Chapter 4. Theory

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4.1 - Introduction

Computation Flow

Life cycle computations in CRiSP Harvest are performed on an annual basis. The sequence of computations reverses the procedures employed in the cohort analysis used to generate the stock-specific input data. The annual computational sequence is illustrated in Fig. 4.1 and outlined below:

- Population ageing
- Natural ocean mortality
- Preterminal (ocean) fishing mortality
  - Legal harvest
  - Incidental mortality (shakers and CNRs)
- Maturation
- Terminal fishing mortality
  - Legal harvest
  - Incidental mortality (shakers and CNRs)
- Adult escapement (ages 3, 4, and 5)
- Pre-spawning mortality (inter-dam losses) for some stocks
- Spawning escapement
- Production of progeny in the next year.

Incidental fishing mortalities include “shakers” (sub-legal sized fish caught and released during chinook fisheries) and “CNRs” (legal and sub-legal sized fish caught and released during “chinook non-retention” fisheries directed at other species (e.g., coho).

The remaining five sections of this chapter describe the functional relationships of the model. Natural survival processes are described first, followed by production processes, fishing processes, catch ceiling management, and in-river management.

Although many of the parameters are year specific, year indices have been deleted to make the equations easier to interpret. Brief descriptions of all variables follow each equation.

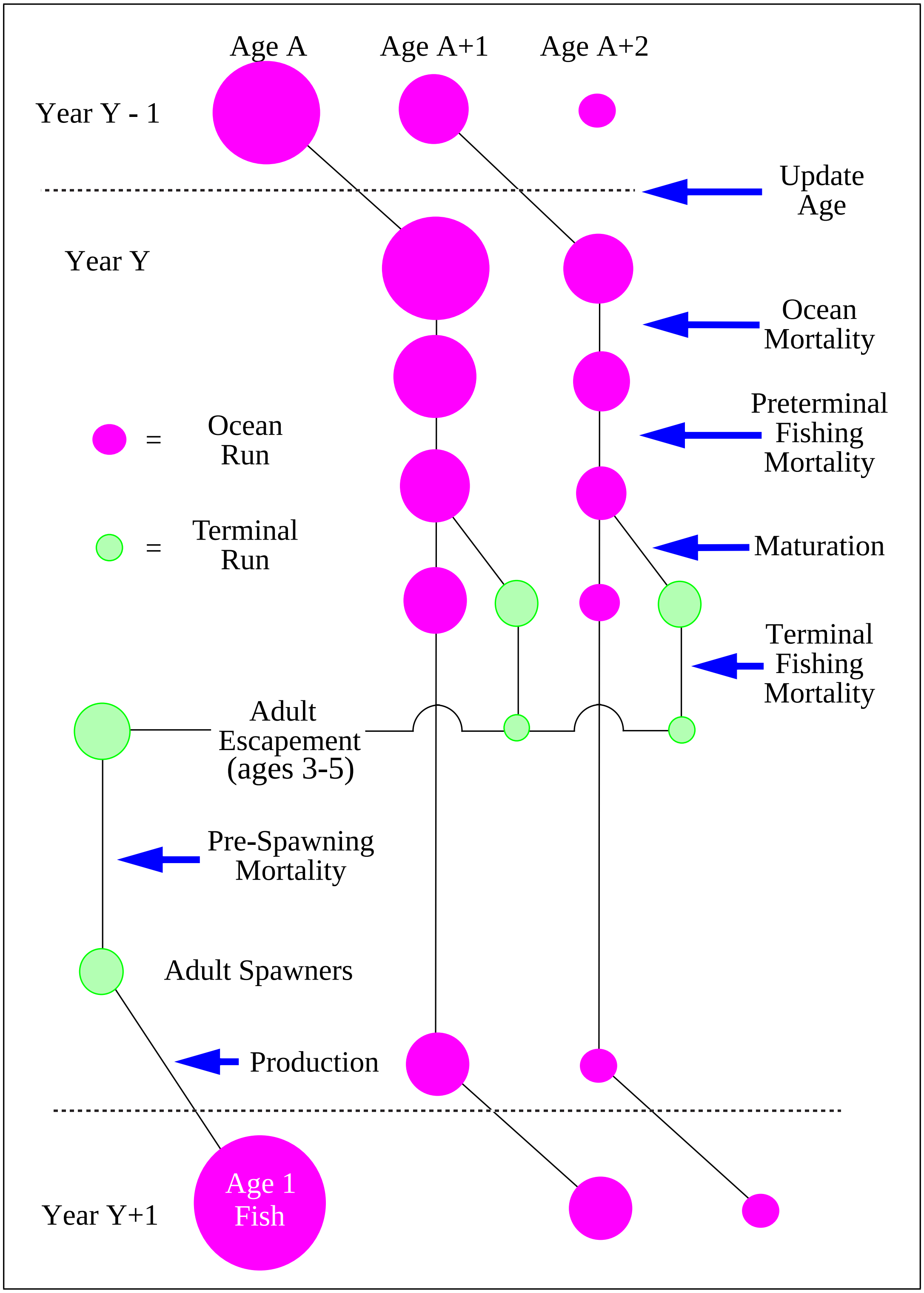

Fig. 4.1 Illustration of the annual computation cycle in CRiSP Harvest.

