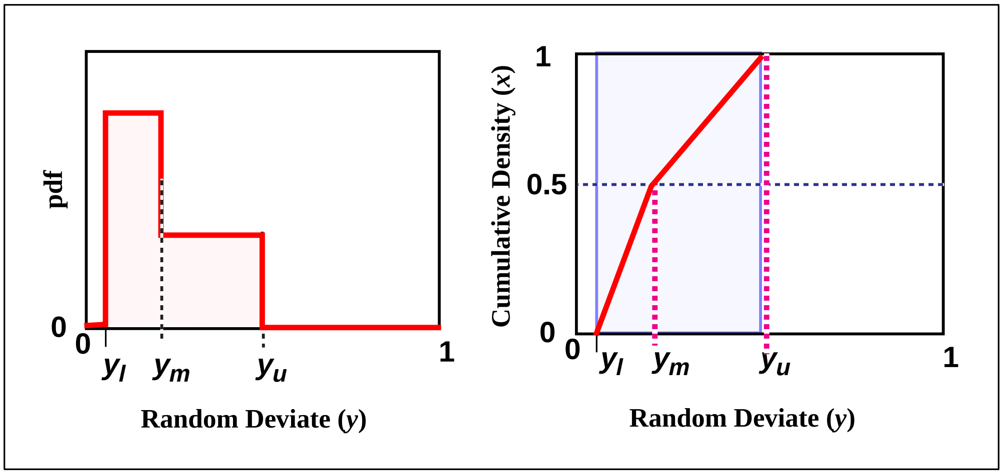

Fig. 54 Probability function (pdf) and cumulative function of the broken-stick probability distribution

Random deviates for this broken-stick density distribution are obtained from the following transformation formula:

$$\begin{aligned} y &= y_l + 2x(y_m - y_l) && y \le y_m \\ y &= y_m + 2(x - 0.5)(y_u - y_m) && y > y_m \end{aligned} \tag{135}$$

where

- x = unit uniform random deviate range 0 < x < 1
- y_l = lower limit of the distribution range
- y_m = distribution of the median value
- y_u = upper limit of the distribution range.

Although the distribution uses the median, the broken-stick input windows in CRiSP.1 use the mean value since most data reports include a mean in addition to the minimum and maximum values. The median is estimated from these three measures as:

$$y_m = \frac{4\bar{y} - y_l - y_u}{2} \tag{136}$$

assuming the mean of the distribution is equal to the average of the mean of the lowest 50% of the distribution and the highest 50%. These are simply the average of the minimum and median, and maximum and median, respectively.

Note that in a skewed distribution the mean and median are different. The result is that the mean specified by the user *must* fall in the middle two quartiles of the distribution, i.e. if the user specifies a minimum of 0 and a maximum of 100 for some distribution, the mean must lie between 25 and 75, inclusive. If the user specifies a distribution outside this range, CRiSP.1 will post a message to that effect in the message window and will direct the user to choose a mean that lies in the acceptable range.

II.7.2 - Stochastic Parameters

Migration

Variability in the migration rate is determined by the equation:

$$r_i(t) = r(t)V(i) \tag{137}$$

where

- $r(t)$ = determined from eq (48) on page 39
- $V(i)$ = variance factor which is different for each release i.

The term $V(i)$ is drawn from the broken-stick distribution. The mean value is set at 100%, representing the deterministic $r(t)$ and the upper and lower values are set with sliders in the **Migration Rate Variance** window in the **Behavior** menu.

The variance factor assumes that variability in migration velocity relative to water velocity is associated with a particular stock of fish. Studies of travel time support this assumption since particular stocks exhibit their own unique relationship with flow.

Flow

In the Scenario Mode, daily flow variations are described by a random process in headwater flow. Details of this process are described in the Headwater Modulation section on page 21.

Dam Passage

Variability in dam passage parameters is applied in each dam time slice, typically 6 hours. The variability is generated from the broken-stick distribution and is applied to the following variables:

- bypass mortality
- spill mortality
- turbine mortality
- transportation mortality
- day / night FGE
- spill efficiency.

II.7.3 - Scales of Stochastic Variability

The scales over which stochastic variability are applied is given in Table 45.

Table 45 Model probability density functions

Process	Equation	pdf	Scale
Migration rate variance	eq (52) on page 41	broken-stick	release group
Flow in Scenario	eq (16) on page 21	Normal	12 hrs

Table 45 Model probability density functions

Process	Equation	pdf	Scale
FGE & dam mortality	eq (127) on page 105	broken-stick	6 hrs
Spill efficiency	eq (128) on page 106	Normal	6 hrs

III. Calibration

III.1 - Calibration Overview

CRiSP.1 is a composite of individual, integrated, process submodels that jointly determine smolt migration and survival.

The model has many parameters which must be determined. The parameters with ecological meaning can often be determined from data sets from other related studies and systems. For the empirical parameters, the model or a submodel are calibrated to lab and field data using a variety of mathematical (optimization) fitting methods. The end result is that through the parameter determination and calibration process, diverse theories and data sets are synthesized into a consistent picture of the process of fish migration and survival through the river system.

Environmental variables describe the observable state of the environment in which fish live. These variables have been determined from historical records dating back as far as 1937 for some of the variables and dating back to 1970 for all variables. Future values of these variables are assessed from runs of hydromodels and management-derived scenarios of river operations. The environmental variable sets must be determined before the model can be calibrated.

Fish passage observations involve a variety of data, extending back several decades, on the passage timing and survival of fish through various segments of the river and hydrosystem. The observations range from relatively small-scale information on the passage of individual groups of fish at individual dams to system-wide estimates of passage and survival of species over specific years. Observations include brand release studies conducted during the 1970’s and 1980’s and PIT-tag studies starting in the late 1980’s. These data sets yield two levels of information. The direct observations provide passage numbers and timing at individual dams as well as returns of adults to dams and collection points. These raw numbers can be further reduced to estimates of migration rates and fish survival between points in the river and in some cases collection efficiencies at dams.

After all possible variables and parameters have been determined and after any submodels which can be calibrated externally to the model have been calibrated, the parameters related to reservoir passage survival and travel time are calibrated within the model. That is, the model-predicted survivals and travel times are calibrated to National Marine Fisheries Service (NMFS) survival estimates and to PIT-tag passage data (courtesy of Pacific States Marine Fisheries Commission). In this way, the whole model is ultimately calibrated to data.

The CRiSP.1 model contains a number of different theoretical constructs that can be selected at run time. The selection of which construct to use depends on the available information, the effect of the feature on the calibration, and its ecological soundness. Any calibration of the model is only specific to a particular choice of theoretical constructs.

III.1.1 - Parameter Determination and Calibration Techniques

Ecological model parameters are determined (estimated) from both field observations and laboratory studies. Estimates made from field observations (such as fish passage timing or mortality rates) are used with the corresponding environmental variables. Estimates made from laboratory experiments are analyzed assuming the corresponding laboratory conditions and are used to infer the relevant ecological parameters. For example, the estimation of mortality from gas bubble disease is made based upon laboratory experiments.

Parameter determination involves mixing results from laboratory experiments, isolated field studies on aspects of migration, and system-wide studies of survival and timing. Parameters are determined directly from studies where possible. Then the calibration proceeds in a hierarchy of steps where submodels are calibrated first (where possible) and finally the migration (travel time parameters) and survival (predation parameters) submodels are calibrated within the model. The calibration sequence is: river and environmental description, flow processes, dam processes, and finally migration processes and predation mortality. The final two steps are in part connected (e.g., in the model, slower migration can result in higher predation mortality), so they are calibrated iteratively until both converge.

Goodness-of-fit

In calibration, the parameters are adjusted so that the model (or a submodel) prediction best fits the observations according to statistical criteria and within ecological constraints. A variety of goodness-of-fit measures are applied in the calibrations. The choice of method depends on the type and quantity of data and the dimensions of the data being fit. Where possible graphical examples are given along with statistical measures of the goodness-of-fit. The following approaches are used.

- Least Squares, 2 dimensional regressions (Press et al. 1992) used for
  - TDG supersaturation mortality rates vs. time
  - size vs. mortality rate
  - spill efficiency equations
- Nonlinear regression using the Gauss-Newton algorithm to minimize sums of squares (Statistical Sciences, Inc. 1991) used for
  - TDG supersaturation mortality rate vs. TDG level
  - prediction of migration rate parameters vs. flow and fish age
- Hyperbolic “amoeba routine” (Press et al. 1992) used for
  - TDG mortality rate vs. TDG level
- Fourier series analysis (Statistical Sciences, Inc. 1991) used for
  - determining scenario mode flow modulators
- Maximum likelihood estimators via a Marquardt method or a Conjugate Gradient method (Press et al. 1992) are used for
  - determining migration rate parameters
  - determining predation rate parameters

In cases with limited data, statistical techniques might not converge to a unique best fit solution. In this case the calibration is assisted by selecting one of the parameters within its range inferred from ecological constraints, and then calibrating the remaining parameters.

III.1.2 - Parameter Determination and Calibration Status

The calibration process involves fitting the submodels to data using goodness-of-fit measures. Environmental condition variables are ascribed and the ecological parameters are calibrated in a hierarchy that can be organized according to categories of similarity and interdependency.

Status by Type

Environmental variables and ecological parameters are listed below along with a description of the state of their calibration.

- *Environmental conditions* (define river condition)
  - River description parameters relating geometry of river and dams. These parameters are fairly well described and no further improvements of these parameters are expected at this time.
  - Headwater parameters define the river environment flow and temperatures. Flow data exist for years from 1960 through 1999. Temperature data in headwaters exists from 1966 through 1999. These parameters are fairly well described and no improvements are expected at this time (other than adding new data for each new year).
- *Ecological parameters* (characterize ecological interactions)
  - Total dissolved gas supersaturation parameters relate the buildup of gas as function of spill, flow, and temperature. These have been calibrated with data current through 1999.
  - Age at smoltification initiation (`smolt_onset`) and completion (`smolt_finish`) which are release-specific and also may depend on release date itself. Release information along with the predicted passage information at dams and reaches comprises the passage data in the model. These parameters are critical to survival estimates and are under further study.
  - Dam parameters describing passage mortality at dams and fish guidance efficiency have been derived from two decades of studies including results obtained from recent PIT tag studies.
  - Transportation mortality calibration depends on the transport benefit ratio and in-river survival estimates. Although initial estimates have been obtained, both of these factors are under further analysis.
  - Relative predator densities have been derived for each river zone in each reach of the Snake and Columbia rivers and tributaries. These densities were derived from CPUE data where available or converted from predation index data otherwise. For reaches with no data, the densities were assumed to be the same as for nearby reaches. The density information includes base densities for 1990 and prior as well as yearly updates to account for the effects of the pikeminnow removal program.
  - Migration rate parameters have been calibrated for spring/summer and fall chinook and steelhead using data from PIT-tag studies.
  - Predator activity has been derived from pikeminnow consumption information from John Day reservoir for spring and fall chinook and steelhead.
  - Predator temperature response parameters have been calibrated for spring and fall chinook and steelhead using NMFS survival estimates.

Status by Submodel

The CRiSP.1 submodels have been calibrated individually or within the model. Data sources are mentioned in the following list. See also the relevant sections in Chapter 2 as well as the following sections on calibration of gas supersaturation and calibration of migration and predation rate parameters.

Travel Time (Migration Rate)

The travel time submodel was calibrated for fall chinook, spring chinook, and steelhead using tagging data from the entire river system and over the entire migration season. Two separate calibration steps were applied: one to measure the spread of fish as they move through the reservoir, and the other to measure the change in relative migration velocity with fish age. The first used marked, individual stock releases over a short period of time, and the second used marked and recaptured fish over entire seasons.

Predation Survival (Predation Rate)

The predator densities were derived from predation studies in John Day Reservoir and information on the CPUE or the predation index for each of the major reservoirs. The densities were adjusted after 1990 to account for the pikeminnow removal program.

Predator-prey interactions including predator temperature response were calibrated to NMFS survival estimates for fall chinook (1995-1998), spring chinook (1993-1998), and steelhead (1994-1998). Predator activities in the forebay and main reservoir were set to the ratio of smolt consumption by pikeminnow in those zones.

Gas Bubble Disease

The rate of mortality was calibrated from dose-response studies conducted in both field and laboratory conditions.

Dam Passage

Fish guidance efficiency and spill efficiency were calibrated from a number of studies at a variety of dams. Mortalities in dam passage were determined from mark-recapture studies at dams, and we used the values produced by PATH.

Transportation Passage

Separation of large and small fish in transportation was applied from general information on separation criterion for each transportation facility compiled from various sources on the juvenile fishery operations and transportation plans and studies. A transportation mortality was estimated for each species. In addition, time to transport fish through the river system was specified.

Total Dissolved Gas Supersaturation

Total dissolved gas (TDG) supersaturation models were calibrated with data from the U.S. Army Corps of Engineers. The data includes information collected in the 1992 drawdown study in Lower Granite Reservoir and Little Goose Reservoir (Wik et al. 1993), and total dissolved measurements from basin-wide gas monitoring stations from 1994 to 1999.

Flow

Headwater flows in the Scenario Mode were calibrated from information on stream flows provided by the U.S. Geological Survey. In Monte Carlo Mode, modulators of the period average hydroregulation model flows were calibrated with daily flow records at dams.

Water Velocity

Water velocity requires information on reservoir and geometry. The relationship between geometry and elevation and free flowing stream velocities were determined from Lower Granite Reservoir drawdown studies.

Stochastic Processes

The ranges for variables used in the Monte Carlo Mode have been calibrated to available data in the above mentioned studies.

III.2 - Total Dissolved Gas Calibration

WES Linear and Exponential Curves

The majority of the total dissolved gas (TDG) calibration work is based on published documents by Waterways Experiment Station (WES), U.S. Army Corps of Engineers. Some of WES's calibrations were not used because of structural modifications to the dam or additional data that suggested a different dynamic. For these dams, the calibration of the new production equations were developed from the gas monitoring station data[1]. The empirical equations derived from the WES calibrations depend on spill alone, and hence if there are significant structural or operational changes to a specific dam, new calibrations would most likely needed.

Different day and night spill patterns for adult and juvenile fish passage at the dams require different production equations. In the case where there is no discernible difference between night and day gas production, the day and night equations are set to be the same.

Table 46 Lower Snake and Lower Columbia dams, gas production curves using linear or exponential models.

Project	%TDG =		Reference
BON	$0.12 \cdot Q_s + 105.61$		WES 1996
TDA	$124.3 - 9 \cdot \exp(-0.273 \cdot Q_s/12)$	juvenile pattern (night)	WES 1997a
	$124.3 - 9 \cdot \exp(-0.2731 \cdot Q_s/23)$	adult pattern (day)	WES 1997a
JDA	$121.1 - 17.7 \cdot \exp(-0.016 \cdot Q_s)$	juvenile pattern (night) 1998 (with new deflectors)	
	$128.4 - 24.4 \cdot \exp(-0.024 \cdot Q_s)$	adult pattern (day) 1998 (with new deflectors)	
	$0.203 \cdot Q_s + 108.5$	Before 1998[a]	WES 1997a
MCN	$0.0487 \cdot Q_s + 114.9$		WES 1997a

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[1] As of 1998, all major dams in the Columbia Basin have fixed gas monitoring stations in the tailwater recording water quality data.

Table 46 Lower Snake and Lower Columbia dams, gas production curves using linear or exponential models.

Project	%TDG =		Reference
IHR	$120.9 - 20.5 \cdot \exp(-0.023 \cdot Q_s)$	1998 (with 2 additional deflectors), current	
	$130.9 - 26.5 \cdot \exp(-0.022 \cdot Q_s)$	1997 (with new deflectors)	
	$138.7 - 79 \cdot \exp(-0.0591 \cdot Q_s)$	Before 1997	WES 1997a
LMN	$132.7 - 24.56 \cdot \exp(-0.0225 \cdot Q_s)$	juvenile pattern (night)	
	$131.2 - 36.1 \cdot \exp(-0.0592 \cdot Q_s)$	adult pattern (day)[a]	
LGS	$131.3 - 32.0 \cdot \exp(-0.01985 \cdot Q_s)$	juvenile pattern (night)	WES 1997a
	$0.53 \cdot Q_s + 100.5$	adult pattern (day)[a]	WES 1996
LWG	$138.0 - 35.8 \cdot \exp(-0.10 \cdot Q_s/6)$	(1996)	WES 1997a
	$138.0 - 35.8 \cdot \exp(-0.10 \cdot Q_s/8)$	(1995), current	WES 1997a

a. In CRiSP.1, an upper bound of roughly 145% was added to these equations.

For Lower Granite (LWG) and The Dalles (TDA) dams, WES (1997a) reference gave the production curve in the terms of q_s, discharge per spillbay. Here, q_s was converted to Q_s/n assuming the total discharge Q_s was uniformly distributed between the number n of spillbays. In general, because of possible construction or repairs at a dam, the number of spillbays will have to be set separately for each year. For example, the number of spillbays in use for Lower Granite was different for 1995 and 1996.

In the cases where the WES (1996) equations were used—Bonneville Dam, Lower Monumental juvenile pattern, and Little Goose juvenile pattern—there was no new recommendation in the 1997 documentation. In fact, the authors felt that there was not a good fit available. The equations given in WES (1996) were nevertheless taken as a starting point for the new gas production model.

For the upper Columbia dams, the “best” fitting of the empirical gas production equations was chosen based on available hourly tailrace TDG data from 1995-1998. The bounded exponential equation performed well in all cases and is applied to all upper Columbia dams except Wells Dam, which uses the linear equation. The results of this calibration are shown in Table 47.

Table 47 Upper Columbia dams and Dworshak Dam gas production curves using linear or exponential model

Project	%TDG =
PRD	$130.9 - 25.15 \cdot \exp(-0.01045 \cdot Q_s)$
WAN	$139.45 - 26.87 \cdot \exp(-0.00915 \cdot Q_s)$
RIS	$141.1 - 26.9 \cdot \exp(-0.00874 \cdot Q_s)$
RRH	$137.6 - 21.4 \cdot \exp(-0.00733 \cdot Q_s)$

Table 47 Upper Columbia dams and Dworshak Dam gas production curves using linear or exponential model

Project	%TDG =
WEL	$0.15 \cdot Q_s + 107.2$ Night $0.47 \cdot Q_s + 107.9$ Day
CHJ	$140.1 - 34.8 \cdot \exp(-0.0241 \cdot Q_s)$
DWR	$135.95 - 71.1 \cdot \exp(-0.4787 \cdot Q_s)$

There was no data for Hells Canyon Dam, so a “generic” set of coefficients was used for this dam. The bounded exponential model, the one predominantly used for the other dams, was chosen and the coefficients were set for moderate gas production.

Table 48 Hells Canyon Dam gas production curves using exponential model

Project	% TDG =
HCY	$138 - 36 \cdot \exp(-0.02 \cdot Q_s)$

These calibrations are based on spill and typically represent the river best in moderate to high levels of spill. All gas production curves break down when spill is only a few kcfs. In this case, the spill flow retains the dissolved gas level of the forebay.

Exponential Empirical Equation

The parameters in Table 49 were obtained by fitting the exponential empirical submodel to the rating curves. This is the backup model under some circumstances for the dams listed in the table.

Table 49 Values for exponential empirical TDG model

Dam	a	b	k
Default	30.0	0.025	0.03
Bonneville	30.0	0.025	0.03
McNary	30.0	0.025	0.03
Priest Rapids	30.0	0.025	0.03
Wanapum	30.0	0.025	0.03
Rock Island	30.0	0.025	0.03
Rocky Reach	30.0	0.025	0.03
Chief Joseph	30.0	0.025	0.03
Little Goose	45.483192	0.010609	0.03

Table 49 Values for exponential empirical TDG model

Dam	*a*	*b*	*k*
Lower Granite	30.0	0.025	0.03
Dworshak	34.5	0.007248	0.03
Hells Canyon	32.35294	0.025	0.03

Hyperbolic Empirical Equation

This model is retained for backward compatibility. The calibration is applied to the hyperbolic empirical model given by eq (90) on page 75 where

- G = percent supersaturation above 100%
- Q_S = spillway flow volume in kcfs
- a, b and h = coefficients specific to each dam, derived from TDG rating curves provided by the U.S. Army Corps of Engineers.

Data for fitting these parameters were obtained from rating curves provided by Bolyvong Tanovan of the U.S. Army Corps of Engineers, North Pacific Division, Portland, OR. The graphs showing observed TDG concentrations in supersaturation for spill flows were copies of in-house documents (un-referenced and unpublished). The graphs were identified with the codes NPDEN-WC, DLL/KPA, 8MAR79. The ruling of the rating curves allowed a precision of ±0.5 kcfs and ±0.1 % saturation.

The parameters in Table 50 were obtained by fitting the hyperbolic submodel of eq (90) to the rating curves using a nonlinear “amoeba” routine from Press et al. (1992). Constraints on fitted parameters were

$$0 \le a \le 50$$
$$0 \le b \le 0.12$$
$$0 \le h \le 100.$$

The hyperbolic gas model is used as the backup equation at John Day Dam, only.