4.2 - Biological Processes

Natural Ocean Mortality

Non-fishing and fishing mortalities occur independently and at different times of the year. For most stocks, non-fishing mortality is composed entirely of natural ocean mortality and is assessed at the beginning of each year. For Columbia River stocks that spawn upriver from dams, additional non-fishing mortality (called pre-spawning mortality or inter-dam losses) is assessed after fishing mortality to account for losses between dams (Fig. 4.2).

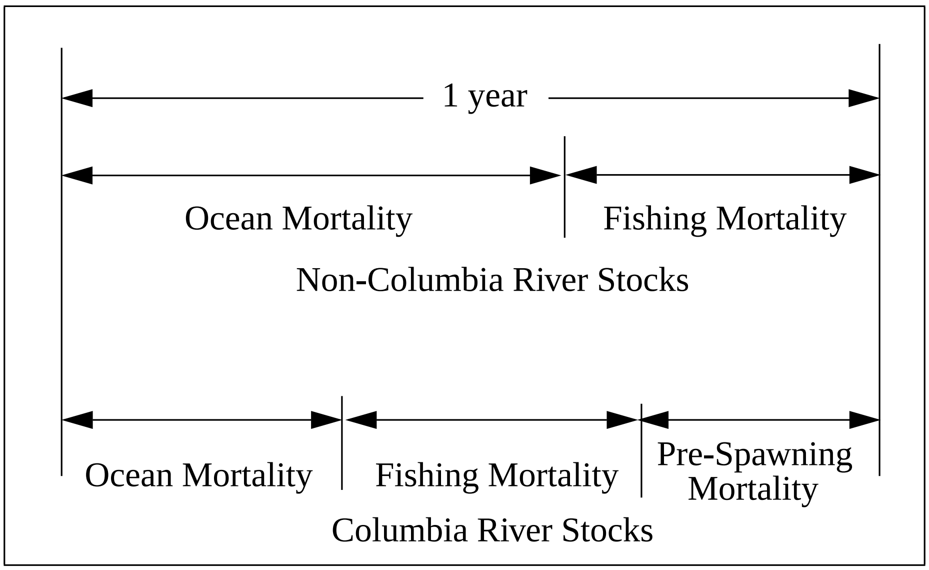

Fig. 4.2 Assessment of mortalities during one year.

Natural ocean mortalities are age specific, but not stock specific. For example, age two fish from all stocks have the same natural ocean mortality, or survival, rate. Thus, at the start of each year, ocean run sizes for each cohort are updated as follows:

$$OcnRun(s, a) = Cohort(s, a)OcnSurvRt(a) \tag{4.1}$$

where

- *OcnRun(s,a)* = ocean run size of stock *s*, age *a*
- *Cohort(s,a)* = cohort size of stock *s*, age *a* at the start of the year
- *OcnSurvRt(a)* = natural ocean survival rate for age *a*.

The following description of natural mortality estimation procedures is taken from CTC (1988). Direct estimates of natural (non-catch) mortality for chinook salmon are lacking. The numbers used in the cohort analysis were chosen to conform to the numbers used in the Georgia strait virtual population analysis (Argue et al., 1982--spreadsheet version). Specifically, the argue paper used a natural mortality of 1.5% per month for ages three to five and 3% per month for age two. These values calculate to 31% and 17% per year for age two and ages three through five, respectively.

In 1982, when these cohort analysis procedures were begun (undocumented), it was decided to use stepped values of mortality by age. The values chosen are given in Table 4.1 The mean of the values used for ages three through five is 20% (similar to the 17% used in the Argue paper). The 40% continues the stepped progression.

Table 4.1 Natural ocean mortality and survival rates for ages 1-5.

Age (*a*)	*OcnMortRt(a)*	*OcnSurvRt(a)*
1	.5	.5
2	.4	.6
3	.3	.7
4	.2	.8
5	.1	.9

Maturation

Stocks mature at ages two through five and begin their return migration to the spawning grounds. Maturation rates are stock and age specific. The mature fish in each cohort are called the terminal run.

$$TermRun(s, a) = (OcnRun(s, a) - PreTermMort(s, a))MatRt(s, a) \qquad (4.2)$$

where

- *TermRun(s,a)* = terminal run for stock *s*, age *a*
- *PreTermMort(s,a)* = preterminal fishing mortalities for stock *s*, age *a* (over all fisheries)
- *MatRt(s,a)* = maturation rate for stock *s*, age *a*.

Recent analyses indicate that age specific maturation rates can vary substantially from year to year for some stocks. When annual maturation rate estimates are available, they are allowed to vary each year in the model.

Adult Escapement

Terminal run fish must pass two obstacles before reaching the spawning grounds: (1) terminal fisheries; and (2) river obstructions, such as dams. Fish passing all terminal fisheries are called the adult escapement. The age two fish returning to the river are not considered reproductively viable, and are not included in the adult escapement for each stock.

$$AdltEsc(s) = \sum_{a=3}^{5} (TermRun(s, a) - TermMort(s, a)) \tag{4.3}$$

where

- *AdltEsc(s)* = adult escapement for stock *s*
- *TermMort(s,a)* = terminal fishing mortalities for stock *s*, age *a* (over all fisheries).

Pre-Spawning Mortality

Three stocks, all from the Columbia River system (Upriver Brights, Spring Creek, and Lyons Ferry), are assessed pre-spawning mortality (also called “Inter-Dam Losses”). All other stocks have 100% survival between the terminal fishing area and the spawning grounds. Pre-spawning mortality is applied to the total adult escapement as follows:

$$Spawners(s) = AdltEsc(s)PreSpSurvRt(s) \tag{4.4}$$

where

- *Spawners(s)* = number of spawners for stock *s*
- *PreSpSurvRt(s)* = pre-spawner survival rate for stock *s*.

Note that all age classes in the adult escapement are assessed the same mortality rate. Thus, the model assumes that age and size have no influence on the upstream survival rate.

4.3 - Production Processes

Overview

For each stock, the relationship between *Spawners* in year *y* and progeny (termed *AgeOneFish*) in year *y* + 1 is perhaps the most critical component of the model. It is through this relationship that time dynamics are incorporated into the analysis of alternative stock rebuilding strategies.

Stocks in the PSC Chinook Model are divided into two categories based on their production type: hatchery or natural. In general, hatchery production is modeled as a simple linear relationship between *Spawners* and *AgeOneFish* while natural production is modeled by a truncated Ricker curve relating spawners to adult recruitment, which is then corrected to *AgeOneFish* through a procedure outlined in detail later.

For both types of stocks, *AgeOneFish* are adjusted to make allowances for recruitment variability by incorporating "Environmental Variability" (EV) scalars. EV scalars can be thought of as pre-recruitment (i.e., prior to age one) survival scalars that compensate for both environmental variation and any bias in the original production parameter estimates. EV scalars for the calibration period are determined during calibration, while EV scalars for the simulation period are specified by the user. Model results are known to be very sensitive to the choice of EV scalars during the simulation period.

Hatchery Production

A simple linear model is used to relate hatchery spawners in year *y* to *AgeOneFish* in year *y* + 1. When the number of spawners does not exceed hatchery capacity, we have

$$AgeOneFish(s, y+1) = Spawners(s, y) \cdot e^{HatchProd(s)} \tag{4.5}$$

where

- *AgeOneFish(s,y+1)* = number of progeny for stock *s* in year *y* + 1.
- *Spawners(s,y)* = number of spawners for stock *s* in year *y.*
- *HatchProd(s)* = base period hatchery production efficiency for stock *s*.

The *HatchProd(s)* parameter is given in exponential form because the analogous productivity term in the Ricker function for natural stocks is represented in exponential form. If *Spawners(s,y)* > S_{opt} (= average hatchery production during the base period 1979-1981), the excess spawners are transferred into terminal catch.

The model assumes that hatchery production is maintained at the average 1979-1981 level unless instructed otherwise. In such cases, the first step in modeling changes in enhancement activities (which are input as changes in smolt production) is to compute the increased (or decreased) number of spawners required to meet the new smolt production goal:

$$EnhSpawners(s) = \frac{Smolts(s) \cdot SmoltSurvRt(s)}{e^{EnhProd(s)}} \tag{4.6}$$

where

- *Smolts(s)* = change in smolt production for stock *s*
- *EnhSpawners(s)* = number of required to produce *Smolts(s)*
- *SmoltSurvRt(s)* = smolt to age on survival rate for stock *s*
- *EnhProd(s)* = enhancement production efficiency for stock *s*.

EnhProd(s) is generally smaller than *HatchProd(s),* reflecting the decrease in efficiency when producing more smolts.

If production is decreased, eq (4.5) is used to compute *AgeOneFish,* but the hatchery spawning goal is reduced to S_{opt} - *EnhSpawners*. Again, excess spawners are transferred to terminal catch.