Table 50 Values for hyperbolic empirical TDG model

Dam	*a*	*b*	*h*
Default	30.00	0.0250	6.00
John Day to 1995	45.00	0.0250	6.00
John Day 1996, 1997	36.11	0.0250	6.00
John Day 1998, current	25.00	0.0247	7.67

GasSpill 1 and GasSpill 2 Mechanistic Equations

The mechanistic TDG saturation submodels were calibrated using flow/spill/gas saturation data from the rating curve data from 1984 to 1990. This data set was supplied by Tom Miller of the Walla Walla District, U.S. Army Corps of Engineers. The data originated from the Columbia River Operations Hydrological Monitoring System (CROHMS) database. At each dam, the data consisted of: hourly flow and spill, forebay saturation, forebay elevation, tailrace elevation, and temperature, all measured throughout the summer. Using the same gas dissipation mechanism as was used in earlier versions of CRiSP.1, the tailrace gas saturation was back-calculated from the next dam downstream.

For each point in time, the three parameters *a*, *b*, and *c* were estimated using a multiple linear regression of the equation defining K_{20} in terms of the energy loss rate, the forebay concentration, and the entrainment coefficient. The mechanistic model for GasSpill 2 assumes that these parameters are related as is given by eq (98) on page 77 where:

- K_{20} = entrainment coefficient
- E = energy loss rate
- P = forebay percent saturation
- *a*, *b*, and *c* = coefficients calculated from multiple linear regression of data in Table 51.

For each dam, K_{20} is calculated from data using:

$$K_{20} = 1.028^{20-T} \cdot \frac{Q_s}{W \cdot L \cdot \Delta} \cdot \log \frac{\bar{P} - \hat{G}_{fb}}{\bar{P} - \hat{G}_{sw}} \tag{138}$$

where

- T = water temperature in the forebay in ˚C
- Q_s= spill in kcfs
- W = spillway width (gates x width/gate)
- L = stilling basin length in feet
- $\hat{G}_{sf}$ = forebay gas saturation
- $\hat{G}_{sw}$ = back-calculated spillway gas saturation
- $\bar{P} = P_0 + (sgr \cdot \alpha \cdot 0.5 \cdot (D - Y_0)) + (0.25 \cdot \alpha \cdot (D + Y_0))$

  where

  - P_0 = barometric pressure in atmospheres (assume P_0 is 1)
  - sgr = specific gravity of roller (usually 1)
  - α = 0.0295 (density of water)
  - D = stilling basin depth in feet
  - $Y_0 = S/(W \cdot \sqrt{2gH})$
  - H = hydraulic head in ft is obtained from information in Table 52
  - g = 32.2 (gravitational constant)

  and

- $\Delta = \sqrt[3]{\bar{P} + 0.25\alpha(D + Y_0)} - \sqrt[3]{\bar{P} - 0.25\alpha(D + Y_0}.$

GasSpill 2 is used as the backup model at the dams listed in Table 51. GasSpill 1 is not currently calibrated for any dams.

Table 51 Parameters for GasSpill 2 model equation

Dam	*L*	Basin Floor Elev.	gate wd	# gates	sgr	*a*	*b*	*c*
Default GasSpill 2						3.31	0.41	-0.032
The Dalles	170.0	55.0	60	23	0.50	37.00	3.255	-0.394
Ice Harbor	178.0	304.0	60	10	1.0	28.05	1.38	-0.284
Lower Monumental	218.7	392.0	50	8	1.0	-2.55	4.53	0.018
Wells	30.0	670.0	46	11	1.0	27.84	2.40	-0.281

Table 52 Variables for reservoir geometry, in feet

Dam	Max. Forebay Elevation	Full Pool Depth at Head	Full Pool Forebay Depth	Elevation Spillway Crest	Normal Tailwater Elevation
Bonneville	82.5	68	93	24	16
The Dalles	182.3	85	105	121	80
John Day	276.5	105	149	210	163
McNary	357	75	105	291	269
Ice Harbor	446	100	110	391	343
Lower Monumental	548.3	100	118	483	440
Little Goose	646.5	98	140	581	540
Lower Granite	746.5	100	140	681	638
Priest Rapids	488	82.5	101.0		416
Wanapum	575	83.5	116		497
Rock Island	619	54	84		558
Rocky Reach	710	93	108.4		614
Wells	791	72	1111		707.4

K Entrainment

Model runs of CRiSP1.6 were used to determine the optimal value of the parameter `k_entrain`. This method is computationally intensive, but has certain advantages over simpler regressions. In particular, water travel time is computed based on river geometry and input information on flows and elevations and does not need to be input into the regression for each simulation.

For each dam in turn, CRiSP.1.6 was run with historical data sets from 1995 through 1998, and for each year, a range of `k_entrain` values between 0 and 1 was used to obtain total dissolved gas (TDG) output at the forebay of the downstream dam. CRiSP.1 produces values for the left and right side of the segment. These values were averaged to produce a single value for the downstream forebay. Then the output was compared to the Columbia River DART database on a day-by-day basis.

To examine the `k_entrain` values at Priest Rapids (PRD) and Ice Harbor (IHR), values at both dams were varied simultaneously since they both contribute to mixed waters at the confluence of the Snake and Columbia rivers.

The overall success of the `k_entrain` parameter for each of the model runs was determined by taking the mean sum of squares (MSS) for all days when there was both an observation and a model prediction:

$$MSS = \frac{\sum_{days}(G_{obs} - G_{model})^2}{n} . \tag{139}$$

A second test examined the sensitivity of the mixing coefficient θ_{dam} to a range of changes in `k_entrain`. This involved a series of runs for various levels of θ_{dam} and `k_entrain`.

The `k_entrain` values change from year to year. The optimized `k_entrain` values for each year and dam are shown in Table 32 on page 81; the analysis was restricted to values of TDG > 100% for both the observed DART values and the CRiSP.1 model predicted values. Ice Harbor, Priest Rapids and Bonneville dams were not evaluated.

Where CRiSP.1 is poor at fitting the data, even with the entrainment coefficient, other avenues should be explored: values of other gas parameters, accuracy of flow and spill archives, accuracy of historical gas data, functional form of the entrainment coefficient, etc.

Examples of the optimization profiles for 1998 are shown in Fig. 55. Sensitivity of gas production to the θ_{dam} values is very limited. Variation in the MSS was 1% or less across the range of theta from 0 to 10 for all the dams tested in 1997 and 1998. The only significant sensitivity was for Wanapum (WAN) in 1995 (11%) and 1997 (7.5%).

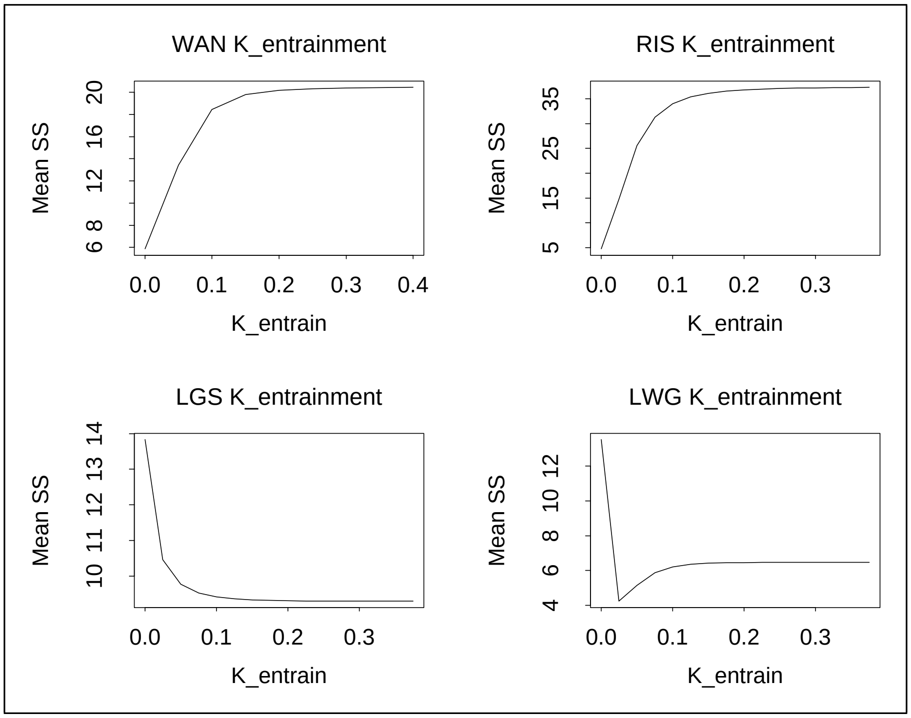


Fig. 55 Example of optimization of `k_entrain` values for 1998 for Wanapum (WAN), Rock Island (RIS), Little Goose (LGS), and Lower Granite (LWG).

III.3 - Predation Rate Parameter Calibration

The final sets of parameters to be calibrated are those for predation rate–including temperature response–and migration rate. Both of these sets are calibrated by using optimization routines to adjust parameters so as to *best fit* the model to relevant data.

Though travel time is not explicitly represented in the predation rate, it clearly factors into overall predation mortality in the model since slower migrants have more opportunity to become prey. In the same way, predation rate implicitly affects median travel time in the model since a higher predation rate has greater effect on the slower migrants. For this reason, the travel time and predation rate calibrations are run alternately until both calibrations have converged. We only have survival data for one stock from each species (spring chinook, fall chinook, steelhead); as a result, the predation rate parameters found by this process are then used for all stocks in that species.

The predation rate equation is based on the following parameters (from equations (61) and (63)):

- $\alpha_{forebay}, \alpha_{reach}$ and $\alpha_{tailrace}$ = predator activity in the river zones
- C_{MAX}, α and T_{INF} = temperature response equation parameters
- P = predator density (by zone in each river segment)
- T = water temperature in the river segment.

Note that C_{MAX} multiplies the three activity coefficients (depending on river zone) and thus can be thought of as scaling them. It was never intended that C_{MAX}, $\alpha_{forebay}, \alpha_{reach}$ and $\alpha_{tailrace}$

be calibrated simultaneously (as that would confound the optimization).

Survival Data

The survival data consists of National Marine Fisheries Service (NMFS) survival estimates and standard errors for both wild and hatchery released fish. The NMFS survival estimates for spring chinook, fall chinook, and steelhead were taken from the following studies.

Spring chinook and steelhead
    Iwamoto et al. 1994
    Muir et al. 1995
    Muir et al. 1996
    Smith et al. 1998
    Hockersmith et al. 1999
    Smith et al. 2000
Fall chinook
    Williams and Bjornn 1997
    Williams and Bjornn 1998
    Muir et al. 1999

Fall chinook survival estimates for 1998 were provided directly by Steve Smith of NMFS, Northwest Fisheries Science Center.

The spring chinook survival estimates consist of fish released above the Lower Granite Reservoir (RES) on multiple days in 1993-1995, and fish releases regrouped by week in the Lower Granite tailrace (LGR) for 1995-1998. A *survival reach* is defined as being from tailrace to tailrace. Estimates for survival are given from release (RLS) to Lower Granite tailrace (LGR), LGR to Little Goose tailrace (LGS), LGS to Lower Monumental tailrace (LMN), and LMN to McNary tailrace (MCN). Not all data exists for all years.

The fall chinook survival estimates consist of fish releases regrouped by week in Lower Granite tailrace (LGR) for 1995-1998 with estimates to LGS and LMN.

The steelhead survival estimates consist of fish releases regrouped by week in Lower Granite tailrace (LGR) for 1995-1998 with estimates to LGS, LMN and MCN, and fish releases regrouped by week in McNary tailrace for 1997-1998 with estimates to John Day tailrace (JDA) and Bonneville tailrace (BON).

Survival Calibration Process

For survival/predation parameter calibration, we produce a modeled survival S^m corresponding to each point S^o of the survival data. This relationship can be expressed as:

$$S^o_{i,j} = S^m_{i,j}(\Theta_{fixed}, \Theta_{pred}) + \varepsilon_{i,j}. \tag{140}$$

The model-estimated survivals depend both on parameters that are fixed Θ_{fixed} (e.g. flows, temperatures, predator densities as well as the migration rate parameters) and on the predation rate parameters Θ_{pred} that are adjusted to calibrate the modeled survival to the survival data.

The calibration process utilizes a conjugate gradient method (an optimization technique) to minimize the sum-of-squares difference between the survival data and the model-predicted survival in each survival reach *j* for each cohort (or release) *i* in each year:

$$SS = \sum_{year}\sum_{i,\,j} W_{i,\,j} \cdot (S^o_{i,\,j} - S^m_{i,\,j})^2 \tag{141}$$

where the weights are given (as they are in Hockersmith et al. 1999) as

$$W_{i,\,j} = w_{i,\,j} \Big/ \left(\sum_i w_{i,\,j}\right) \text{ for each } j \text{, where } \quad w_{i,\,j} = \frac{(S^o_{i,\,j})^2}{Var_{i,\,j}}.$$

The survival data in the numerator of the weighting counteracts the tendency of lower survivals having lower variances. This weighting also diminishes the relative weight of the lower survivals (which are thought to be less accurate).

III.3.1 - Parameter Determination and Calibration

Predator Densities

The predator densities have been determined (by zone and reach) from CPUE indices as described in Section II.4.2 Predation Mortality on page 45. We will revisit this below in the Section III.3.2 because of difficulties encountered in the calibration process due, in part, to the high variability of the predator densities between reaches.

Predator Activity Coefficient Determination

Since the survival data is given by reach, from tailrace to tailrace, there is currently no data to differentiate predation occurring in the forebay from that occurring in the reach (pool) and tailrace (or from mortality due to total dissolved gas supersaturation or dam passage). If we were to calibrate the three activity coefficients α_{reach}, $\alpha_{forebay}$, $\alpha_{tailrace}$ simultaneously, it is likely that the calibration tool would allocate all of the predation activity to the one segment of the model (e.g., forebay) that most closely mimics the survival data.

To avoid this problem, we set $\alpha_{forebay}$ and α_{reach} in the *ratio* of consumption rates (per predator) of smolt by pikeminnow as found by Vigg et al. (1991). That is we set $\alpha_{forebay} = 15.6$ and $\alpha_{reach} = 12.7$ for spring migrants (chinook and steelhead), and we set $\alpha_{forebay} = 20.0$ and $\alpha_{reach} = 12.4$ for fall chinook (see Table 17 and Table 18 on page 51). Calibration of the parameter C_{MAX} then scales the activity coefficients.

The tailrace mortality is handled differently in the model (see Zone Specific Formulations of the Predation Model section on page 47). In the calibration, we set $\alpha_{tailrace}$ so that tailrace mortality would be 1% for spring migrants and 2% for fall migrants (set by PATH) if the temperature was at its mean (10.9˚C for spring migrants, 17˚C for fall migrants) and the tailrace predator density was at its mean (15000 preds/km^2). The tailrace predations will, of course, vary since the actual temperatures and densities vary.

Temperature Response

Vigg and Burley (1991) provide laboratory results showing the activity response of predators (pikeminnow) to temperature. We thought it is important to try to see this temperature response in the survival data, so we did not wish to use their parameter values.

The survival data for spring chinook and steelhead, for example, corresponds only to temperatures in the 7-14˚C range (mostly 8-12˚C), and so the data cannot be used to predict the upper asymptote of the sigmoidal response. It turned out that many sigmoidal curves would produce a nearly-optimal fit. To counter this problem, we chose that the 95% level of consumption should correspond to a temperature of 15˚C (22˚C for fall). This is reasonable given the temperature range of the survival data.

The results from these fixed 95% level runs were used to provide good initial values for our final calibration runs (without the fixed point).

III.3.2 - Predator Density - Temperature Response Interaction

The most challenging problem of the spring chinook calibration effort related to the interaction between the predator density data and the temperature response equation and parameters in the spring chinook calibration. Three factors combined to cause the difficulty:

- lower than expected (by the model) survival data from Lower Monumental tailrace through McNary tailrace,
- lower predator densities in Ice Harbor and McNary reaches than in surrounding reaches, and
- slightly higher water temperatures in Ice Harbor and McNary reaches than between Lower Granite Reservoir and Lower Monumental Dam.

We observed that the calibration tool was trying to jack up the temperature response, using slightly higher downstream temperatures (i.e., higher activity) to make up for lower densities but higher predation in Ice Harbor and McNary reaches. To do this, the calibration tool was producing an extremely steep temperature response function—one with a predation rate as much as 50 times higher at 15˚C than at 10˚C for a given predator density. For comparison, Vigg and Burley's (1991) laboratory study found the predation rate to be approximately a 5.5 times higher at 15˚C than at 10˚C.

As a result, the late-season modeled survival rates were very low compared to the NMFS survival estimates. Also, the model was decimating the smolt downstream in the Columbia where both temperatures and densities were high.

Density Data Revised

In reaction to this problem of overly steep temperature response, we decided to level out the predator densities—either by averaging the densities for all reaches, all forebays and all tailraces, or by finding an average for each separately in the Snake (Lower Granite Reservoir to confluence), Mid-Columbia (confluence to Bonneville) and Estuary (below Bonneville) regions.

The five predator density options we studied were:

1. River-wide density averages (from 1990 data) for reach, forebay and tailrace.
2. Separate density averages (from 1990 data) in the Snake, Mid-Columbia and below Bonneville.
3. River-wide averages; adjusted (after 1990) for the pikeminnow removal program.
4. Separate averages in the Snake, Mid-Columbia and below Bonneville; adjusted (after 1990) for the pikeminnow removal program.
5. Original densities; adjusted (after 1990) for the pikeminnow removal program.

When the averaged density options (first four) were used, the calibrated sum-of-squares was in the range of 145 to 151. Also, the temperature response curves were of similar steepness to those found by Vigg and Burley (1991) (with $\alpha = 0.4$). It would be meaningless to compare our temperature response curve to Vigg and Burley's directly, since our C_{MAX} is scaled by the activity coefficient as well as by the relative predator density in each reach, forebay and tailrace.

When the full original density data (fifth option) was used, the minimum sum-of-squares was 174 and the temperature response curve was *unreasonably* steep (α much too large).

We opted for the 4th option as most reasonable: separate averages in the Snake, Mid-Columbia and below Bonneville; adjusted (after 1990) for the pikeminnow removal program. The predator densities in the data files (for spring chinook and steelhead) reflect this simplification. At this time, the predator densities for the fall chinook migration have not been averaged in this way.

III.3.3 - Results for Snake River Stocks

Tables 53, 54 and 55 compare CRiSP.1 modeled yearly average survivals to NMFS yearly average survivals in the research reach (for which NMFS estimates are given) and for the extended reach (research reach extended to Bonneville).

Figures 56, 57 and 58 show modeled verses observed (NMFS estimated) weekly survivals for spring and fall chinook and steelhead over all years for which data exists.

For fall chinook in particular (Fig. 58), the model has difficulty explaining variations in the data. Notice first that for the late season releases (after julian day 230, August 18) the NMFS estimates tend to be particularly low. An explanation for this might include fish residualizing. Also, the 1997 survivals tended to be low. This may be partially explained by the fact that 1997 was an extremely high flow year.

In fitting the predation parameters for the fall chinook, we found no temperature response. Since CRiSP.1 ultimately models changes in migration and predation due to changes in flow and temperature, the model has a particularly difficult time mimicking variations in the fall chinook survival estimates.

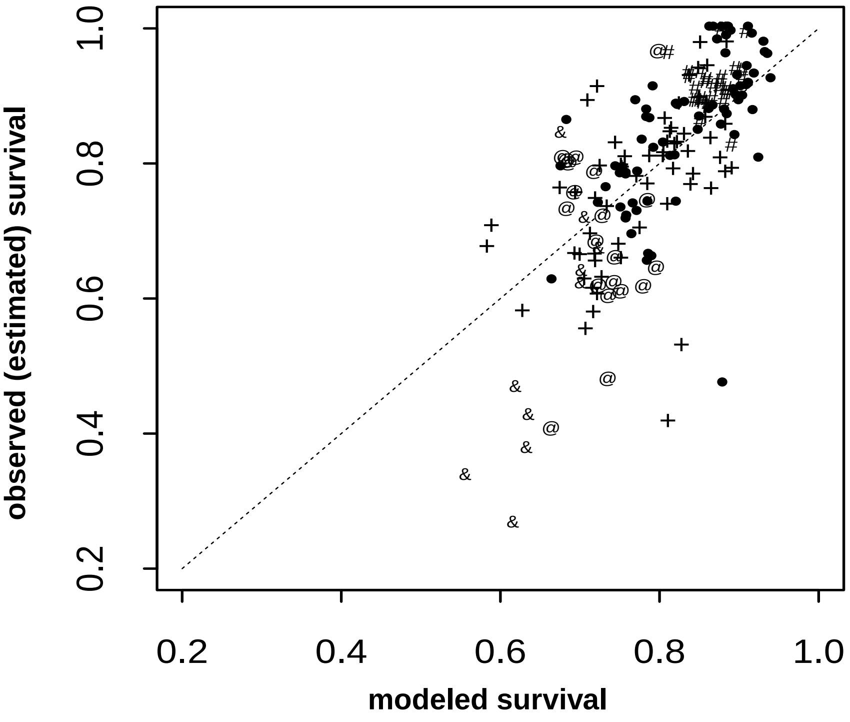
Table 53 Spring chinook CRiSP.1 survivals and NMFS survivals for the research reach and down to Bonneville for each year.