If production is increased, additional *AgeOneFish* are computed using eq (4.5), with *EnhProd* replacing *HatchProd* to reflect the lower production efficiency. If the number of spawners exceeds the number required for both base and enhanced production, the excess spawners are added to the terminal catch, with the exception of one stock --Georgia Strait Hatchery (GSH). In this case, the additional spawners (up to a maximum of 5,000) are assumed to be returned to the river and are modeled as natural spawners using the truncated Ricker curve (described in the next section). Additional excess spawners are transferred to terminal catch. Fig. 4.3 illustrates all hatchery production functions.

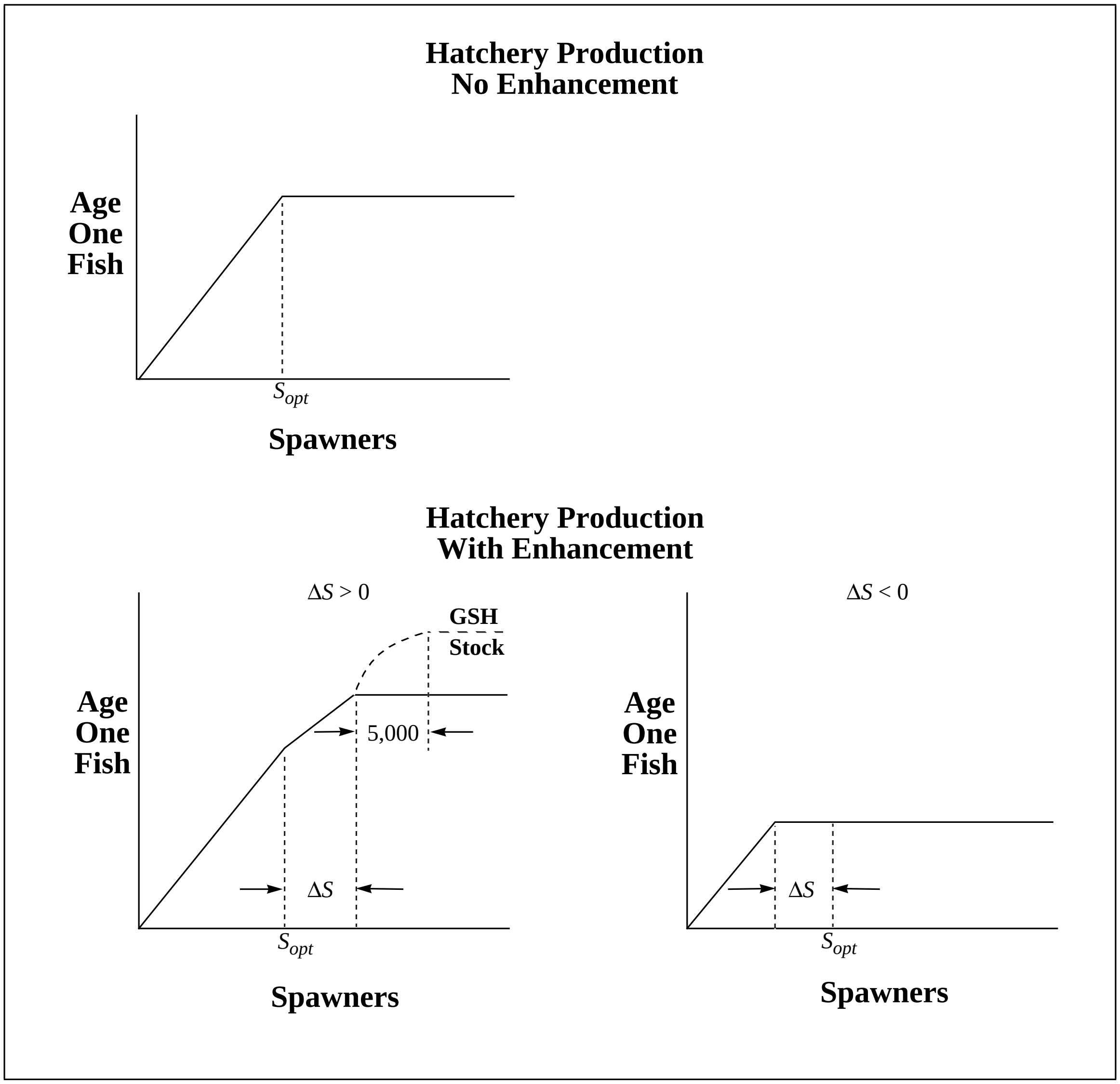

Fig. 4.3 Hatchery production functions, with and without enhancement. The term ΔS equals *EnhSpawners* (i.e., the change in the number of spawners required to meet the changed smolt production goal).

Natural Stocks

All natural stocks incorporate a truncated Ricker Spawner/Recruit Relationship (SRR) relating spawners to adult equivalent recruitment. The general form of the Ricker SRR is:

$$Recruits = (Spawners)e^{\alpha\left(1 - \frac{Spawners}{\beta}\right)} \tag{4.7}$$

where

- *Spawners* = number of adult spawners on the spawning grounds
- *Recruits* = number of adults recruiting to the fishery
- α = productivity parameter
- β = capacity parameter.