Year	Survival Through Research Reach			Extrapolated Survival		
	Research Reach	NMFS Estimates	CRiSP.1 Survivals	Extended Reach	NMFS Projections	CRiSP.1 Survivals
1993	RES-LGS	.75	.76	RES-BON	.32	.41
1994	RES-LMN	.64	.72	RES-BON	.31	.38
1995	RES-MCN	.66	.60	RES-BON	.51	.40
	LGR-MCN		.67	LGR-BON		.46
1996	LGR-MCN	.65	.73	LGR-BON	.47	.57
1997	LGR-MCN	.65	.76	LGR-BON	.48	.59

Table 53 Spring chinook CRiSP.1 survivals and NMFS survivals for the research reach and down to Bonneville for each year.

Year	Survival Through Research Reach			Extrapolated Survival		
	Research Reach	NMFS Estimates	CRiSP.1 Survivals	Extended Reach	NMFS Projections	CRiSP.1 Survivals
1998	LGR-MCN	.77	.68	LGR-BON	.63	.49
1999	LGR-BON	.56	.54			

1. The model is calibrated to weekly or daily survival estimates, not to the yearly average.
2. The NMFS survival projections are made by assuming that survival is equivalent in each reach during that year. This is an extremely simplistic model. We do not calibrate the model to those results and do not strive to reproduce those results.
3. The distribution of release numbers across a season can effect CRiSP.1 model survivals. In most cases, we do not have actual release numbers, and so have estimated a release distribution across the season based on release distributions from the few years with known release distributions.
4. At the time of this writing, we did not have NMFS survival estimates for the 1999 migrations, and so the model was not calibrated to the estimates for those years. The 1999 results are given for comparison; 1998 fish releases were used with 1999 temperature, flow and other river condition data to produce those results.



r	1993 - 1995	1995 - 1998
#	RES - LGR	
•	RES - LGS	LGR - LGS
+	RES - LMN	LGR - LMN
@		LGR - MCN (except 95)
&		LGR - MCN (95 only)

Fig. 56 Spring chinook, modeled vs. observed (NMFS estimated) survivals. The LGR - MCN survivals for 1995 were singled out to highlight the poor behavior of the late season portion of that data.

Table 54 Steelhead CRiSP.1 survivals and NMFS survivals for the research reach and down to Bonneville for each year.

Year	Survival Through Research Reach			Extrapolated Survival		
	Research Reach	NMFS Estimates	CRiSP.1 Survivals	Extended Reach	NMFS Projections	CRiSP.1 Survivals
1994	LGR-LMN	.77	.77	LGR-BON	.40	.35

Table 54 Steelhead CRiSP.1 survivals and NMFS survivals for the research reach and down to Bonneville for each year.

Year	Survival Through Research Reach			Extrapolated Survival		
	Research Reach	NMFS Estimates	CRiSP.1 Survivals	Extended Reach	NMFS Projections	CRiSP.1 Survivals
1995	LGR-LMN	.86	.80	LGR-BON	.59	.42
1996	LGR-MCN	.69	.67	LGR-BON	.52	.47
1997	LGR-MCN	.73	.71	LGR-BON	.47	.52
	MCN-BON	.65	.73			
1998	LGR-MCN	.65	.66	LGR-BON	.50	.45
	MCN-BON	.77	.69			
1999	LGR-BON	.50	.44			

1. The model is calibrated to weekly or daily survival estimates, not to the yearly average.
2. The NMFS survival projections are made by assuming that survival is equivalent in each reach during that year. This is an extremely simplistic model. We do not calibrate the model to those results and do not strive to reproduce those results.
3. For steelhead, the 1997 and 1998 projections to BON are actually the product of the LGR-MCN and MCN-BON survivals.
4. The distribution of release numbers across a season can effect CRiSP.1 model survivals. In most cases, we do not have actual release numbers, and so have estimated a release distribution across the season based on release distributions from the few years with known release distributions.
5. At the time of this writing, we did not have NMFS survival estimates for the 1999 migrations, and so the model was not calibrated to the estimates for those years. The 1999 results are given for comparison; 1998 fish releases were used with 1999 temperature, flow and other river condition data to produce those results.

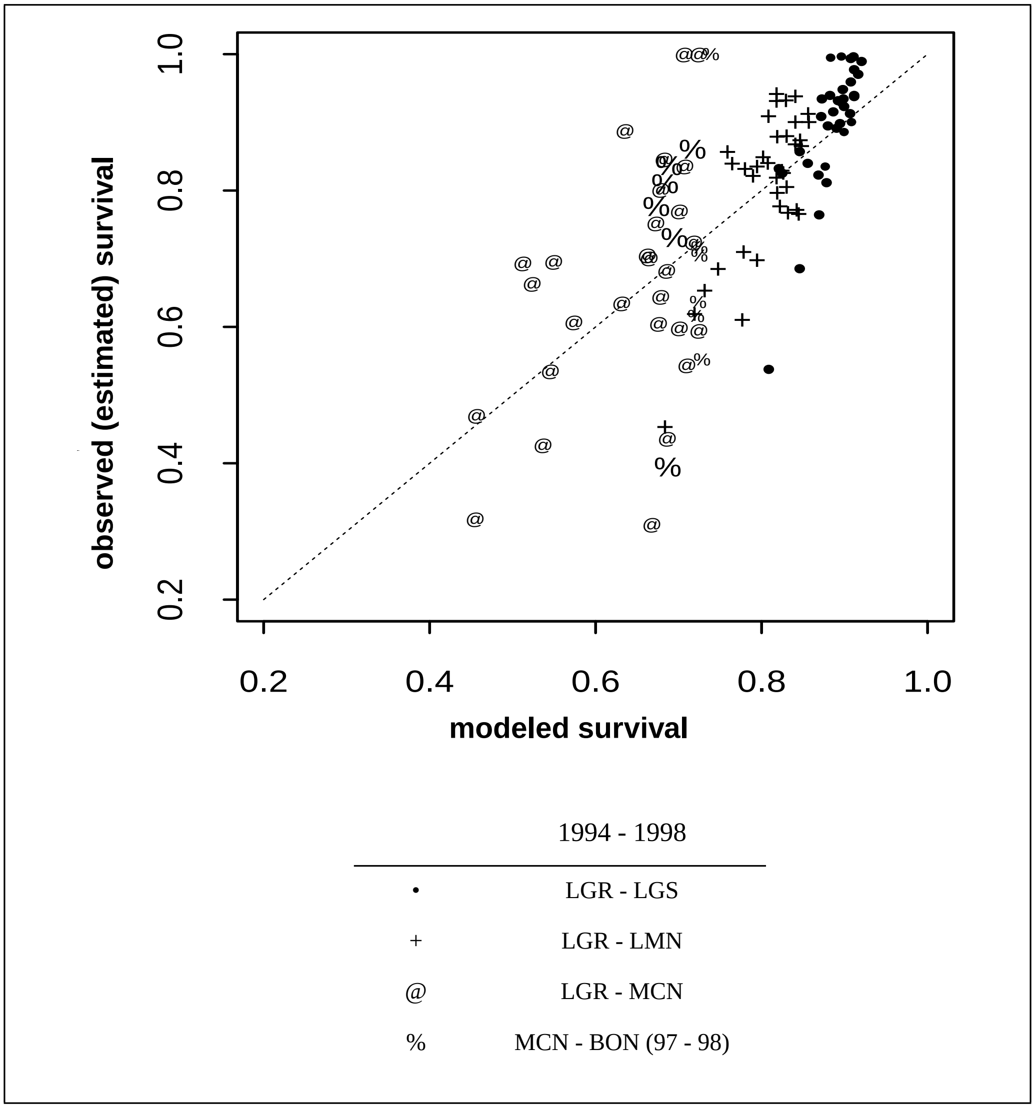


Fig. 57 Steelhead, modeled vs. observed (NMFS estimated) survival.

Table 55 Fall chinook CRiSP.1 survivals and NMFS survivals for the research reach and down to Bonneville for each year.

Year	Survival Through Research Reach			Extrapolated Survival	
	Research Reach	NMFS Estimates	CRiSP.1 Survivals	Extended Reach	CRiSP.1 Survivals
1995	LGR-LMN	.69	.66	LGR-BON	.32
1996	LGR-LMN	.67	.65	LGR-BON	.33
1997	LGR-LMN	.37	.63	LGR-BON	.31
1998	LGR-LMN	.73	.57	LGR-BON	.29

1. The model is calibrated to weekly or daily survival estimates, not to the yearly average.
2. The NMFS survival projections are made by assuming that survival is equivalent in each reach during that year. This is an extremely simplistic model. We do not calibrate the model to those results and do not strive to reproduce those results.
3. The distribution of release numbers across a season can effect CRiSP.1 model survivals. In most cases, we do not have actual release numbers, and so have estimated a release distribution across the season based on release distributions from the few years with known release distributions.

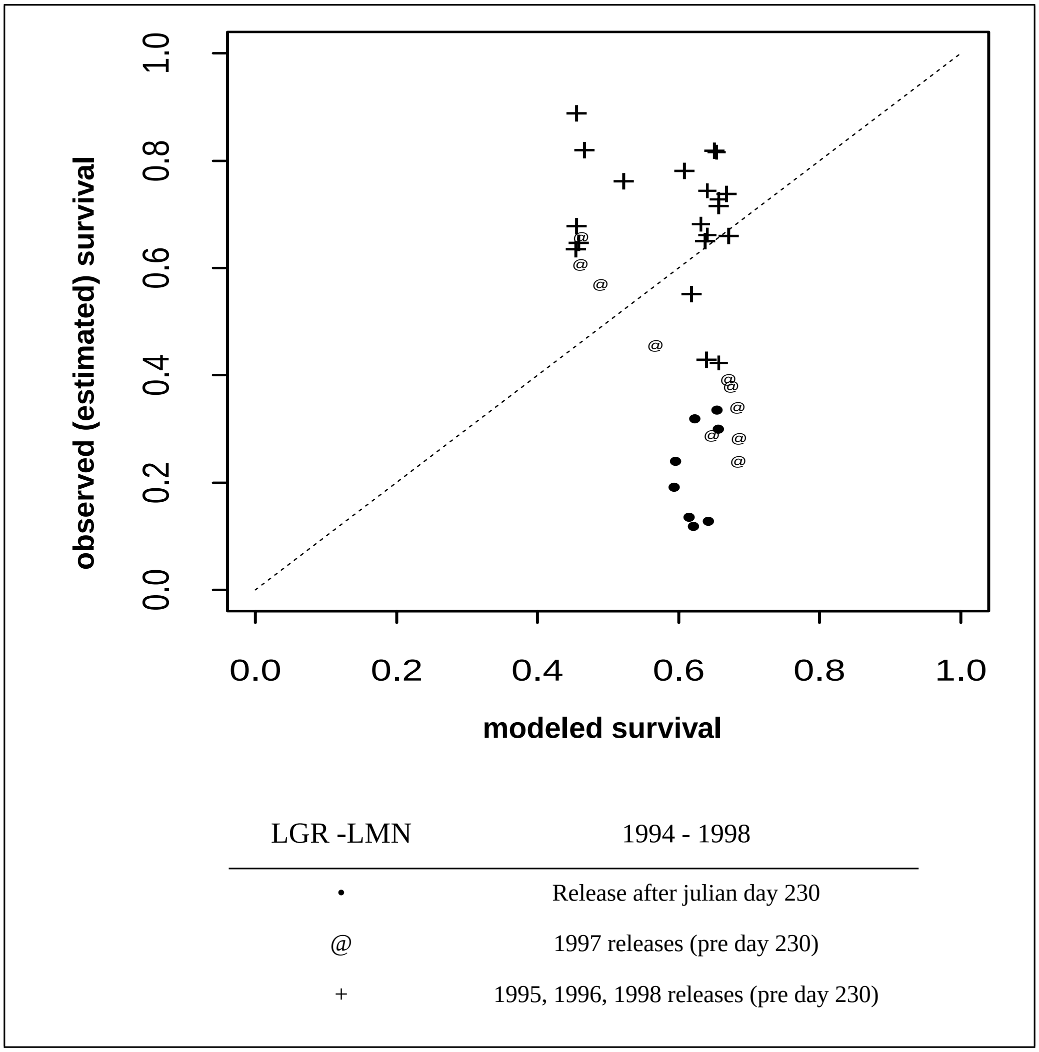


Fig. 58 Fall chinook, modeled vs. observed (NMFS estimated) survivals. The late season releases have been singled out as have the 1997 releases.

III.3.4 - Results for Upper Columbia River Stocks

As with the Snake River fall chinook, the model had a difficult time explaining variations in survival estimates (data) for the Upper Columbia *yearling* fall chinook. Figure 59, presenting modeled versus observed (NMFS estimated) survivals on a reach by reach basis, illustrates this. Figure 60, showing modeled versus observed survival from release to the John Day Dam tailrace, puts this fitting in a somewhat better light and indicates that the problems are at least partially caused by the irregularity of the survival estimates. Figures 61 and especially 62 show that the survival/predation calibration effort for the Upper Columbia steelhead was more successful.

Table 56 compares CRiSP.1 modeled yearly average survivals to estimated yearly average survivals in the research reach and for the extended reach (research reach extended to Bonneville). The survival estimates for the calibration of fall chinook are from Tables 10-16 in Eppard et al. (1999). The survival estimates for the calibration of steelhead are from Tables 4-

2 and 4-7 in Stevenson et al. (2000). The yearly averages reported in Table 56 are weighted averages for all releases calculated from those data sources.

For steelhead, the calibration decisively indicated no temperature response. But, with only a single year of data (1999), this is not a meaningful result. It should be noted that the calibration appeared to produce a temperature response, but it was an apparition. The first clue is that T_{INF} was near zero (to be meaningful it should be between about 7 and 18). Second, the SS was equal to that of a calibration where the temperature response was turned off (that is, with $\alpha = 0$). Third, by plotting the temperature response curve, one can see that all of the variation in response took place below 5˚C—below the range of temperatures to be encountered.

Note that for the Upper Columbia fall chinook stocks, the species level information in the **.dat** file is `Chinook_1` based on their *yearling* status and on their April to May downstream migration dates.

Calibration strategy for fall chinook

For the Upper Columbia fall chinook, the response surface was nearly flat within the range of physically *reasonable* temperature response parameters. Unfortunately, parameters outside this range produced the *best fit* as measured by the sum of squares (SS) difference between modeled and observed survivals.

The strategy for calibrating the predation/survival parameters was then to fix the temperature response steepness parameter α at values of 0.0, 0.2, 0.4 and 0.67 for separate calibration runs. The SS for all these cases was very similar. But, it turned out that the travel time/migration parameter calibration was extremely sensitive to the choice of temperature response parameters—giving, for example, an SS of double for α at 0.67 as for 0.2. (This level of sensitivity was not observed in the calibration for any other species.) The value α=0.2 turned out to be the best choice (least unstable) when the travel time calibration results were considered. Still, this calibration never reached a steady state. For all other species, the travel time and survival calibrations were run alternately until both *settled down*. For the Upper Columbia fall chinook, the sensitivity of the calibrations (especially of the travel time calibration to changes in predation parameters) made it necessary to *judge* which choice of parameters gave an overall best fit. This is worrisome since it indicates that the results may be very sensitive to small changes in environmental conditions.

It should also be noted that the zone-specific predation activity coefficients for each Upper Columbia species were taken from the Snake River species calibration. The two reasons for this were: only a single year of survival estimates was available for each species (so fitting of additional parameters would be of dubious value); and there is only space in the **.dat** files for one set of these parameters per species.

Predator Density

One possible factor in the calibration difficulties is the predator density values for the Upper Columbia. These were calculated at a different time from the Snake/Lower Columbia densities and may not be as reliable. Also, since the densities are *relative*, not absolute, it is possible that the Upper Columbia densities are not scaled properly as compared to the Lower Columbia densities.

Because of the high variability of densities between reaches (and the questionable reliability), the densities were averaged for each zone in the Upper Columbia.

Recently received CPUE data for all river zones on the Columbia and Snake Rivers will certainly improve our density values in future calibrations and may remedy these problems as well as other density related problems recounted in Section III.3.2.

Caveat

It should be pointed out again that for both Upper Columbia chinook and steelhead, there exists only one year of survival estimates. This is certainly not enough data to obtain a very meaningful calibration.

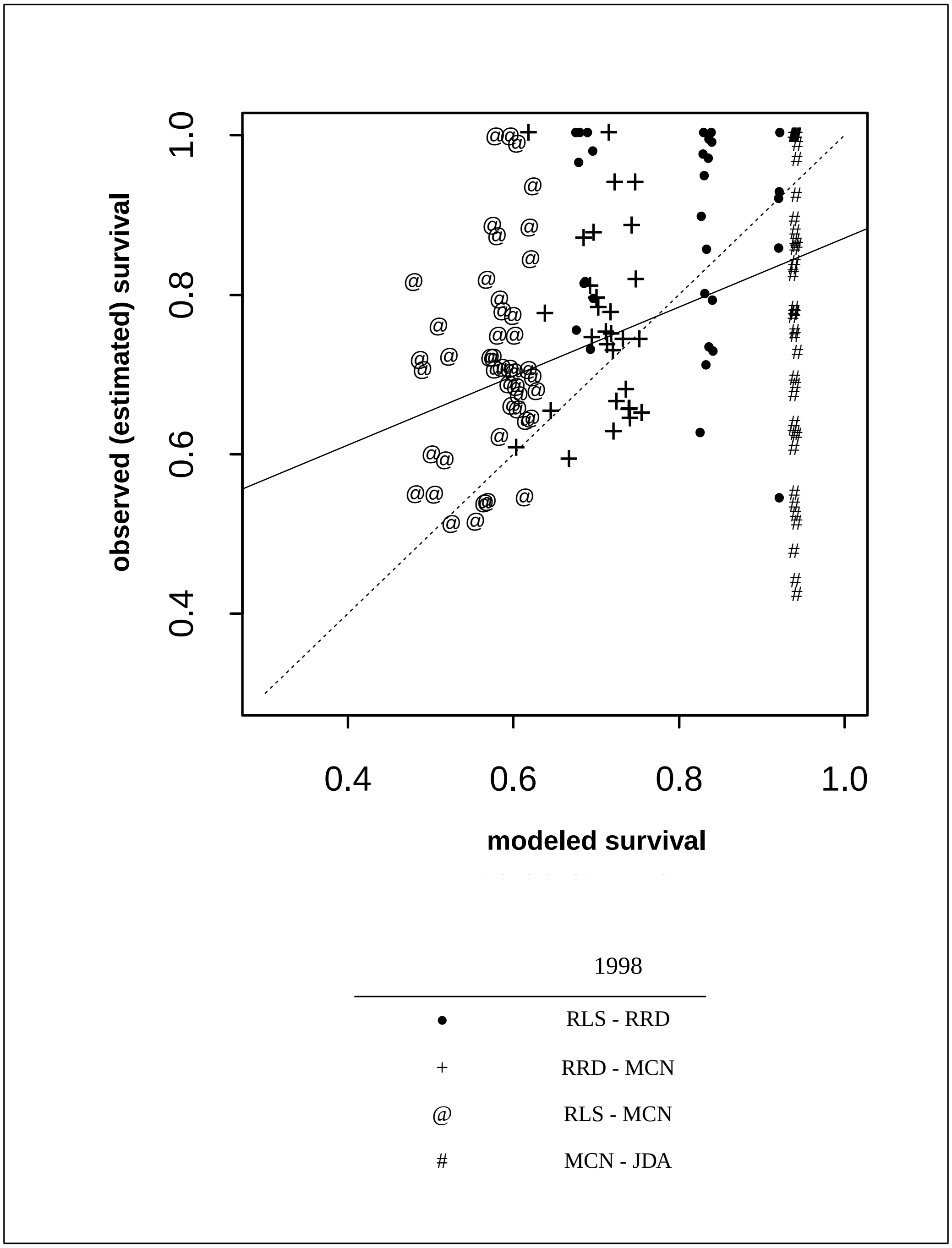


Fig. 59 Upper Columbia yearling fall chinook, modeled vs. observed (NMFS estimated) survivals. 1998 releases (RLS) are from Rock Island, Rocky Reach and Wells tailraces as well as Rocky Reach forebay. The dotted line is the one-to-one line, the solid line is the linear best fit to the modeled vs. observed plot.

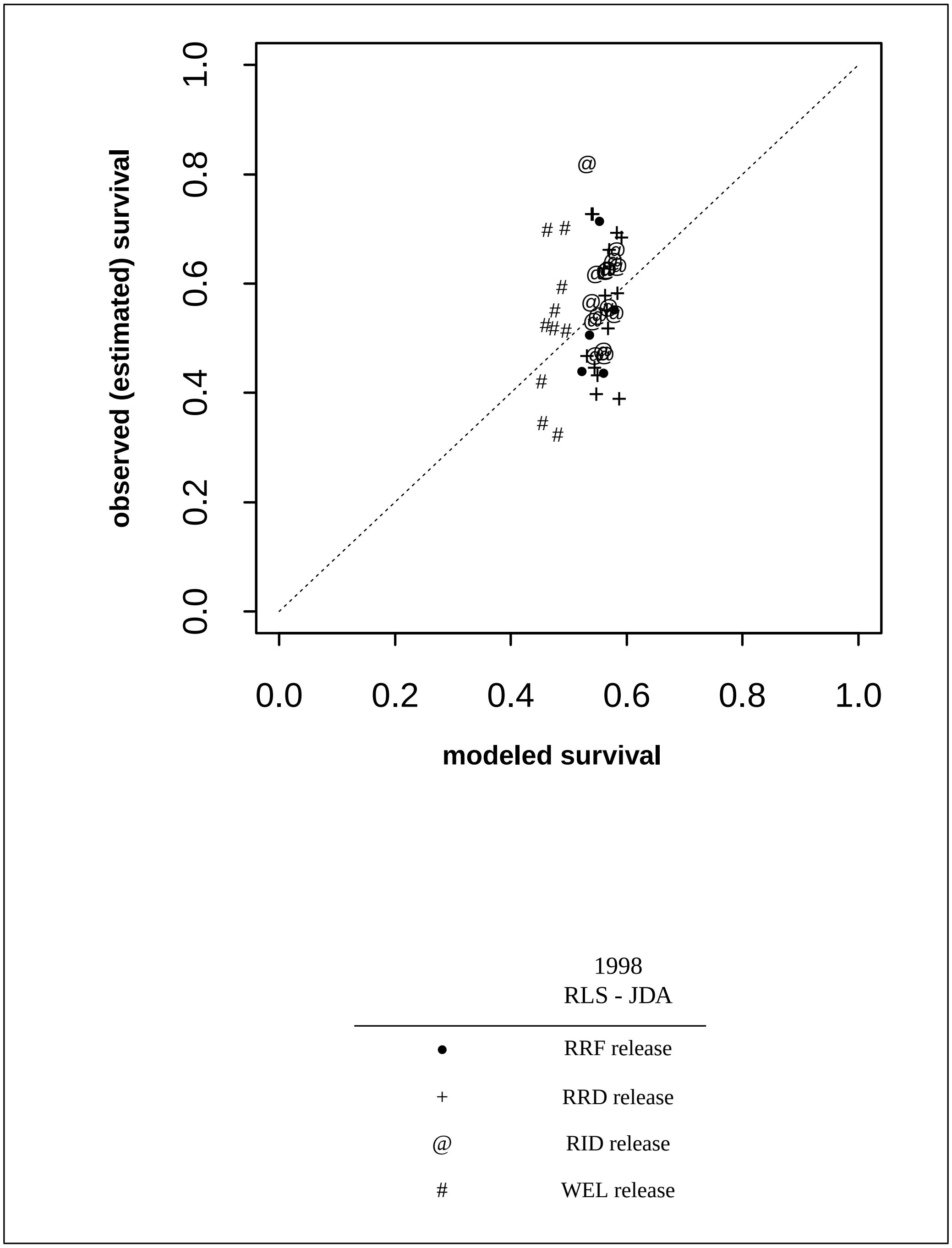


Fig. 60 Upper Columbia yearling fall chinook, modeled vs. observed (NMFS estimated) survivals from release to John Day Dam. 1998 releases are from Rocky Reach forebay, Rocky Reach, Rock Island, and Wells Dam tailraces.

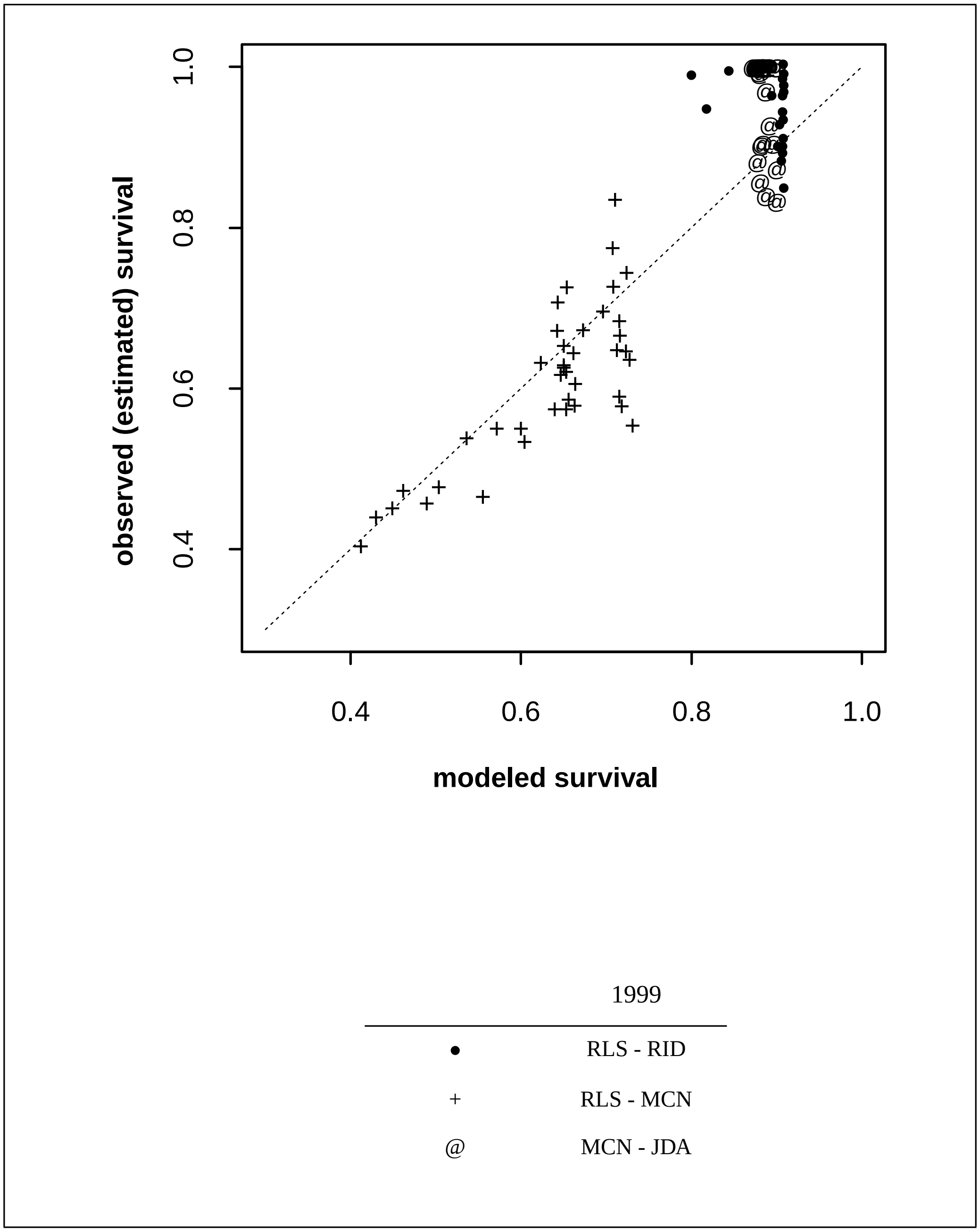


Fig. 61 Upper Columbia steelhead, modeled vs. observed (NMFS estimated) survivals. 1999 releases (RLS) are from Rock Island and Rocky Reach Dam tailraces.

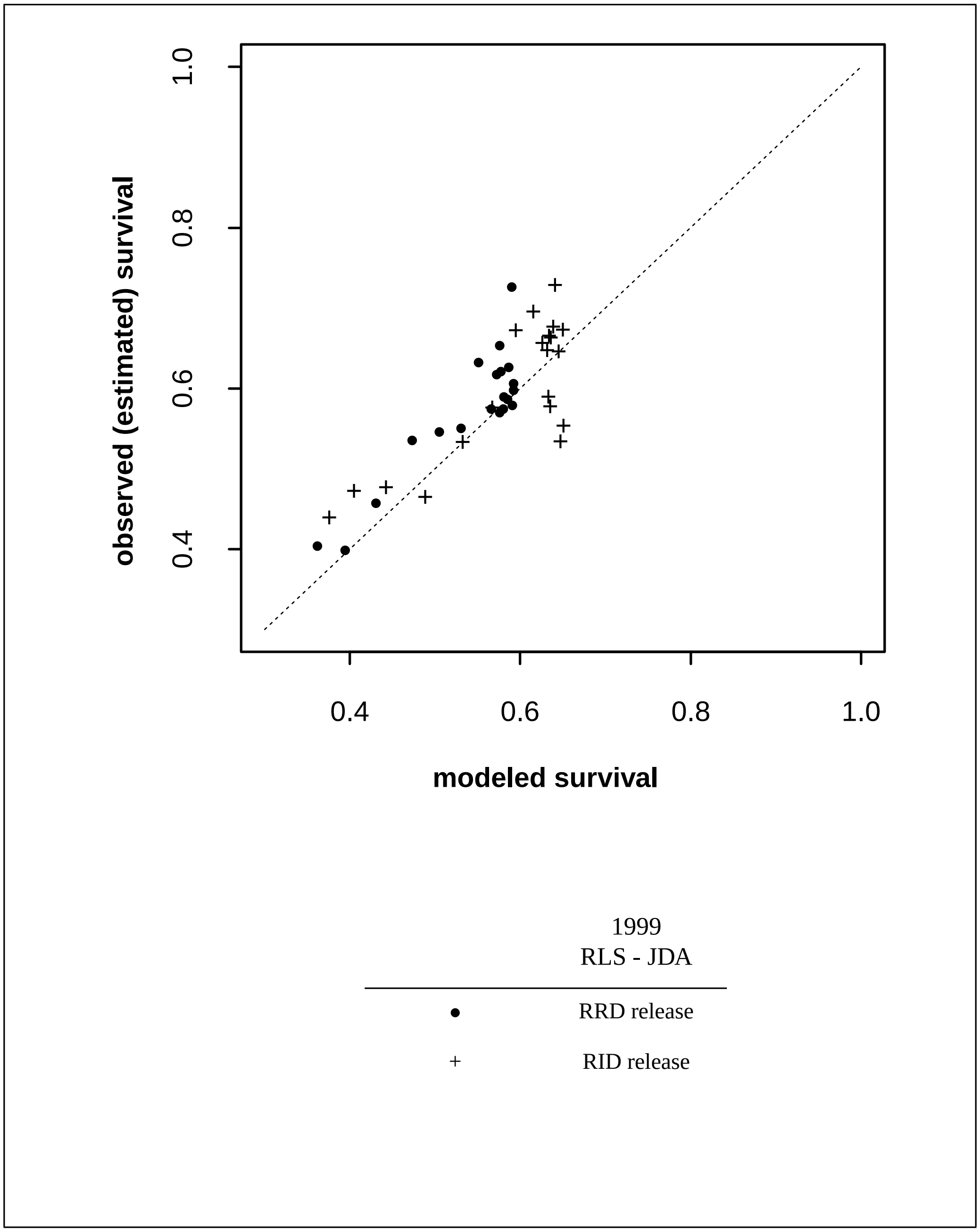


Fig. 62 Upper Columbia steelhead, modeled vs. observed (NMFS estimated) survivals from release to John Day Dam. 1999 releases are from Rocky Reach and Rock Island Dam tailraces.

Table 56 Upper Columbia steelhead and yearling fall chinook CRiSP.1 survivals and estimated survivals for the research reach and down to Bonneville for each year.

Species Year	Survival Through Research Reach			Extrapolated Survival	
	Research Reach	Survival Estimates	CRiSP.1 Survivals	Extended Reach	CRiSP.1 Survivals
fall chinook 1998	RLS-JDA	.52	.54	RLS-BON	.49
steelhead 1999	RLS-JDA	.59	.58	RLS-BON	.51

1. The model is calibrated to weekly or daily survival estimates, not to the yearly average.
2. Survival estimates were calculated as a weighted average of daily releases for all release sites.
3. The distribution of release numbers across a season can effect CRiSP.1 model survivals. In most cases, we do not have actual release numbers, and so have estimated a release distribution across the season based on release distributions from the few years with known release distributions.

III.4 - Calibration of Fish Travel Time Algorithms

After the combined survival/travel time calibrations are performed for each species (or a particular stock), the travel time parameters for the remaining stocks in each species are calibrated. The predation rate parameters found in the combined runs for each species are used in these additional stock runs.

The migration rate equation (eq (48) on page 39) has the following coefficients:

- $r(t)$ = migration rate (miles/day)
- t = julian date
- β_0, β_1, β_{FLOW} = migration rate regression coefficients
- V_f = average river velocity during the average migration period
- α_1, α_2= slope parameters
- T_{SEASN} = inflection point of flow dependent term (julian day)
- T_{RLS} = release date (julian day).

Other models containing a subset of these parameters are also used when appropriate (see eq (50) and eq (51) on page 40).

Travel Time Calibration Process

The procedure is to first organize fish into cohorts, which is comprised of fish released on the same day or on several consecutive days (see Construction of Cohorts section on page 161 for details). Based on these cohorts, the weighted sum of squares difference between modeled and observed median travel times is minimized with respect to the migration rate parameters:

$$SS = \sum_{year} \sum_{i=1}^{n} \sum_{j=1}^{k} W_{i,j} \cdot (tt_{i,j}^{m} - tt_{i,j}^{o})^2 \tag{142}$$

where the weights are given (as they are in Hockersmith et al. 1999) as:

$W_{i,j} = w_{i,j} / \left(\sum_i w_{i,j} \right)$ for each j, where $w_{i,j} = \frac{(tt_{i,j}^{o})^2}{Var_{i,j}}$, n is the total number of cohorts, and k is the total number of observation sites. This equation is fit using a conjugate gradient routine or a Levenberg-Marquardt routine (Press et al. 1992), with derivatives calculated numerically using a finite difference method (Gill, Murray, and Wright 1981).

The estimated migration rate parameters are provided, along with plots that compare the model-predicted average travel times to observed average travel times in Section III.4.1.

Estimating Velocity Variance (Vvar)

Velocity variance (Vvar) determines the rate of spreading of the cohort of fish and requires more detailed information to estimate than the migration rate parameters, which just require average travel time information. Estimating Vvar requires the distribution of travel times for a cohort; thus the unit of information for calibration is the daily counts. Since there is a great deal of variability in the variances associated with the daily counts, generalized least squares (Draper and Smith 1981) is used to estimate Vvar. Zabel (1994) provides the details of this procedure.

Smolt Start/Stop Date

The smolt dates determine when fish initiate migration. Before smolt start date, no migration occurs. After smolt start date and before smolt stop date, a proportion of the release initiate migration on a daily basis. After smolt stop date, all fish in the release have initiated migration. Note that these dates are only relevant if fish are released before they are ready to migrate. If the fish are active migrants, then smolt start and stop dates should be set to dates previous to release dates.

In order to estimate these dates, we require data of fish released before they are ready to migrate. Based on the arrival distribution at the first observation point and the travel time to reach that point, smolt start and stop dates can be estimated.

Migration Rate Variance

Variability in plots of observed versus modeled average travel times result from variations among particular releases. To account for this, a multiplicative variance is introduced by eq (52) on page 41 where:

- r = determined
- $V(i)$ = variance factor that varies *between* releases only.

$V(i)$ is drawn from the broken-stick distribution. The default values for spring and fall chinook and steelhead are mean = 1, low = 0.7, and high = 1.3.

Travel Time Data

Several criteria are used to select appropriate data sets. First, because migration rate is related to date in season and date of release, it is essential that the calibration data sets have fish released over long periods of time so these effects can be measured. Also, it is desirable to have fish released from the same site over multiple years so that a variety of river conditions are encountered. Sufficient numbers of fish must be observed at downstream observation sites, and fish must be observed at multiple sites. Finally, data sets are selected to represent as many stocks of fish and sections of the river as possible.

Construction of Cohorts

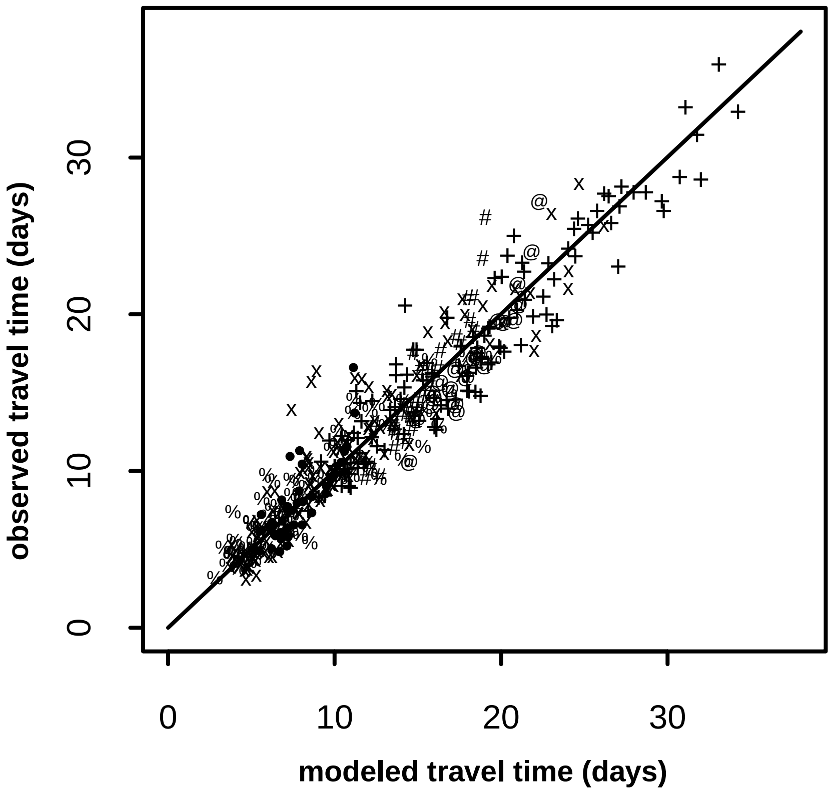
Before the calibration can be run, cohorts are constructed from available PIT-tag data. We set a target number of observations at downstream observation sites, minimum sample size at each site, and a maximum number of consecutive days that could be combined when forming a cohort. The goals of this process are to create relatively uniform sample sizes, restrict the range of release dates to capture seasonal variation, and maintain a minimum sample size to permit calculation of the rate of spreading of the population. Two methods were used to construct cohorts, depending on whether fish were tagged during the period of active migration or at upstream rearing grounds. In each case, all releases on the same julian day were combined in the same cohort.

For actively migrating fish, cohorts were formed based on dates of release. Releases were combined into a cohort until the target sample size was obtained for all included observation sites. If the target sample size was not reached when the maximum span of consecutive release days was reached and the minimum sample size was not achieved, then the cohort was rejected. In this case, the first julian day of releases in the cohort was dropped and the subsequent julian day of releases was added. This process was repeated until the cohort met the criteria and all release groups were examined.

In some cases, fish were collected in their rearing grounds and tagged prior to active migration. The travel time to the first observation site includes both pre-migration and migration periods. In our study of migration rates, this pre-migration period confounds the analysis. To restrict the analysis to actively migrating fish, we ignored migration prior to the first observation of an individual fish. To do this, we first identified individual fish that were observed at Lower Granite Dam and at least one subsequent site. This yields a measure of travel time between two points in the system for actively migrating fish. Each fish was assigned the “release date” of its observation at Lower Granite Dam and all the fish from a single day were considered a single release. Cohorts were constructed from these releases as above.

III.4.1 - Results for Snake River Stocks

Figures 63, 64 and 65 show modeled versus observed (PIT-tag data) travel times for spring and fall chinook and steelhead.