The general form of the Ricker SRR is illustrated in Fig. 4.4. The slope of the curve at the origin is e^{α} and β is the spawning level at the point where the SRR intersects the exact replacement line (in most cases, this is equivalent to the equilibrium condition in the absence of harvesting).

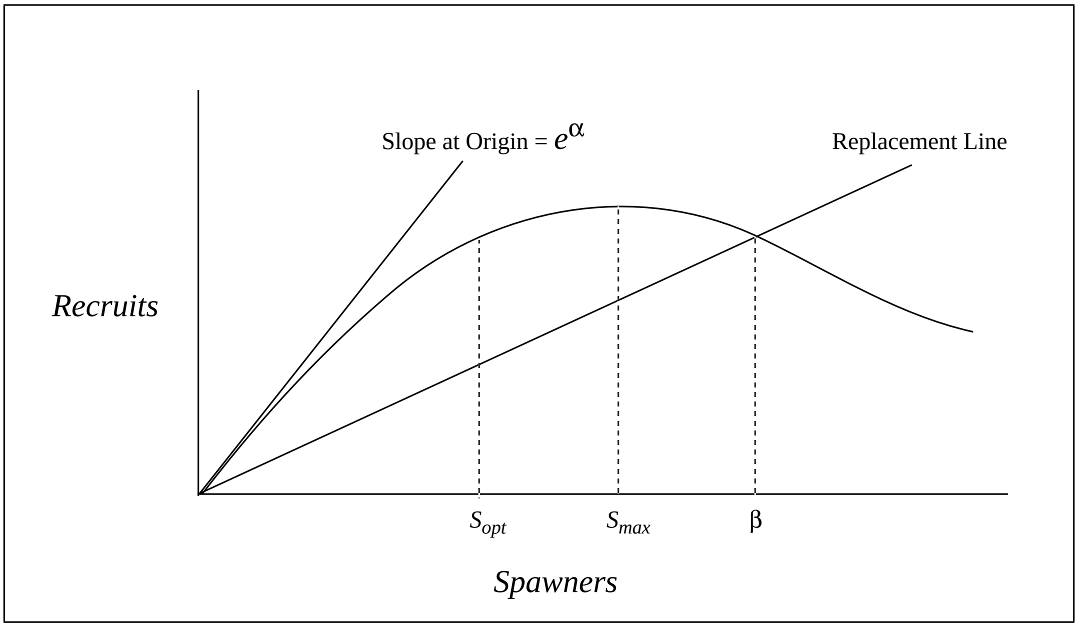

Fig. 4.4 Typical Ricker spawner-recruit relationship. S_{opt} is the spawning level that produces maximum sustainable harvest (i.e., maximum difference between recruitment and exact replacement line), S_{max} produces the maximum number of recruits, and β is the equilibrium spawning level in the absence of harvest.

For each stock, the input data files provide α, but not β. Instead the model inputs the estimated optimum number of spawners (S_{opt}), as determined from historical data and field observations. The Ricker β parameter is then computed from S_{opt} and α using the approximation given by Hilborn (1985):

$$\beta = \frac{S_{opt}}{0.5 - 0.07\alpha} \tag{4.8}$$

Maximum production (S_{max}) is given by

$$S_{max} = \frac{\beta}{\alpha} \tag{4.9}$$

Note that *Recruits* in eq (4.7) includes ages two through five. For modeling purposes, it is necessary to simulate the production of *AgeOneFish*, not the mature fish recruiting to the fishery. For chinook salmon stocks, several year classes may contribute to the spawning stock. In the equilibrium condition with no fishing, the age distribution is stationary and there is a constant linear relationship between adult recruitment and *AgeOneFish* (Fig. 4.5).