	LGR Reservoir Release 1989 - 1996	LGR Tailrace Release 1995, 1996, 1998
%	RLS - LGR	
x	RLS - LGS	LGR - LGS
●	RLS - LMN	LGR - LMN
+	RLS - MCN	LGR - MCN
#		LGR - JDA
@		LGR - BON

Fig. 63 Spring chinook, modeled vs. observed travel times

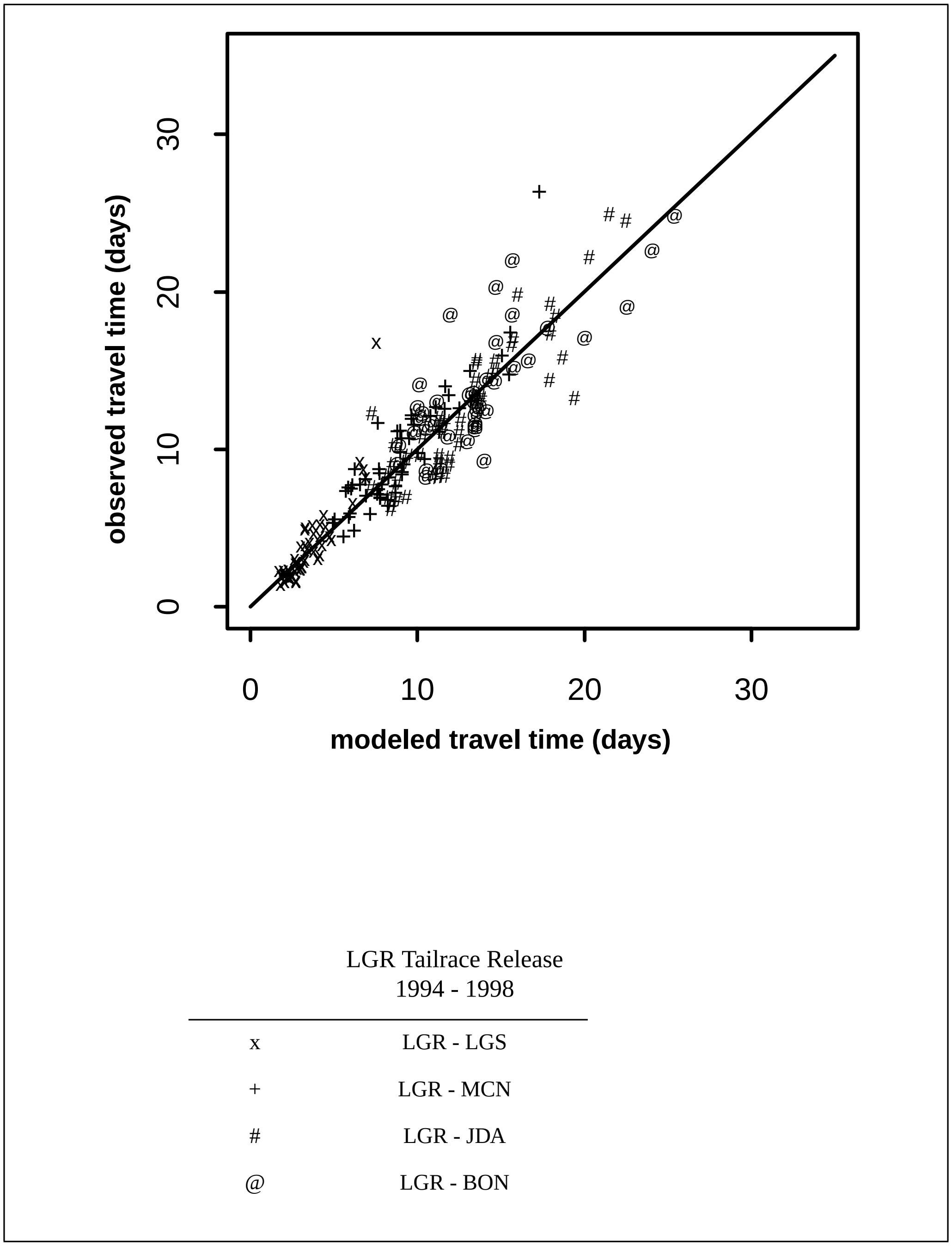


Fig. 64 Steelhead, modeled vs. observed travel times

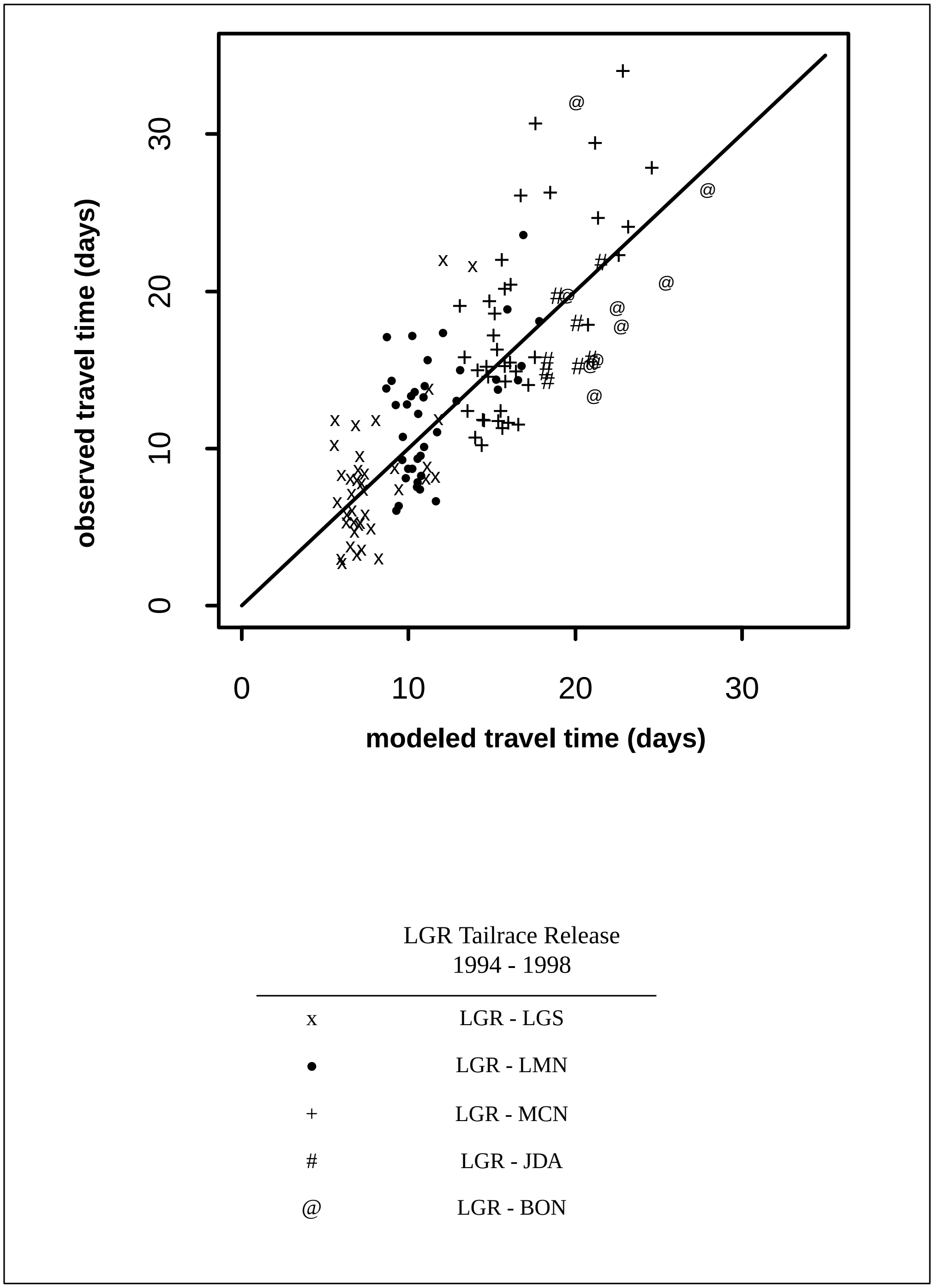


Fig. 65 Fall chinook, modeled vs. observed travel times

III.4.2 - Results for Upper Columbia Stocks

Figures 66 and 67 show modeled versus observed (PIT-tag data) travel times for Upper Columbia yearling fall chinook and Upper Columbia steelhead. The Upper Columbia yearling fall chinook calibration was troublesome. As mentioned in Section III.3.4, it was extremely sensitive to the choice of predation parameters. The result (see Fig. 66) was less satisfying than any of the other travel time calibrations. Factors in this could include the lack of data (only two years of light data) and the fact that much of the data consisted of travel times in the range of 25 to 40 days (Wells Dam releases being monitored at McNary, John Day and Bonneville as well as Rocky Reach). For most other species, the bulk of the data was between 5 and 20 days.

These long travel times are characteristic of fall chinook, which typically spend time, after release, milling about before heading downstream. Until we get a better handle on modeling that difficult aspect of their migration, the model will continue to have difficulty with calibration to the travel time data for fall chinook. Some of those difficulties are discussed in Section III.3.4.

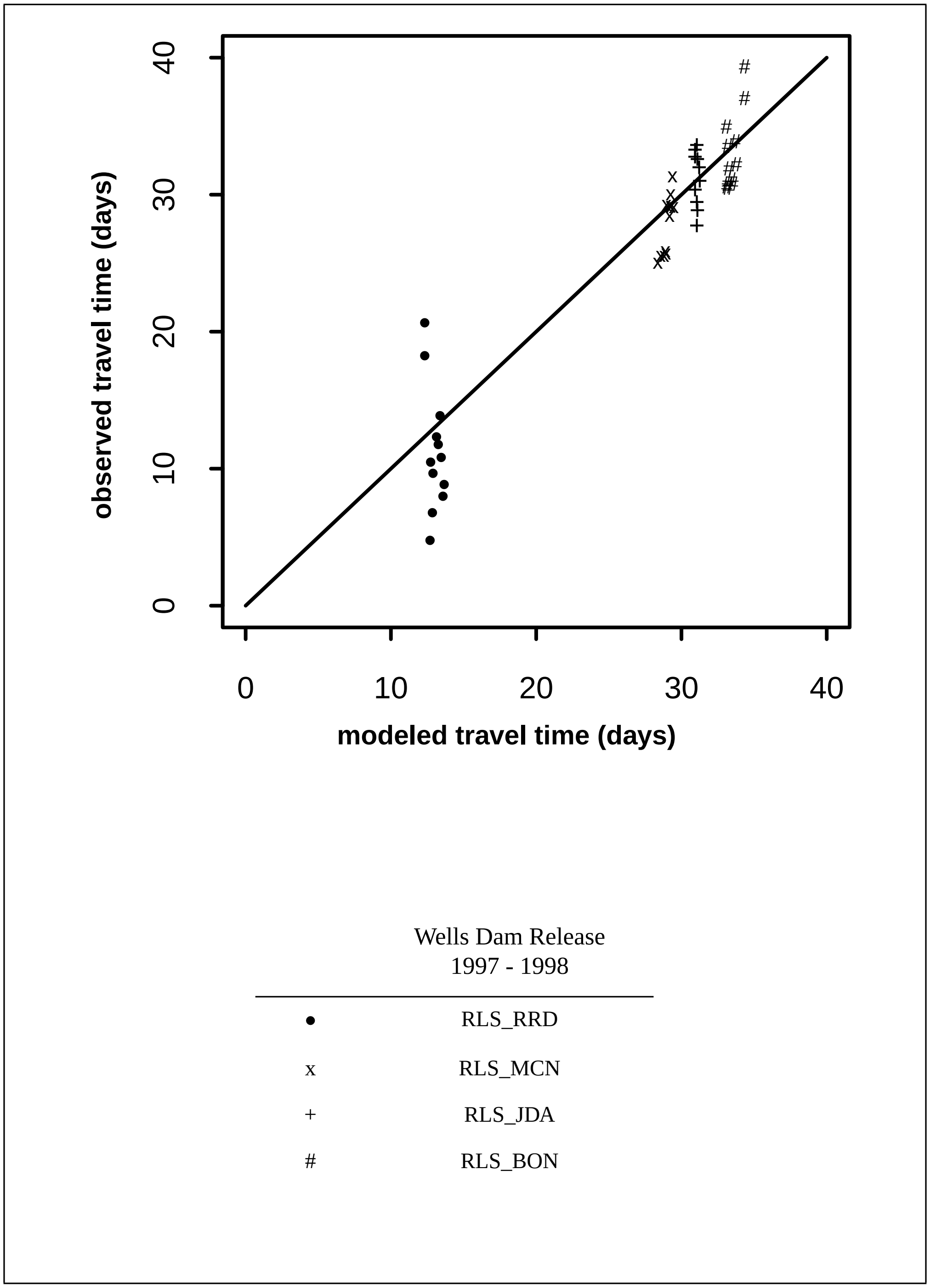


Fig. 66 Upper Columbia yearling fall chinook, modeled vs. observed travel times for 1997-1998 releases from Wells Dam tailrace.

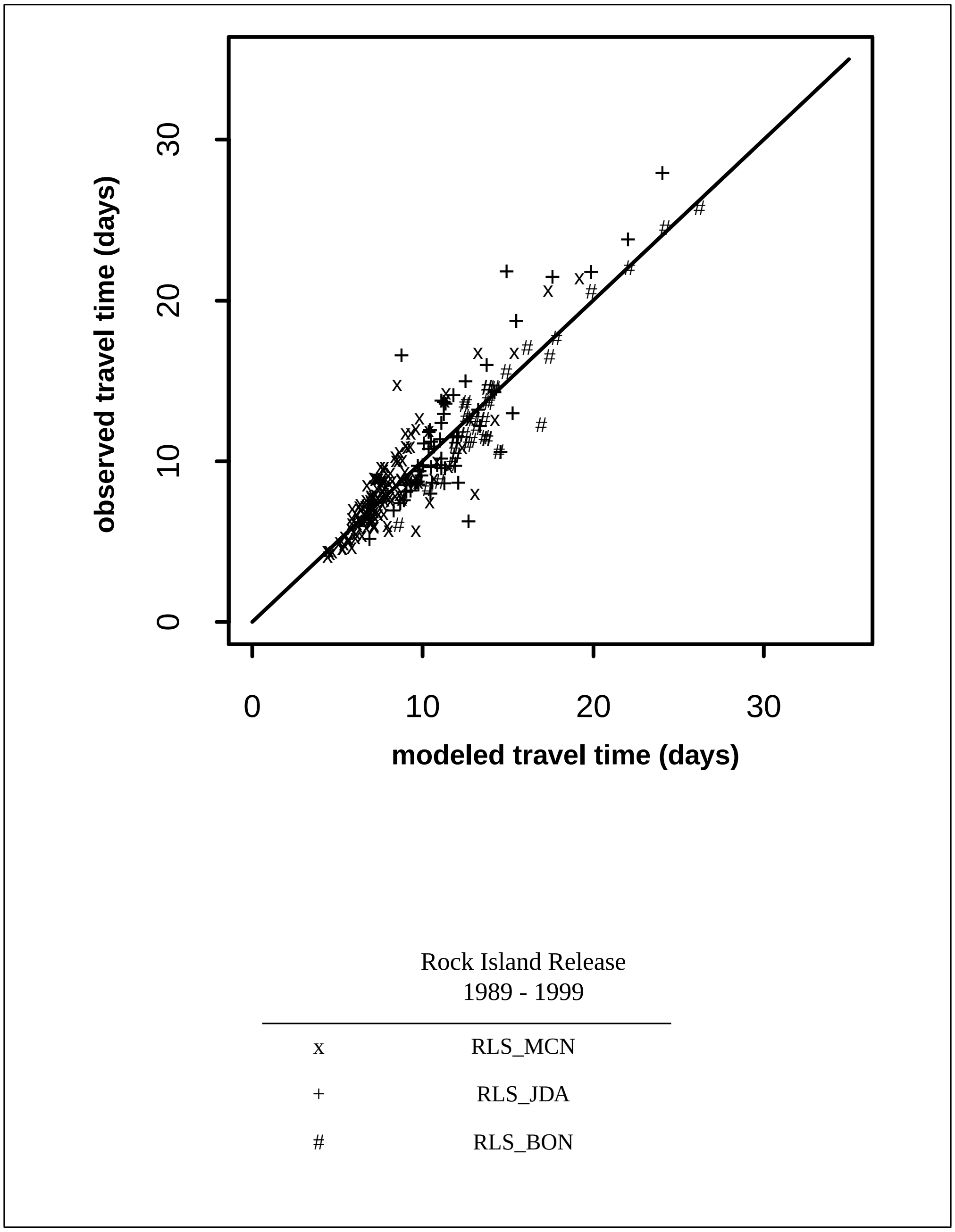


Fig. 67 Upper Columbia steelhead, modeled vs. observed travel times for 1989-1999 releases from Rock Island Dam tailrace

IV. Sensitivity Analysis

IV.1 - Description

CRiSP.1 is a complex model, with hundreds of parameters. It is impossible to examine the potential interactions of all of these parameters. Consequently, sensitivity of fish survival for a number of single parameters is evaluated independently.

In general, sensitivity is determined by first obtaining some base case output—the survival of a species under specific conditions. Individual parameters are then changed to some reasonable limit values, while all other parameters are held constant, and the resulting impact on model output is recorded. For flow, several values for flow augmentation in the Snake and Columbia headwaters are chosen separately and the output for all possible combinations is recorded.

IV.1.1 - Methods

Some parameters were modified by two different methods. The first method was setting a specific value and running the model. For example, FGE was modified by setting all FGE values to 0.9 for each dam. The second method involved multiplying each of the parameters by a scalar to represent a systematic proportional change in the parameter. For example, FGE values were scaled by a proportion such as 1.25 in order to simulate an increase of 25%. With this second approach, any values outside of the possible range were truncated to fall within range. For example, FGE must be between 0 and 1.

The model was initiated and run using 1998 parameter values with a single release of yearling (spring) chinook, subyearling (fall) chinook, or steelhead at the head of Lower Granite Pool. Survival to below Bonneville Dam was observed as a result of variation in:

- Fish Guidance Efficiency set at an absolute level for all dams
- Fish Guidance Efficiency scaled up or down for each dam separately
- Flow levels in the Columbia and Snake headwaters increased by a fixed amount for each day
- Temperature + or - a fixed amount in the first reach below each of the headwaters
- Spill levels set at an absolute level for each dam
- Spill levels scaled up or down for each dam separately.

Analysis of the individual parameters are presented as graphs of survival as a function of the parameter, and pairs of flow augmentation values are shown as similar response surfaces in three-dimensional space. In the case of the scaled values (spill and FGE), the scalar of 1.0 reproduces the base case results which are shown as a horizontal line in the graphs.

IV.2 - Results

Results are shown in the following figures. The scales of survival are different for each plot. Survival due to variation in flow and temperature in the Snake and Columbia headwaters are in Fig. 68, survival due to variation in fixed FGE and scaled FGE are in Fig. 69, and survival due to variation in fixed spill and scaled spill levels are in Fig. 70.

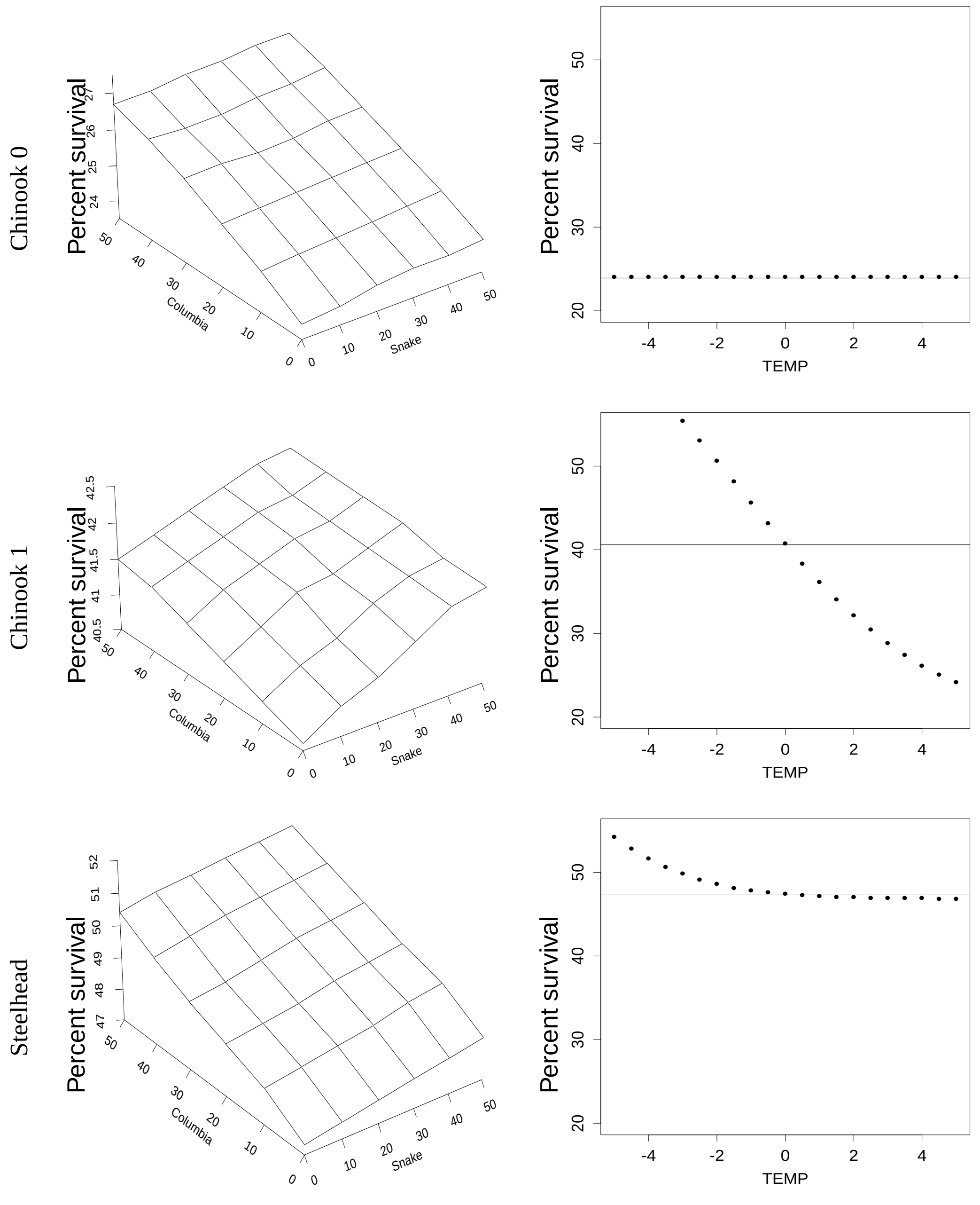


Fig. 68 Systemic flow and temperature changes. Survival from SNAKER (upper Lower Granite Pool) to below Bonneville Dam as a function of increase in flow (kcfs) at the Columbia and Snake headwaters (left) or change in water temperature (˚C) (right). The horizontal line shows the base case survival for the release in 1998.

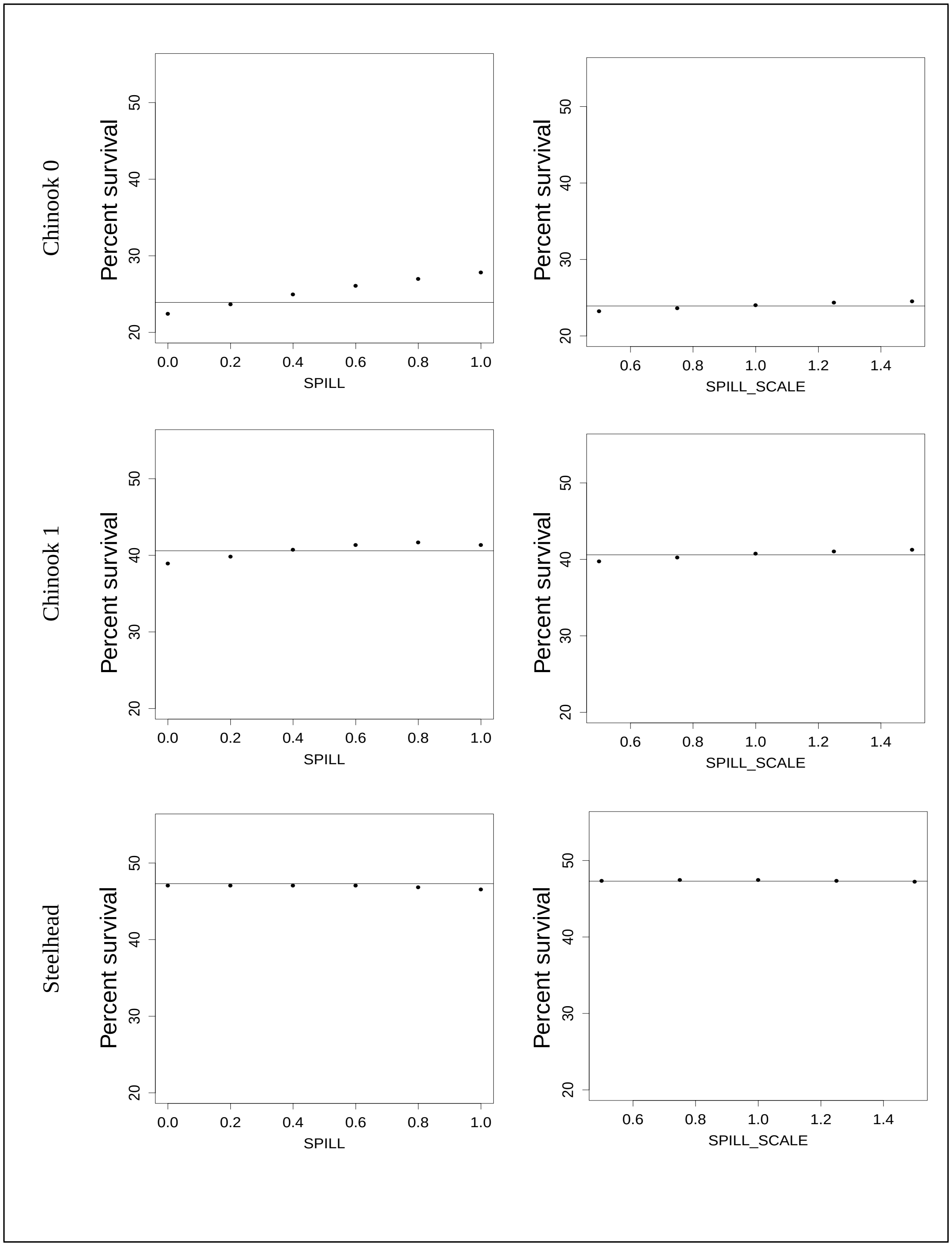


Fig. 69 Survival as a function of spill fraction held at fixed levels (left) and spill scaled by a fraction (right). The horizontal line shows the base case survival for the release in 1998.

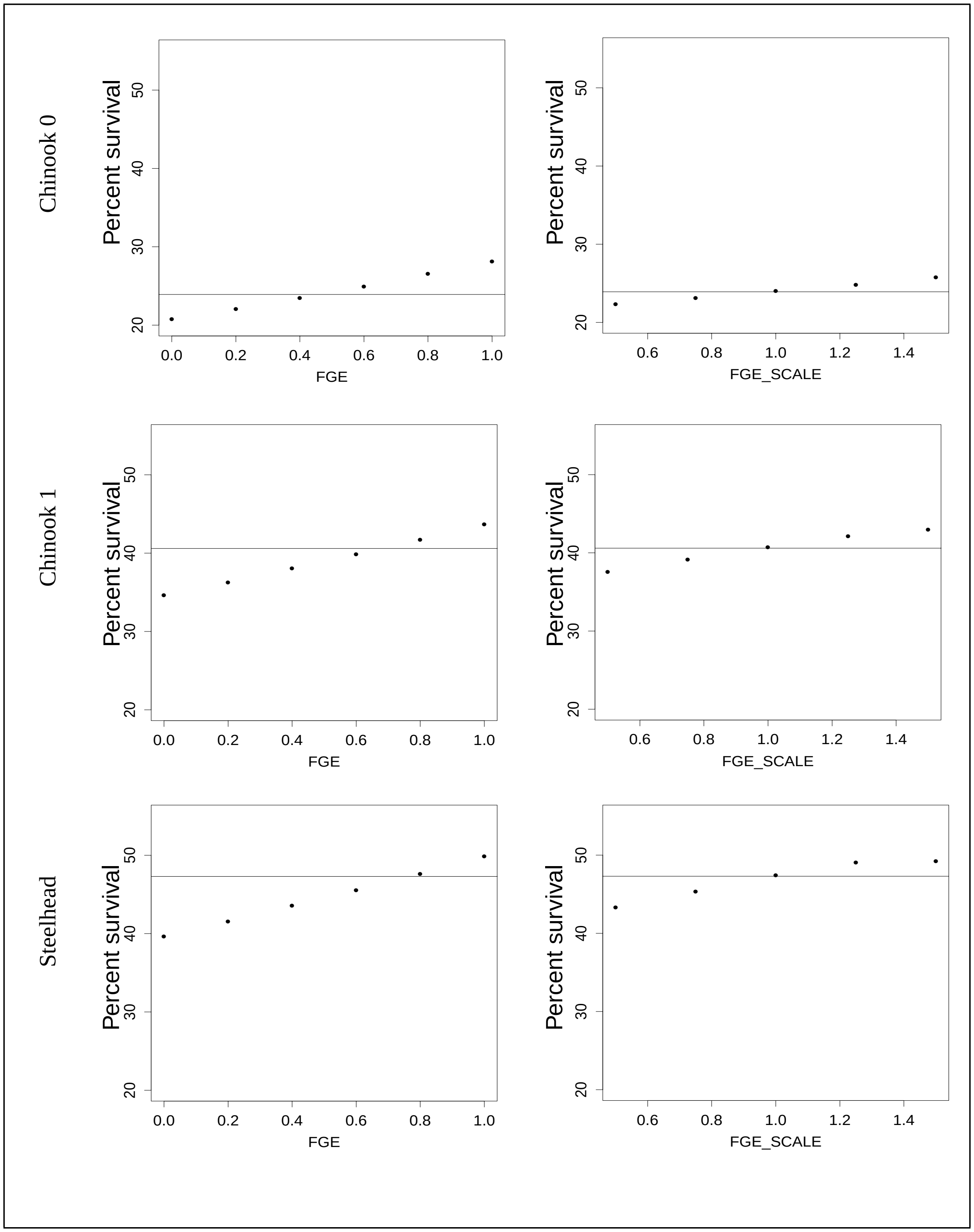


Fig. 70 FGE at fixed (left) and scaled levels (right). The horizontal line shows the base case survival for the release in 1998.

IV.3 - Summary

While all the parameters examined have some influence on the outcome of model runs, it is clear that some are substantially more important than others depending on the species in question. The three species (Steelhead, Chinook 0 and Chinook 1) were comparably sensitive to FGE in both the absolute value and scaled runs. Flow increases had less impact than FGE: spring chinook (Chinook 1) were most sensitive to increases in the Snake River flow while fall chinook (Chinook 0) and steelhead were more sensitive to changes in Columbia River flow. Steelhead survival is noticeably higher for cooler temperatures. Chinook 0 are most sensitive to spill. Chinook 1 are very sensitive to all water temperature changes and can best take advantage of increased flows in the Snake River.

There are substantial nonlinearities in some responses. This is due to the underlying theory of the model in these cases, which is itself nonlinear. The relationship between flow and survival is a result of several interacting submodels: because increased flow increases fish velocity, it reduces the mortality suffered due to predation, and thus increasing flow produces increasing survival. As flows increase, however, water is forced into the spillway, which produces elevated dissolved gas levels (TDG). This causes mortality via gas bubble disease; as spill increases, this mortality increases unless this is offset by reduced mortality from other sources.

Analyzed Range and Observed Range

In performing a sensitivity analysis, the range examined for each parameter is to some extent arbitrary. For some parameters, obvious extremes are suggested: for spill fraction, for example, the range from 0% spill to 100% spill is a natural choice to examine. At the same time, managers are interested in the real range of these parameters and how the model responds within reasonable system operations. For this reason, the scaled value sensitivity was performed in order to see how a small percentage alteration in the parameter can affect survival.

For those parameters to which the model is relatively insensitive, this indicates that the real system may be even more insensitive to changes in the modeled process, and that therefore mitigation measures that focus on those areas will be unlikely to produce significant benefit. At the same time, even those parameters which produce moderate to large impacts on survival may in reality be confined to a much narrower band in the actual hydrosystem.

There has been considerable pressure to make improvements in the hydrosystem that lead to improved juvenile salmonid survival; in that sense, the current configuration is, within its constraints, close to optimized for fish survival. The small changes that are allowed within system operation guidelines are unlikely to produce other than equally small changes in fish survival. This is a property of the real world system that is reflected accurately in CRiSP.1.

V. Parameter Definitions

Equation parameters and their descriptions are given in Table 57. Dam and reservoir activities are assumed to be identical for all dams and reservoirs. Exceptions are treated individually, so there is no index for the specific dam or reservoir. Within CRiSP.1, parameters for each dam and reservoir are unique.

Table 57 Equation parameters and their descriptions

Equation Parameters	Page
$F(t)_{\text{week (j)}}$ = weekly variation in flow for headwater dam j	12
G = flow scaling factor in kcfs	12
a_n, b_n = Fourier coefficients	12
t = day of the year	12
δ = offset for day of week alignment	12
F_{day} = daily variation in flow in kcfs at headwater dam	13
r = deterministic rate of change of flow per unit of flow (the range is confined such that $0 < r < 1$)	13
σ = intensity on the random variations in flow	13
$w(t)$ = Gaussian white noise process describing the temporal aspects of the flow variation	13
$F_{D(r)}$ = flow output at dam immediately below reach r	16
$F_{L(r)}$ = new flow loss at reach r, as adjusted for mass imbalance	16
$F_{M(r)}$ = flow maximum at reach r	16
$F_{M(i)}$ = flow maximum at reach i	16
$F_{R(j)}$ = flow at regulation point j	16
n = number of upstream regulated points	16
p = number of reaches between dam r and all regulation point	16
$F_{loss\ (i)}$ = modulated flow loss at downstream dam i	17
σ_{i} = the standard deviation of the difference in flows (kcfs) at dam i and i +1 as computed by daily observed flows at all dams over the years 1979-1981	17
$F_{TU(r)}$ = total unregulated flow input to dam r	19
p = number of regulated flows in region	19
$F_{D(r)}$ = flow output at dam r	19
$F_{R(j)}$ = flow output at regulation point j	19
K_i = flow coefficient at unregulated headwater i	19
q = number of adjacent unregulated headwaters in region	19
$F_{U\ max\ (i)}$ = maximum flow at unregulated headwater i or j	19

Table 57 Equation parameters and their descriptions

Equation Parameters	Page
$F_{D(r)}$ = flow output at dam immediately below reach r	20
$F_{L(r)}$ = new flow loss at reach r, as adjusted for mass imbalance	20
$F_{M(r)}$ = flow maximum at reach r *or* i	20
$F_{R(j)}$ = flow at regulation point j	20
$F_{U(i)}$ = flow at unregulated headwater i	20
m = number of unregulated headwaters above r ($m = 3$ in Fig. 17)	20
n = number of regulated points adjacent to nearest upstream regulation point ($n = 2$ in Fig. 17)	20
p = number of reaches between dam r and all upstream regulation points ($p = 9$ in Fig. 17)	20
$F_i(t)$ = flow at regulation point i at reservoir time increment t	20
$F_{L(i)}$ = flow loss at reach i	20
$F_j(t)$ = flow at regulation point j immediately upstream at reservoir time increment t	20
$F(t)_i$ = modulated flow at dam i	20
$F(t)_{\text{arch(i)}}$ = archive flow at dam i	21
$F(t)_{\text{day(j)}}$ = daily modulated flow in regulated headwater j	21
$F(t)_{\text{week(j)}}$ = weekly modulated flow in regulated headwater j	21
$F_{\text{loss(i)}}$ = loss modulated flow in river segment upstream of dam i	21
$F_{\text{min(i)}}$ = minimum allowable flow at dam i	21
J = number of regulated headwaters upstream of dam i	21
I = number of dams upstream of dam i, including dam i	21
t = julian day ($t = 1$ to 365)	22
Y_t = estimated daily flow	22
m = mean annual flow computed over a 10 year period	22
p = fraction of mean annual flow for the scenario	22
e_t = stochastic error term	22
F_t = Fourier term	22
a_k, b_k = Fourier coefficients estimated for each river	22
$\omega = 2\pi/365$	22
r_t = randomly generated variable from a normal distribution centered on 0 with variance appropriate for dry and wet years as described above	22
$e_0 = 0$	22
dV = change in reservoir volume in acre-ft	22
dt = time increment, typically 1 day	22

Table 57 Equation parameters and their descriptions

Equation Parameters	Page
F_U = unregulated natural flow into the reservoir in kcfs	22
F_R = regulated flow out of the reservoir, which is controlled by the user under volume constraints in kcfs	23
$V(i)$ = reservoir volume time step i with units of acre-ft	23
Δt = one day increment	23
F_U = unregulated flows in kcfs	23
F_R = regulated flows in kcfs	23
c = 1983.5, which is a conversion factor	23
F_R = outflow from reservoir according to the constraints	23
F_U = unregulated inflow to reservoir	23
V_{request} = requested volume from reservoir	23
F_{request} = requested outflow from reservoir	23
$V(\mathrm{i})$ = reservoir volume in reservoir time step i	24
$V_{\max}$ = maximum reservoir volume	24
$V_{\min}$ = minimum reservoir volume	24
$\omega = 2\pi/365$	24
k = value between 0 and 4	24
H_u = full pool depth at the upstream end of the segment	28
H_d = full pool depth at the downstream end of the segment	28
L = pool length at full pool	28
x = pool length at lowered pool	28
E = pool elevation drop below full pool elevation	28
W = pool width averaged over reach length at full pool	28
θ = average slope of the pool side	28
F = flow through the pool in kcfs	28
U_{free} = velocity of free flowing river	28
$V(E)$ = pool volume (ft^3) as a function of elevation drop E in feet	32
F = flow in 1000 cubic feet per second (kcfs)	32
L = segment length in miles	32
x = pool length defined by eq (27) and with units of feet	32
U_{free} = velocity of water in the free stream (kfs)	32
T = residence time in this calculation is in kilo seconds (ks)	32

Table 57 Equation parameters and their descriptions

Equation Parameters	Page
H_u = full pool depth at the upstream end of the segment	32
U = average river velocity in ft/s	33
U_{free} = the velocity of a free flowing stream in ft/s	33
F = flow in kcfs	33
E = elevation drop (positive downward) in ft	33
H_u = depth of the upper end of the segment in ft	33
V_1 and V_2 = volume elements defined by eq (31) and (32)	33
$V(0)$ = pool volume at full pool	33
$F_i(t)$ = flow from headwater i through the river segment in question on day t	35
$\theta_i(t)$ = temperature from headwater i on day t	35
$\theta(t)$ = temperature for selected river segment on day t	35
X = position of a fish down the axis of the river	36
dX/dt = velocity of fish in migration	36
r = average velocity of fish in the segment; this is a combination of water movement and fish behavior	36
σ = spread parameter setting variability in the fish velocity	36
$W(t)$ = Gaussian white noise process to represent variation in velocity	36
Φ = cumulative distribution of the standard normal distribution	38
L = segment length	38
r = average migration velocity through the segment	38
$r(t)$ = migration rate (miles/day)	39
t = julian date	39
b’s = regression coefficients, described above	39
a_1 , a_2 = slope parameters	39
T_{SEASN} = seasonal inflection point (in julian days)	39
T_{RLS} = release date (in julian days)	39
$r(t)$ = determined from eq (48)	41
$V(i)$ = variance factor that varies *between* releases only	41
S = measure of smolt density in the river segment and can be taken as the total number in the segment	43
φ = mortality rate from all causes	43
M_p = mortality rate from predation with units of time^{-1}	44

Table 57 Equation parameters and their descriptions

Equation Parameters	Page
M_{tdg} = mortality rate from total dissolved gas supersaturation with units of time^{-1}	44
S = number of smolts leaving reservoir per day (smolts reservoir $^{-1}$)	44
φ = combined mortality rate as used in eq (54)	44
S_0 (t_j | t_i) = potential number of fish that enter the segment on day t_i and survive to leave the segment on day t_j	44
S (t_j | t_i) = actual number of fish that enter the segment on day t_i and leave on day t_j	44
Δt = reservoir computational time increment	44
N (t_i) = number of fish that enter the river segment on day t_i	45
ΔP (t_j | t_i) = probability that a fish entering on day t_i survives to exit on day t_j (defined by eq (46) on page 38)	45
T = temperature (˚C)	46
P_{ij} = the predator density in the ith zone (forebay, tailrace, or reach) for the jth project	46
a_i = the predator activity coefficient in the ith reservoir zone	46
$f(T)$ = the temperature response equation	46
C_{MAX} = the maximum consumption rate	46
αT = a slope parameter	46
T_{INF} = the inflection point of the curve	46
H = forebay (tailrace) depth at full pool	59
h = forebay (tailrace) depth at a lowered pool	59
P = predator density at full pool for the forebay (tailrace)	59
G_s = percent TDG *above* 100% as measured at the surface	61
G_c = threshold above 100% at which the gas bubble disease mortality rate is observed to change more rapidly towards more lethal levels	61
a = species-specific gas mortality rate coefficient with units of G^{-1} day^{-1} determining the initial rate of increase of mortality per %-increase in TDG	61
b = species-specific gas mortality rate coefficient with units of G^{-1} day^{-1}, determining the change in mortality rate at G_c	61
H() = Heaviside function, also known as the unit step function; equal to zero when its argument is negative, and equal to one when its argument is positive	61
z_D = depth of the reservoir	61
z_b = maximum depth of fish distribution	61
z_m = mode of fish distribution	61
m_0 = slope of distribution function above mode	61
m_1 = slope of distribution function below mode	61

Table 57 Equation parameters and their descriptions

Equation Parameters	Page
$M_{tdg}(L)$ = TDG mortality rate as a function of fish length	62
L = fish length in mm	62
a = 0.000472 mm^{-1}, length coefficient for TDG mortality rate (regression of all data from the 112% shallow tank experiments conducted by Dawley et al. (1976))	62
L = length of fish in environment	62
L_e = length of fish in TDG mortality experiments	62
G_{right} , G_{left} = percent TDG in the flow entering the reach on the respective sides	63
S_{fr} = percent of river in the right-bank flow	63
G_{mix} = flow weighted average of the TDG values in each flow	63
G_{dif} = difference between the original concentrations of the two flows	63
E = percent TDG in water at equilibrium, 100% saturation or 0% supersaturation	63
q = diffusion rate constant in units of (mile)-1, a model parameter set for each reach	63
v = average water velocity through the river segment	63
x = distance downstream	63
t = average water travel-time	63
x = distance downstream and , where L is the pool length (miles)	63
c_1 = Gmix - E	63
c_2 = G_{dif} . (1-S_{fr}) for the right-bank flow	63
c_2 = - G_{dif} . S_{fr} for the left-bank flow (see eq (103) and eq (104) on page 88)	63
q = reservoir mixing coefficient in (miles)-1	64
E = equilibrium value (0% supersaturation)	64
z = fish depth	64
m = a slope parameter	64
g_c = critical gas supersaturation at the surface where GBD mortality rate changes more rapidly towards more lethal levels	64
n = indexes the julian day	64
i = indexes the side of the river and hence the level of TDG on that side of the river; 1 indexes the right-bank and 2 indexes the left-bank	64
a = species-specific gas mortality rate coefficient with units of G^{-1} day^{-1} determining the initial rate of increase of mortality per %-increase in TDG	64
b = species-specific gas mortality rate coefficient with units of G^{-1} day^{-1}, determining the change in mortality rate above G_c	65
S = cumulative survival	65
M_{tdg} = TDG mortality rate at a specific level of supersaturation	65