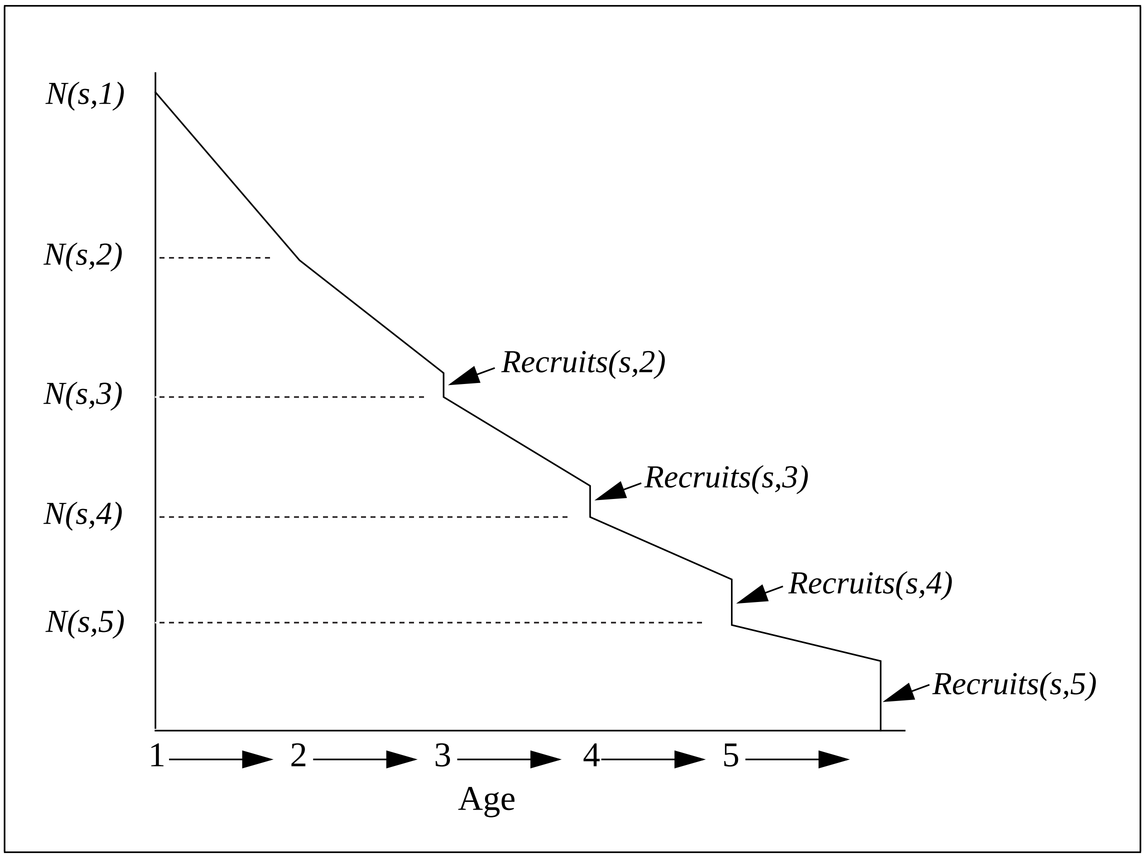

Fig. 4.5 Illustration of abundance and recruitment when there is no fishing mortality and the age distribution is stationary.

For ages three, four and five, the abundance at the start of each year and the number of mature fish returning to spawn are given by

$$N(s, a) = N(s, a-1)SurvRt(s, a-1)(1 - MatRt(s, a-1)) \tag{4.10}$$

$$Recruits(s, a) = N(s, a)SurvRt(s, a)MatRt(s, a) \tag{4.11}$$

The model relates spawners to *AgeOneFish* by computing a constant scaling factor called *RecAtAge1*. This value is computed by setting *N(s,1)* equal to one and recursively computing *N(s,a)* using eq (4.10) and summing *Recruits(s,a)* for ages two through five:

$$RectAtAge1(s) = \sum_{a=2}^{5} Recruits(s,a) \qquad (4.12)$$

When maturation rates are permitted to vary by year, new *RectAtAge1* parameters are computed each year. The number of AgeOneFish is computed by:

$$AgeOneFish(s) = \frac{Recruits(s,a)}{RectAtAge1(s)} \qquad (4.13)$$

For natural stocks without supplementation, the Ricker SRR is truncated at either S_{opt} or S_{max} (Fig. 4.6).