Table 57 Equation parameters and their descriptions

Equation Parameters	Page
t = exposure time	65
G_s = TDG at the surface	68
$g_{correction}$ = TDG experienced by the fish	68
z = fish depth	69
m = a slope parameter	69
$S(t)$ = reservoir survival after t days of migration	72
A = 14.07	72
B = 0.1822	72
S(t) = reservoir survival after t days of migration	73
A = 6.73 e-06 (TURB1); 8.623 e-04 (TURB4); 8.87 e-06 (TURB5)	73
B = 3.16 (TURB1); 1.43 (TURB4); 3.02 (TURB5)	73
G = percent total dissolved gas saturation above equilibrium (100%)	74
Q_s = total amount of spill in kcfs	74
m, b = empirically fit slope and intercept parameters	74
G = percent total dissolved gas saturation above equilibrium (100%)	74
Q_s = total amount of spill in kcfs	74
q_s = amount of spill through an individual spillbay	74
a,b,c = empirically fit model parameters	74
G = percent total dissolved gas saturation above equilibrium (100%)	75
Q_s = total amount of spill in kcfs	75
a, b and k = coefficients specific to each dam derived from TDG rating curves provided by the Bolyvong Tanovan of the U.S. Army Corps of Engineers	75
G = percent total dissolved gas saturation above equilibrium (100%)	75
Q_s = total amount of spill in kcfs	75
a, b and h = coefficients specific to each dam and can be derived from TDG rating curves available from the U.S. Army Corps of Engineers	75
Q = total flow in kcfs	76
Q_s = spillway flow in kcfs	76
G_{sb} = TDG concentration exiting the stilling basin in mg/l	76
G_{fb} = TDG concentration in the forebay in mg/l	76
G_{eq} = TDG equilibrium concentration as a function of temperature (˚C) at one atmosphere of pressure (mgl^{-1} atm^{-1})	76
L = length of the stilling basin in feet	76

Table 57 Equation parameters and their descriptions

Equation Parameters	Page
P_0 = barometric pressure in atmospheres (assume P_0 is 1)	76
α = density of water (0.0295 atm/ft)	76
α_0 = specific gravity of the roller at the base of the spill	76
W = spillway width	76
D = water depth at the end of the stilling basin	76
Y_0 = thickness of the spill at the stilling basin entrance, where	76
H = hydraulic head expressing the forebay elevation minus the elevation of the spilling basin floor (H is in ft and gravity constant g is 32 ft s^{-2})	77
Δ = differential pressure factor defined	77
K_e = bubble entrainment coefficient with units of ft $s^{-1}atm^{-1/3}$ and is defined	77
T = temperature (˚C)	77
K_{20} = temperature compensated entrainment coefficient	77
E = energy loss rate expressed as total headloss divided by residence time of water in the stilling basin	77
P = forebay percent saturation	77
a, b, and c = dam dependent empirical coefficients	77
G_{spill} = percent TDG in the spill side flow exiting the tailrace	80
G_{phouse} = percent TDG in the powerhouse side flow exiting the tailrace	80
S_{fr} = percent of river in the spill side flow	80
G_{mix} = flow weighted average of two gas levels	80
G_{dif} = difference between the original concentrations of the two flows	80
G_{spill} = percent TDG in the spill side flow exiting the tailrace	81
G_{phouse} = percent TDG in the powerhouse side flow exiting the tailrace	81
$G_{forebay}$ = percent TDG in the forebay	81
Q_s = total amount of spill flow	81
G_{right} , G_{left} = percent TDG in the flow entering the reach on the respective sides	88
S_{fr} = percent of river in the right-bank flow	88
G_{mix} = flow weighted average of the TDG values in each flow	88
G_{dif} = difference between the original concentrations of the two flows at the head of the reach	88
E = percent TDG in water at equilibrium, 100% saturation or 0% supersaturation	88
q = diffusion rate constant in units of $(mile)^{-1}$, a model parameter set for each reach	88
k = dissipation rate constant in units of $(day)^{-1}$, a model parameter calculated for each reach based on the river depth, velocity and a diffusion constant (see eq (107))	88

Table 57 Equation parameters and their descriptions

Equation Parameters	Page
x = longitudinal distance, where x is in miles	88
v = river velocity, in miles per day	88
Q = total flow through the dam in kcfs	90
Q_s = spill flow in kcfs	90
G = tailrace TDG supersaturation (in percent)	90
G_{fb} = forebay TDG supersaturation (in percent)	90
G_{sf} = spill water TDG in percent saturation as defined by an empirical or mechanistic saturation equation	90
Q_i = flow in kcfs in segment i	91
G_i = TDG in percent supersaturation in segment i of the confluences	91
Φ = flux of TDG across the air/water interface	91
G = TDG supersaturation concentration in the segment	91
G_{eq} = TDG equilibrium concentration	91
A = surface area of the segment	91
K_d = transfer coefficient defined	91
D_m = molecular diffusion coefficient of TDG	91
U = hydraulic stream velocity	91
D = depth of the segment	91
D_m = order of 2×10^{-5} $cm^2 s^{-1}$ (Richards 1965)	92
U = order of 3 cm/s (20 miles/day), note this changes on a daily basis and for each reach in the model	92
D = order of 900 cm, note this changes on a reach specific basis and is dependent on reservoir elevation	92
the constant 700.75 gives the coefficient k in unit of day^{-1}	92
G_{eq} = TDG equilibrium concentration	92
$G(0)$ = tailrace concentration defined by eq (109)	92
k = dissipation coefficient defined by eq (115)	92
t = time in a river segment	92
$Volume$ = pool volume at a specific elevation	92
W = average pool width at full pool	92
L = length of pool	92
λ_t = instantaneous probability of passage	95
p = proportion of time step during day	95

Table 57 Equation parameters and their descriptions

Equation Parameters	Page
(1-p) = proportion of time step during night	95
V_t = upstream river velocity in mi/day	95
SP_t = proportion of river spilled	95
D_t = julian date	95
α’s and β’s = parameters that vary by dam and species	95
Y = fraction of total fish passed in spill	97
X = fraction of water spilled	97
a and b = regression coefficients	97
e = error term (var) selected from random distribution	97
fge = fish guidance efficiency	99
z = median depth of fish in the forebay at a distance from the dam where fish are susceptible to being drawn into the intake	99
D = screen depth relative to full pool forebay elevation	99
D_c = FGE calibration parameter	99
E = amount the pool is lowered below full pool elevation	99
t = fish age since the onset of smoltification	100
t_0 = onset of change in FGE relative to the onset of smoltification, set in the **Release** window	100
Δt = increment of time over which FGE changes	100
z_0 = initial mean fish depth (at age t equals 0) in the forebay	100
z_1 = final mean fish depth (at age t equals $t_0 + \Delta t$) in the forebay	100
fge_0 = FGE at onset of smoltification	100
$E(t)$ = elevation drop	100
D = fraction of fish that pass dam during spill hours	105
F_{sp} = fraction of daily flow that passes in spill	105
SE = fraction of fish that pass in spill relative to the fraction of flow passing in spill	105
FGE = fraction of fish passing into turbine intake that are bypassed	105
x = deterministic part of the random parameter fixed for each species and dam	105
x’ = stochastic part of the parameter taken from a broken-stick distribution (see Section II.7.1 Stochastic Parameter Probability Density on page 127) over each dam time slice	105
y = spill efficiency	106
x = percent flow	106
a and b = deterministic parameters	106

Table 57 Equation parameters and their descriptions

Equation Parameters	Page
e = stochastic parameter selected from a normal distribution	106
N_{tu} = number of fish passing in a time increment (6 hours)	106
N_{fo} = number of fish in forebay ready to pass in the increment	106
p = probability of passing during the increment (1 - P_1 from eq (119) on page 95)	106
m_{fo} = mortality in forebay (see Section II.4.2 Predation Mortality on page 45)	106
m_{tu} = mortality in turbine passage	106
fge = fish guidance efficiency for a day or night period	106
Y = proportion of fish passage in spill defined by spill efficiency equation (see eq (120) on page 97)	106
m_{by} = mortality in the bypass	106
m_{tr} = mortality in the transport	106
m_{sp} = mortality in the spill passage	107
T/C = ratio of survival of transport fish to control fish from transport experiments	126
V_n = in river survival of spring chinook smolts	126
a = 5.8259, b = 5.3533, V_t = 0.98	126
T/C = ratio of survival of transport fish to control fish from transport experiments	127
V_n = in river survival of spring chinook smolts	127
a = 0.3281 (TURB1); 0.3330 (TURB4); 0.3292 (TURB5)	127
b = 0.1936 (TURB1); 0.1596 (TURB4); 0.1868 (TURB5)	127
x = unit uniform random deviate range $0 < x < 1$	128
y_l = lower limit of the distribution range	128
y_m = distribution of the median value	128
y_u = upper limit of the distribution range	128
$r(t)$ = determined from eq (48) on page 39	129
$V(i)$ = variance factor which is different for each release i	129
G = percent supersaturation above 100%	138
Q_s = spillway flow volume in kcfs	138
a, b and h = coefficients specific to each dam, derived from TDG rating curves provided by the U.S. Army Corps of Engineers	138
K_{20} = entrainment coefficient	139
E = energy loss rate	139
P = forebay percent saturation	139
a, b, and c = coefficients calculated from multiple linear regression of data in Table 51	139

Table 57 Equation parameters and their descriptions

Equation Parameters	Page
T = water temperature in the forebay in ˚C	139
Q_s= spill in kcfs	139
W = spillway width (gates x width/gate)	139
L = stilling basin length in feet	139
T = water temperature in the river segment	142
$r(t)$ = migration rate (miles/day)	159
t = julian date	159
b_0, b_1, b_{FLOW} = migration rate regression coefficients	159
V_f = average river velocity during the average migration period	159
α_1, a_2= slope parameters	159
T_{SEASN} = inflection point of flow dependent term (julian day)	159
T_{RLS} = release date (julian day)	159

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VII. Glossaries

VII.1 - Glossary

- **anadromous fish**: Fish such as salmon or steelhead that hatch in freshwater, migrate to the ocean where they mature, and then return to freshwater to spawn.
- **BRZ**: Boat restricted zone.
- **bubble entrainment**: The capture of bubbles into moving water, from the surface to the depths, at dam intakes and diversions.
- **bypass**: A channel or conduit designed to route juvenile fish around the dam’s turbines.
- **chinook 0**: Subyearling chinook smolts. Also known as fall chinook for the season when the adults run.
- **chinook 1**: Yearling chinook smolts. Also known as spring chinook for the season when the adults run.
- **coeff variance**: Coefficient of variation (cv). The standard deviation divided by the mean.
- **confluence**: In CRiSP.1, a point where two upstream flows combine to create the flow downstream of the point.
- **CPUE**: Catch per unit effort.
- **dam**: Federally funded and maintained dams on the Snake and Columbia rivers. In CRiSP.1, a dam is a point that regulates flow; however, only dams specified in the flow archive file are considered to be regulation points.
- **diel**: Varying on a day/night basis, e.g. “diel variation in fge.”
- **entrainment**: Gas is added into the powerhouse flow, increasing the level of total dissolved gas, as the result of the amount of spill going over the spillway into the tailrace of the dam.
- **fish guidance efficiency (FGE)**: Fish guidance efficiency (FGE) is the percentage of total number of juvenile fish approaching a turbine intake that are successfully “guided” away from the turbine by a guidance device such as a submersible traveling screen.
- **forebay**: Portion of the reservoir from which water is taken to run the turbines of a dam.
- **gas bubble disease (GBD)**: Adverse effect to fish caused by absorbing dissolved gas from supersaturated water.
- **headloss**: The difference between the elevations of surfaces in a volume of water before and after drawdown in the flow.
- **headwater**: The source and extreme upper reaches of a stream or river.
- **hydraulic capacity**: The maximum flow a dam can pass through its turbines.
- **HYDROSIM**: A model that produces estimated flows at points along the Columbia and Snake Rivers based on power and flood control requirements. This model is administered by the BPA for use by the River Operations System Experts (ROSE) Group.
- **hydrostatic pressure**: The pressure exerted or transmitted by water at rest.
- **HYSSR**: HYdro System Seasonal Regulation model, simulates power generating and flood control characteristics of the Columbia/Snake Basin, producing predicted flows at federal projects along the river. This model is administered by the U.S. Army Corps of Engineers.

- **input**: Refers to data in a file that is read by CRiSP.1 to set certain values when the model is run. It also refers to any addition or change in the number or value of something, such as “input of fish to a reservoir.”
- **kcfs**: Thousand cubic feet per second.
- **latlon**: The latitude and longitude coordinate for a point in the river system, e.g. latlon 46 09 00 N 123 16 00 W marks 46 degrees 9 minutes north latitude, 123 degrees 16 minutes west longitude.
- **loss**: In CRiSP.1, a withdrawal (+) or deposit (-) of water to a river segment from an unspecified source. Losses are used to represent irrigation removals and ground water returns to river segments.
- **model**: Refers to either CRiSP.1 or some other mathematical representation of a process.
- **Monte Carlo**: A technique for producing estimates of “true” outcomes of stochastic processes by simply running many iterations of the model process and averaging the outcomes together. Results are given as statistics, e.g. mean and standard deviation of variable X.
- **nitrogen supersaturation**: This term is no longer used. See **total dissolved gas supersaturation**.
- **output**: Refers to a result that is reported by CRiSP.1 or some other outcome or product such as “flow output from an upstream segment.”
- **PIT tag**: Passive Interrogative Transponder tag; a tag that is typically inserted into the peritoneal cavity and allows identification of individual fish when they pass a detection facility.
- **predator**: Northern pikeminnow (*Ptychocheilus oregonensis*). The major piscivorous predators on juvenile salmonids are northern pikeminnow formerly known as northern squawfish, smallmouth bass (*Micropterus dolomieu*), and walleye (*Stizostedion vitreum*). In CRiSP.1, smallmouth bass and walleye are converted to *pikeminnow equivalents* based on their consumption rates relative to pikeminnow consumption rates.
- **primary powerhouse**: At dams with more than one powerhouse (e.g., Bonneville), the powerhouse that is operated preferentially.
- **reach**: A continuous stretch or expanse of the river.
- **regulated**: Condition whereby stream flow is constrained by a dam.
- **regulated headwater**: In CRiSP.1, a segment containing a dam, a storage reservoir, and a river source.
- **release group**: A group of fish either wild or released from a hatchery identified by a unique set of parameters.
- **reservoir**: An artificial lake where water is collected and kept in quantity for use.
- **roller**: Turbulent, aerated water in the stilling basin below the spillway.
- **run-of-river**: A hydroelectric project that has limited regulation capacity (usually limited storage capacity) and operates primarily for hydropower generation. The majority of the major dams in the Columbia Basin are run-of-river projects: Chief Joseph, Wells, Rocky Reach, Rock Island, Wanapum, Priest Rapids, Lower Granite, Little Goose, Lower Monumental, Ice Harbor, McNary, The Dalles, Bonneville, and Hells Canyon. In CRiSP.1, Chief Joseph and Hells Canyon dams are defined as storage reservoirs (see definition).
- **runoff**: Portion of rain or snowmelt that runs across the land surface and flows through the surface soil, ultimately reaching the stream or river.

- **salmonid**: A member of the family Salmonidae, which includes salmon, trout and whitefish.
- **SAM**: System Analysis Model which produces predicted flows at projects on the Columbia and Snake Rivers based on power and flood control requirements. This model is administered by the BPA.
- **scenario**: A single set of parameter values run through the model for a single year simulation.
- **secondary powerhouse**: At dams with more than one powerhouse, the powerhouse that operates second.
- **sluiceways**: Routes for water around a dam. Also considered a bypass for fish.
- **smolt**: A juvenile salmonid migrating to the ocean and undergoing physiological changes (called smoltification) to adapt from a freshwater to a saltwater environment.
- **smoltification**: See **smolt**.
- **spill**: Water released through a dam's spillway rather than through its turbines.
- **spill allocation**: Indicates the amount of river flow allotted to spill.
- **spillway**: The channel or passageway around or over a dam through which excess water is released without going through the turbines. It is a safety valve for a dam and must be capable of discharging major floods without damaging the dam while maintaining the reservoir level below some predetermined maximum level.
- **stilling basin**: Short area beyond a dam spillway where water is controlled prior to release.
- **stochastic**: Containing some randomness, e.g. "stochastic process."
- **stock**: A population of fish that spawn in a particular stream during a particular season. Such fish generally do not breed with fish spawning in a different stream or at a different time.
- **storage reservoir**: A hydroelectric project that operates primarily for flood control and to adjust the natural flow regime to conform to river use patterns. Storage reservoirs retain water from spring-time snowmelts and release the water as necessary for multiple river uses: power generation, fish passage, irrigation, recreation, and navigation. Actual storage reservoirs in the Columbia Basin include Dworshak, Grand Coulee, Brownlee, and John Day. The storage reservoirs in CRiSP.1 are Dworshak, Chief Joseph (next downstream dam from Grand Coulee), and Hells Canyon (next downstream dam from Brownlee included in CRiSP.1).
- **substock**: A portion of a stock.
- **subyearling**: A juvenile anadromous fish that is less than one year old. This term is used primarily to refer to juvenile salmon such as fall chinook, which become smolts and migrate from freshwater production areas to the ocean at an age of less than one year. Also referred to as chinook 0. Fall chinook refers to the season when adults migrate upstream.
- **tailrace**: An area of rapidly-moving water immediately downstream from a dam, typically about a kilometer in length.
- **thalweg**: The longitudinal profile of a canyon.
- **thalweg volume**: A portion of the total calculated volume of the river, essentially the middle of the river.
- **total dissolved gas (TDG) supersaturation**: When water plunges over the spillway of a dam into the stilling basin, additional air is forced into the water. This results in an amount of total dissolved gas in the water which is greater than the saturation amount (greater than the maximum amount which can remain dissolved for a long period). Over time, the excess dissolved gas will return to the atmosphere. Until then, the water

is referred to as “supersaturated.” TDG is measured in terms of the percentage of gas in excess of the saturation amount.

- **transportation**: Collecting migrating smolt at collection facilities and transporting them in trucks or barges around dams.
- **transportation velocity**: Speed at which fish are moved downstream via barge or truck.
- **turbine**: A mechanism in a dam that rotates with the force of water and produces electricity.
- **unregulated**: Condition whereby streams flow into another stream with no intervening dam.
- **unregulated headwater**: In CRiSP.1, a segment containing a confluence at its downstream end and a river source at its upstream end.
- **upstream propagation**: Back-calculation of flows at upstream locations based on flows at downstream locations.
- **water budget**: A volume of storage water in acre-feet that is reserved to augment spring and summer flows through the hydrosystem.
- **yearling**: Juvenile anadromous fish that are one year old or older. This term is used primarily to refer to juvenile salmon such as coho or spring chinook or steelhead that become smolts and migrate from freshwater production areas to the ocean at an age of one or more years. Also referred to as chinook 1. Spring chinook refers to the season when adults migrate upstream.

VII.2 - Token Glossary

The **Parameter Glossary** includes terms that occur in the CRiSP.1 input files: **columbia.desc** and **base.dat**.

Token [Category]: Description

- `abbrev` [Dam]: Abbreviation by which this dam will be referred to in flow archives, e.g. BON for Bonneville.
- `additional_powerhouse` [Dam]: Names a second powerhouse if one exists at the project. This powerhouse has separate specifications for capacity, priority, schedule, threshold, passage mortalities, and fge. It must have a closing end statement.
- `basin_length` [Dam]: Length, in feet, of the stilling basin.
- `bypass_elevation` [Dam]: The elevation, in feet, of the bypass orifice of a bypass system. When surface is below this level fish bypass is zero. When term is missing the bypass_elevation defaults to the `floor_elevation`.
- `bypass_mort_*` (Species) [Dam]: Species-specific value for mortality suffered in the bypass system. This is a stochastic parameter.
- `dam` [Dam]: 1) Marks the beginning of a dam specification and the name of the dam in the **columbia.desc** file, e.g. dam Bonneville Dam. 2) [Dam] Names the dam and marks the beginning of parameter data for the dam. The dam name must be present in the **columbia.desc** file, and must be paired with an end statement.
- `day_fge_*` (Species) [Dam]: Species-specific parameter describing fge during daylight hours. This is a stochastic parameter.
- `delay_equation` (Species) [Dam]: Defines the delay of fish at a dam depending on the species, time of day, season, and flow relative to hydraulic capacity. The delay is expressed in terms of a passage probability, not in terms of observed passage. The

number following the token dictates the form of the equation used. This must be paired with an end statement.