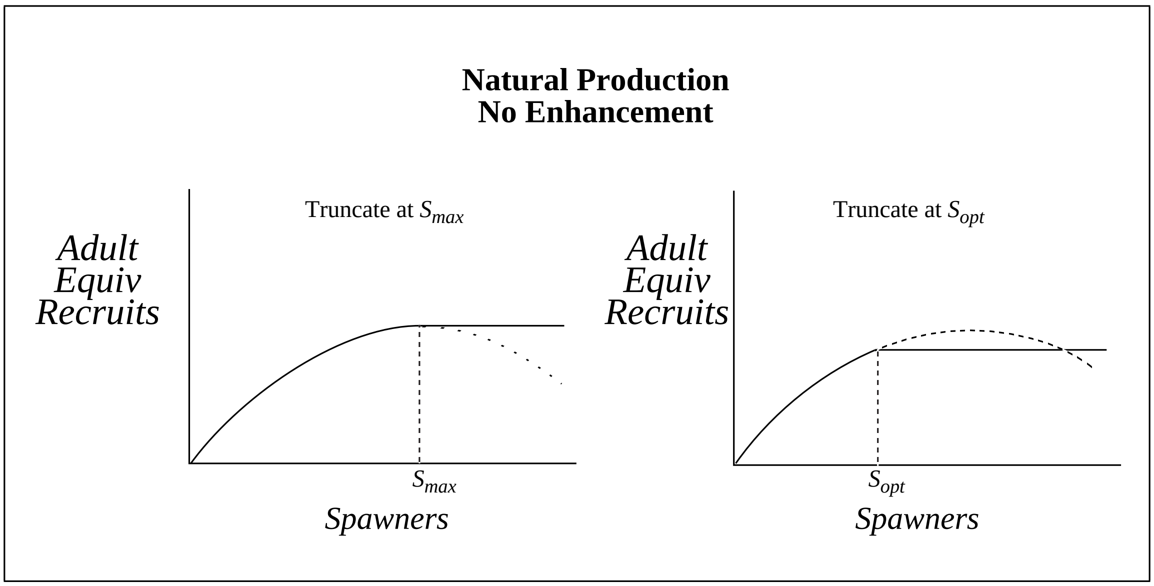

Fig. 4.6 Truncated Ricker curves used for natural production with no enhancement.

Supplementation

The model allows for enhancement of natural stocks (also called supplementation) in which a portion of the natural spawners are removed for hatchery production. The number of spawners removed may not exceed a maximum allowable percentage of the adult spawners.

$$MaxBrood(s) = EnhProp(s) \cdot Spawners(s) \qquad (4.14)$$

where

- *MaxBrood(s)* = maximum number of spawners that can be removed for supplementation for stock *s*.
- *EnhProp(s)* = maximum enhancement proportion for stock *s*.

Smolts from hatchery production are returned back to the river of origin, and therefore may compete with the naturally produced smolts. This competition may be modeled as either density dependent or density independent. In either case, the number of spawners required to meet the smolt production goal (*EnhSpawners*) is computed using eq (4.6), just as for hatchery stocks, truncating to *MaxBrood*, if necessary.

When density independence is assumed, natural and hatchery production are computed independently and added together. The naturally produced portion of *AgeOneFish* is computed from the remaining natural spawners (i.e., *Spawners(s)* - *EnhSpawn(s)*) using the appropriate truncated Ricker curve (Fig. 4.6). Hatchery produced portion of *AgeOneFish* is computed as follows:

$$AgeOneFish(s, y+1) = EnhSpawners(s, y) \cdot e^{EnhProd(s)} \tag{4.15}$$

When density dependence is assumed, *AgeOneFish* is computed using a truncated Ricker curve (Fig. 4.6), but the “effective” size of the spawning stock is increased to reflect the fact that eggs from some of the spawners are reared in a hatchery. The enhancement efficiency of the hatchery is given by

$$EnhEff(s) = \frac{e^{HatchProd(s)}}{e^{\alpha(s)}} \tag{4.16}$$

In general, *HatchProd(s)* is greater than α*(s)* so *EnhEff(s)* is usually greater than one. The effective number of spawners is given by

$$EffSpawners = EnhSpawn\frac{EnhEff}{\alpha} + (AdltEsc - EnhSpawn) \tag{4.17}$$