- `delta_water_temp` [Reach]: Array of values (can be positive or negative) in degrees Celsius to be applied to the water temperature that comes from upstream. For example, if this is set to 1 then the water temperature in the reach will be adjusted to be 1 degree Celsius warmer than the value that CRiSP.1 calculates for the reach. There is no GUI for this parameter.
- `depth` [Reach]: Not recommended. Average depth in the reach, in feet. When possible, use the preferred parameters `upper_depth` and `lower_depth`.
- `elevation_change` [Reach]: Deviation in elevation from full pool, on a daily basis. The value for elevation_change is zero or less, pools may be drawn down but not over-filled.
- `end`: This token is needed to mark the end of a dam specification, a particular reach, a species or stock specification, and equations.
- `fge_equation` (Species) [Dam]: Equation defining time varying fge which differs from constant fge. Used when **age dependent fge** is turned on. The number following the token dictates the form of the equation used. This must be paired with an end statement.
- `fish_depth_eqn` [Species]: Defines the depth profile for each stock modeled. Used together with gas mortality to define the mortality of fish due to gas relationship. The average gas mortality for a reach is calculated by averaging over all gas levels in a reach and also using a fish depth distribution. The number following the token dictates the form of the equation used. This must be paired with an end statement.
- `fish_spill` [Dam]: Days and hours of the day during which planned spill is allocated. These periods indicate the actual hours and days that spill will occur. See Spill section on page 95 for more information on how `fish_spill` and `planned_spill` work together to determine spill operations.
- `floor_elevation` [Dam]: Elevation in feet above sea level of the floor of the forebay above the dam as well as the tailrace downstream from the dam.
- `flow` [Headwater]: An array of daily flow values, in kcfs.
- `flow_coef` (calculated): The flow coefficient is a value between 0 and 1, showing how much of the flow is apportioned to each headwater. When reading from a flow archive file, flows are propagated upstream from dams. If a dam has no other dams upstream of it, then its flow will be apportioned amongst all unregulated headwaters above it (after allowing for any contributions of regulated headwaters above it or losses in intervening reaches). The flow to be apportioned amongst unregulated headwaters is divided up according to their `flow_max` values.
- `flow_max`: 1) This defines a value for the maximum flow measured in a `river` over the last century. CRiSP.1 uses this value to calculate how to divide up flows that are propagated upstream. This should follow the `river` designation. Token used in **columbia.desc** file. 2) [Headwater] 50-year maximum flow in the headwater; this is used to distribute flows at confluences during upstream propagation.
- `flow_mean` [Headwater]: Mean flow for the year at the headwater. This is used as a scale factor for headwater modulation.
- `flow_min`: 1) This defines the lowest flow allowed in a `river`. This should follow the `river` designation. Token used in **columbia.desc** file. 2) [Dam]: Minimum flow allowed at a dam, in kcfs.
- `flush_trans_equation` [Species]: This equation is used to calculate the FLUSH Transport Figure of Merit. The number following the token dictates the form of the equation used. This must be paired with an end statement.

- `forebay_elevation` [Dam]: Elevation of forebay, in feet above sea level, at full pool.
- `forebay_pred_coef_*` [Species]: The dam forebay predation coefficient which effects the rate of predation activity by northern pikeminnows on smolt for a given predator density. The coefficients are species specific and are defined separately for reaches, dam forebays and dam tailraces. This is a stochastic parameter.
- `fork_threshold` [Global]: Defines how big a river fork must be before elevation changes propagate up it.
- `gas_dissp_exp` [Global]: An exponent controlling degassing of total dissolved gas from the water (*10^-4cm^2/sec). This depends on river velocity and depth.
- `gas_mort_eqn` [Species]: Defines the average mortality due to gas for each species in a reach. Used together with Population Density vs. Depth (`fish_depth_eqn`) to define the mortality of fish due to gas relationship. The average gas mortality for a reach is calculated by averaging over all gas levels in a reach and also using a fish depth distribution. The number following the token dictates the form of the equation used. This must be paired with an end statement.
- `gas_theta` [Dam]: Gas theta determines the level of mixing between the left-bank and right-bank flows in the tailrace of the dam and the resulting gas levels in each flow upon exiting the dam. This essentially determines the amount of mixing between the spill flow and the powerhouse flow in the tailrace. See Table 30 for `spill_side` designations for specific dams.
- `gas_theta` [Reach]: Gas theta determines the rate of mixing between the gas levels in the left-bank and right-bank flows of the river (facing downstream). These flows often have different levels of gas upon exiting a dam and become more mixed as the river flows downstream. The mixing rate is with respect to time and is set by default to be 0.075 (mile)^-1, which leads to roughly 95% mixing after 40 miles.
- `gate_width` [Dam]: Width, in feet, of each spill gate at the dam.
- `headwater` [Headwater]: Names the headwater. This name must be present in the **columbia.desc** file, and must have a paired end statement. e.g. `headwater Columbia_Headwater`, and `end headwater (Columbia_Headwater)`.
- `hw_flow_prop` [Global]: Specifies overall water availability in the system relative to an average water year for Scenario Mode runs. This is a portion of mean flow as the fraction of an average water year. Set in the **Headwater Modulation** window.
- `k_entrain` [Dam]: Determines how much gas is added to the powerhouse flow because of amount of spill going over the spillway into the tailrace of the dam. The higher the spill the more gas that is added to the powerhouse flow, with the level of total dissolved gas (tdg) in the powerhouse flow ranging from the forebay tdg level to the tdg level in the spill flow.
- `latlon`: 1) [Dam] Location of the dam in latitude and longitude in the **columbia.desc** file. 2) [Reach] Provides latitude and longitude for points in the course of the reach in the **columbia.desc** file, e.g. `latlon 46 09 00 N 123 16 00 W` marks 46 degrees 9 minutes north latitude, 123 degrees 16 minutes west longitude.
- `length` [Release]: Specifies the average length (in mm) of the fish at the time of the release.
- `loss` [Reach]: Daily loss records, in kcfs, for the reach. This is often 0.
- `loss_max` [Reach]: The maximum amount of flow allowed to be removed from the reach during model operations.
- `loss_min` [Reach]: The maximum amount of flow allowed to be added to the reach during model operations.
- `lower_depth` [Reach]: Depth in feet of the downstream end of the reach.

- `lower_elev` [Reach]: Elevation above sea level of the river bottom at the lower end of each reach.
- `mean_forebay_transit_time` (Species) [Dam]: Species-specific average time (in hours) that it takes the fish to travel from the entry point of the dam segment to the dam face where it will enter the bypass, spillway or turbine passage route. The default for each species at each dam is 2 hours. This measure is used in calculating passage mortality and is part of the dam delay model. There is no GUI for this parameter.
- `migr_var_coef_*` [Species]: Defines the relative variability in fish migration velocity. This is a stochastic parameter.
- `migration_eqn` [Species]: Defines the velocity of fish as a function of flow, age and time of release. The number following the token dictates the form of the equation used. This must be paired with an end statement.
- `mod_*` [Dam/Headwater]: Parameters used in modulation of flows.
- `mod_coeffs_*` [Headwater]: Coefficients for a nine-term Fourier series that describes the average annual shape of river flow.
- `mod_coeffs_a` [Headwater]: Cosine coefficients. The first element, `a_0`, is always 1.
- `mod_coeffs_b` [Headwater]: Sine coefficients. The first element, `b_0`, is always 0.
- `mod_end_hi_sigma` [Headwater]: Day of year to return to low variance.
- `mod_hi_sigma` [Headwater]: Standard deviation for modulation; used for the part of the year when flow variance is high.
- `mod_lo_sigma` [Headwater]: Standard deviation for modulation; used for the part of the year when flow variance is low.
- `mod_norm_sigma` [Dam]: Standard deviation to use when modulating flows at downstream dams.
- `mod_ou_r` [Dam]: Specifies correlation of flow from one day to the next.
- `mod_ou_r` [Headwater]: Autocorrelation parameter for flow.
- `mod_ou_sigma` [Dam]: Standard deviation to use when modulating flows at farthest upstream dams.
- `mod_start_hi_sigma` [Headwater]: Day of year to start using high variance.
- `mod_weekly_amp` [Dam]: Amplitude of weekly variation imposed on modulation.
- `mortality_class` [Global]: Indicates which Mortality Model is being used during Scenario and Monte Carlo runs: Gas & Pred Mortality (`gas_pred`) or Simple Mortality (`simple`). The currently calibrated Mortality Model is Gas & Pred Mortality.
- `ngates` [Dam]: Number of spill gates at the dam.
- `night_fge_*` (Species) [Dam]: Species-specific parameter describing fge during nighttime hours. This is a stochastic parameter.
- `nsat_backup_equation` [Dam]: Defines the production of total dissolved gas supersaturation due to spilling at dams when the spill value falls out of a reasonable range for the equations provided for Day and Night characteristics. This is one of three equations which defines gas production at a dam. The number following the token dictates the form of the equation used. This must be paired with an end statement.
- `nsat_day_equation` [Dam]: Defines the production of total dissolved gas supersaturation due to spilling at dams during day hours (6-18). This is one of three equations which defines gas production at a dam. The number following the token dictates the form of the equation used. This must be paired with an end statement.
- `nsat_night_equation` [Dam]: Defines the production of total dissolved gas supersaturation due to spilling at dams during night hours (0-6 and 18-24). This is one of three equations which defines gas production at a dam. The number following the

token dictates the form of the equation used. This must be paired with an end statement.

- `number` [Release]: An array of numbers of fish released for a period of days which may be a single day or many days. The Release Start day determines on which julian days the releases occur. This array represents the range of the release and the number of fish released per day.
- `output_gas` [Reach/Dam/Headwater]: The default setting is off. If `output_gas` is turned on, it replaces the dissolved gas data at the output of the feature (dam, reach, or headwater). One set of numbers are given, for each dam time slice in the season (366*4, currently). The numbers are applied to both sides of the feature. There is no GUI for this parameter.
- `output_settings` [Reach/Dam/Headwater]: Specifies what detailed information is output for a given reach, dam, or headwater during both Scenario and Monte Carlo runs. The single value is a combination of up to 10 flags, each of which is a single binary digit, arithmetically added together. Thus a value of "41" would indicate that flags "1", "8", and "32" were set, requesting output of passage, flow, and TDG saturation. Flags which are declared for the wrong type of river feature (e.g. spill at a reach) are silently ignored. The following is a list of flags and where they are allowed (Dam, Reach, and/or Headwater):
    - 1 = passage (d, r)
    - 2 = transport passage (d)
    - 4 = routing (d)
    - 8 = flow (d, r, h)
    - 16 = water temperature (d, r, h)
    - 32 = TDG saturation (d, r)
    - 64 = velocity (r)
    - 128 = loss (r)
    - 256 = spill (d)
    - 512 = elevation (r)
- `pergate` [Dam]: Amount of flow passed through each spill gate, in kcfs.
- `planned_spill` [Dam]: Periods of days when spill fractions are planned as part of the water budget and spill allocation agreements and an associated fraction of river flow spilled on an instantaneous basis. Different fractions can be set for different blocks of days. See Spill section on page 95 for more information on how `fish_spill` and `planned_spill` work together to determine spill operations.
- `powerhouse_capacity` [Dam]: Total hydraulic capacity, in kcfs. Same for the second powerhouse (`powerhouse_2_capacity`).
- `powerhouse_capacity` [Dam]: Total hydraulic capacity, in kcfs.
- `powerhouse_priority` [Dam]: Dictates whether the powerhouse is the primary or secondary powerhouse.
- `powerhouse_schedule` [Dam]: Array of hours during which a powerhouse may operate. This generally defaults to 24 hours year round.
- `powerhouse_threshold` [Dam]: Amount of spill allowed over primary powerhouse capacity before secondary powerhouse is turned on.
- `pred_density_forebay` [Dam]: Describes the density of predators in the forebay.
- `pred_density_tailrace` [Dam]: Describes the total predator population in the tailrace.

- `pred_dist` [Reach]: The Predator Distribution Coefficient of the **predator density / volume interaction** for each river segment. The main purpose of the predator density/ volume interaction is to properly scale the effect of initial predator densities on predation rate during reservoir drawdown. Used when predator density/volume interaction is turned on.
- `pred_mean` [Reach]: Predator densities in each river segment. Densities are given as the number of northern pikeminnows per square kilometer of reservoir. This measure, based on full pool dimensions, is effectively a measure of the total number of predators in a river segment. Used as part of the **Gas and Predation Mortality Model**.
- `pred_temp_response_eqn` [Species]: Defines the temperature response component of predator activity as a function of consumption rate and temperature. The number following the token dictates the form of the equation used. This must be paired with an end statement.
- `predation_prob` (Species) [Dam]: Species-specific array of values describing the relative success of predators during each 6-hour segment of the day; generally this is 1 for all periods.
- `reach`: 1) [Reach] Designates the beginning of a reach and its name. 2) [Reach] Defines a reach name, e.g. `reach Estuary` which matches a name defined in the **columbia.desc** file, and is paired with an end statement, e.g. `end reach (Estuary)`.
- `reach_pred_coef_*` [Species]: The reach predation coefficient which effects the rate of predation activity by northern pikeminnows on smolt for a given predator density. The coefficients are species specific and are defined separately for reaches, dam forebays and dam tailraces. Used as part of the **Gas and Predation Mortality Model**. This is a stochastic parameter.
- `release` [Release]: Names release and species released, e.g. `release Steelhead Lower_Granite_Hatchery 141` where species is steelhead, release site is Lower Granite Hatchery - which is defined in the **columbia.desc** file - and 141 is the julian date of the first day of fish release. This token must be paired with an end statement.
- `release_site`: This defines the name of a release site in the system. A release site must have a location associated with it in the latitude/longitude format; it must also coincide with a point also defined in a reach, i.e. release sites must lie exactly on a river point. Token used in **columbia.desc** file.
- `river`: This defines a collection of reaches and assumes that some headwater exists for the river. A river may consist of a number of reaches (e.g. Columbia or Snake) or a single reach (e.g. Imnaha or Grande Ronde). Token used in **columbia.desc** file.
- `runtime_settings` [Global]: Specifies what functional relationships to consider during both Scenario and Monte Carlo runs. The single value is a combination of up to 3 flags, each of which is a single binary digit, arithmetically added together.
- 1 = variance suppression turned on
- 2 = predator density / volume interaction turned on
- 4 = age dependent fge turned on
- `separation_prob` (Species) [Dam]: Species-specific parameter for ability to separate individuals of that species during bypass, in percentage. This is used in transport operations.
- `sgr` [Dam]: Specific gravity of the roller; this can vary from 0 to 1.
- `simple_mort_equation` [Species]: This is the mortality equation for reaches when **Simple Mortality** has been selected as the Mortality Model. The number following the token dictates the form of the equation used. This must be paired with an end statement.
- `slope` [Reach]: The inward slope of the sides of the reach, in degrees.

- `smolt_finish` [Release]: The julian date for the finish of smoltification.
- `smolt_onset` [Release]: The julian date for the onset of smoltification. Fish released prior to this date do not actively migrate.
- `species`: 1) Species tokens must appear first in the **columbia.desc** file. Any species to be used in the model must be identified by the species token, e.g. `species Steelhead`. There is no fixed limit on the number of species that can be specified. 2) [Species]: This identifies the species in question, e.g. `species Chinook_0`. Following the remaining parameter specifications there must be a paired end token, e.g. `end species (Chinook_0)`. The species must be identified in the **columbia.desc** file.
- `spill_cap` [Dam]: Maximum allowable flow that is allowed to pass through spill.
- `spill_equation` (Species) [Dam]: Equation describing the spill efficiency at the dam. The number following the token dictates the form of the equation used. This must be paired with an end statement.
- `spill_mort_*` (Species) [Dam]: species-specific value for mortality suffered as fish pass through the spillway. This is a stochastic parameter.
- `spill_side` [Dam]: Indicates which side looking downstream from a dam is the spill side. For dams, total dissolved gas saturation in percent above 100 is recorded for both the left-bank flow and right-bank flow levels. These flows often have different levels of gas upon exiting a dam because of the gas production from spill. At each dam the two flows are marked as either the powerhouse flow or the spill flow (`spill_side`). Consult Table 30 to determine whether the `spill_side` is left or right at a specific dam, looking downstream.
- `spillway_width` [Dam]: Total width, in feet, of the spillway.
- `stock`: 1) Stock tokens appear after the species tokens in the **columbia.desc** file. Any specific stock to be used in the model must be identified by the stock token, e.g. `stock Catherine Creek Ch1`. There is no fixed limit on the number of stocks that can be specified. 2) [Release]: Identifies the stock of release. This can be set to “Generic” or a specific stock can be selected, e.g. `Catherine Creek Ch1`. The stock must be identified in the **columbia.desc** file.
- `storage_basin` [Dam]: Defines storage behind headwater dams. Takes two parameters: the minimum and maximum storage capacity, in thousand acre feet, e.g. `storage_basin 0.0 5185.5`.
- `storage_volume` [Dam]: Water volume in the reservoir, in kiloacre-feet (kaf), specified by period (single day or range of days). This token only occurs in specifications for dams that are storage reservoirs as defined in the **columbia.desc** file, i.e. Hells Canyon, Dworshak, and Chief Joseph.
- `tailrace_elevation` [Dam]: Elevation of tailrace, in feet above sea level, at full pool.
- `tailrace_length` [Dam]: Not in use. Length of the tailrace in feet. CRiSP.1 previously determined the residence time of fish in the tailrace in terms of the flow, the width of the dam, and a tailrace length. This time was used in calculating predation in the tailrace. The time was set by adjusting the tailrace length. Tailrace length was set to conform to the region of high flows immediately below the dam. This region also contains elevated predator densities.
- `tailrace_pred_coef_*` [Species]: The dam tailrace predation coefficient which effects the rate of predation activity by northern pikeminnows on smolt for a given predator density. The coefficients are species specific and are defined separately for reaches, dam forebays and dam tailraces. Used as part of the Mortality Model. This is a stochastic parameter.

- `trans_mort_equation` (Species) [Dam]: Defines the relationship between water particle travel time (WPTT) and transport survival based on the assumption that changes in flow affect how well fish survive transportation. The number following the token dictates the form of the equation used. This must be paired with an end statement.
- `transport` [Dam]: Defines transport operations.
  - `start_by_date`: 0 = start transportation if daily counts exceed a specified number (`start_count`) in a day; 1 = start transportation on a specified day (`start_date`).
  - `start_date`: Specific julian day to start transportation.
  - `start_count`: Start transportation when this number of fish pass the dam in a day.
  - `max_restarts`: 0 = transportation cannot be restarted; 1 = transportation can be restarted exactly once; -1 = transport can be restarted as often as the conditions are met.
  - `restart_by_date`: 0 = restart transportation if daily count exceeds a specified number (`restart_count`); 1 = restart transportation on a specified day (`restart_date`).
  - `restart_date`: Specific julian day to restart transportation.
  - `restart_count`: Restart transportation when this number of fish pass the dam in a day.
  - `end_date`: Specific julian day to stop transportation.
  - `end_count`: Stop transportation if the daily fish count drops below this number for a given number of sequential days (`num_low_days`).
  - `num_low_days`: Stop transportation if the daily fish count drops below a given number for this number of sequential days.
  - `hfl_passed_perc`: Identifies what percent of the indicator species (`high_flow_species`) must pass to terminate separation. Separators in bypass systems of dams will separate and return smaller fish to the tailrace when flow is above a specified level. The separation is terminated and all fish are collected when passage of a specified stock exceeds a specified percentage.
  - `high_flow`: Identifies flows above which separation starts. Separators in bypass systems of dams will separate and return smaller fish to the tailrace when flow is above a specified level. The separation is terminated and all fish are collected when passage of a specified stock exceeds a specified percentage.
  - `high_flow_species` (Species): Identifies indicator species (Chinook 0, Chinook 1, Chinook Summer, Steelhead) for which its passage will terminate separation. Separators in bypass systems of dams will separate and return smaller fish to the tailrace when flow is above a specified level. The separation is terminated and all fish are collected when passage of a specified stock exceeds a specified percentage.
  - `transport_rate`: Barge or truck transportation speed in miles per day from collection site to release site.
  - `release_point`: River reach into which fish are released.
- `transport_mort_*` (Species) [Dam]: Species-specific value for mortality suffered during the entire transport process. This is a stochastic parameter.
- `turbine_mort_*` (Species) [Dam]: Species-specific value for mortality suffered during turbine passage. This is a stochastic parameter.
- `ufree` [Global]: River velocity in free flowing portions of river (in kcfs*10^-1).
- `upper_depth` [Reach]: Depth in feet of the upstream end of the reach.

- `v_var` [Species]: Variance in velocity; this contributes to “spread” of fish.
- `vitality` [Release]: Not implemented, yet. A measure of the health of the fish in the release.
- `vitality_change` [Release]: Not implemented, yet. Incremental change in vitality for the release.
- `water_temp` [Headwater]: An array of water temperatures, in degrees celsius. Temperatures are determined below confluences by averaging input temperatures weighted by flow volume.
- `water_travel_upper_segment` [Global]: Used in transport mortality calculations. Set by CRiSP.1 to be Little Goose Pool. There is no GUI to set this parameter.
- `water_travel_lower_segment` [Global]: Used in transport mortality calculations. Set by CRiSP.1 to be Estuary. There is no GUI to set this parameter.
- `water_travel_first_day` [Global]: Used in transport mortality calculations. Set by CRiSP.1 to be 1. There is no GUI to set this parameter.
- `water_travel_last_day` [Global]: Used in transport mortality calculations. Set by CRiSP.1 to be 365. There is no GUI to set this parameter.
- `width` [Reach]: Width of the reach in feet.