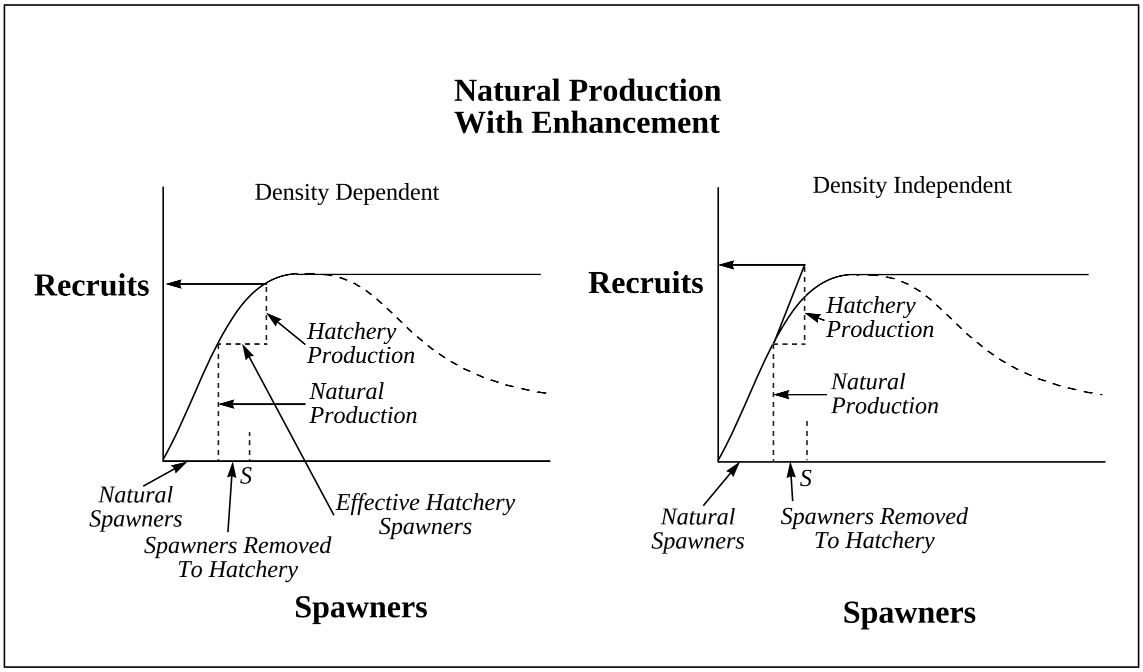

Fig. 4.7 Production functions for natural stocks with enhancement. Ricker curves truncated at S_{max} are shown. Other stocks may have the Ricker curve truncated at S_{opt}.

4.4 - Fishing Mortality

Three types of fisheries are modeled in CRiSP Harvest: troll, net, and sport. Troll and net fisheries are commercial fisheries. The net category includes both purse seine and gillnet fisheries.

Fishing mortality rates are estimated using cohort analysis based on coded-wire-tag (CWT) recoveries and are stock, age, and fishery specific. The estimation procedure is explained in more detail in the next section.

Two types of fishing mortality rates are distinguished. "Exploitation Rates" are expressed in terms of total coastwide abundances, not regional abundances. Thus, an exploitation rate of 0.10 for a given stock, age, and fishery means that 10% of the coastwide abundance of that stock/age cohort is harvested in the given fishery. "Harvest Rates" refer to fishing mortality rates in terminal areas where the regional abundance (i.e., true terminal run) of the stock is known.

Mortalities associated with fishing activities are assessed in two phases—preterminal and terminal—corresponding to the two primary life history phases of each cohort—immature and mature. Within each phase there are legal harvests and incidental mortalities. Incidental mortalities are caused by (1) the inadvertent capture of sublegal sized fish during fisheries targeting on chinook salmon (called shaker mortalities) and (2) the inadvertent capture of sublegal- and legal-sized chinook salmon during fisheries targeting on other salmon species (called chinook non-retention, or CNR, mortalities).

Estimating Fishing Mortality Rates

Parameters are estimated by a technique known as "cohort analysis" or "virtual population analysis". A cohort, in this context, is the total production which results from the escapement of a single year class from a particular group of fish. This type of analysis involves the reconstruction of an annual series of abundance estimates using the following data:

- Catch at age data from fisheries of interest
- Assumptions regarding incidental mortality rates and losses associated with these catches
- Escapements at age data
- Expansion of escapements to account for straying and pre-spawning mortality rates for some stocks
- Assumed rates of natural mortality
- Assumptions regarding the maturity of fish in the catch (i.e., differentiating between terminal and preterminal fisheries).

Data from CWT experiments are employed to produce a profile of harvest and escapement for the entire production of a stock. Data are analyzed through a backwards-stepping procedure, beginning with the oldest age class (assumed to be age five). Escapement, an estimate of pre-spawning mortality (when appropriate) and the terminal catch (including associated incidental mortality) are added to produce a mature run size for that age class. The ocean catches of that age class, associated incidental mortalities, and the cohort size of the next older age class are added to compute the size of the population immediately prior to fishing. This sum is then divided by the survival rate (1 - natural mortality) to give the cohort size for that age class. These calculations are summarized in Fig. 4.8.

Escapement (*a*)
+ Pre-Spawning Mortality (*a*)
+ Terminal Catch (*a*)
+ Incidental Terminal Mortality (*a*)
= Mature Run Size (*a*)
+ Preterminal Catch (*a*)
+ Incidental Preterminal Mortality (*a*)
+ Cohort Abundance (*a* + 1)
= Abundance of age *a* fish immediately prior to ocean fishery

Fig. 4.8 Calculations used in cohort analysis.

Once each cohort has been reconstructed, the following parameters can be estimated:

- Cohort size for each age class at the beginning of each year
- Age specific harvest rates for each preterminal and terminal fishery
- Maturity schedule for all ages
- Estimates of incidental fishing mortalities.

At this stage of development, CRiSP Harvest is a forecasting model and does not estimate parameters. It relies completely on parameters estimated by the PSC Chinook Technical Committee.

Preterminal vs Terminal Fishing Mortalities

All fishing mortalities are computed at the stock/age/fishery level, and thus the model must keep track of which stock/age/fishery mortalities are to be considered preterminal and which terminal. The preterminal/terminal designations are determined by three variables entered at startup and do not change throughout the simulation time period.

Fisheries that harvest only mature individuals from certain stocks are designated "terminal" for those stocks. For example, the Columbia River net fishery is considered terminal for all ages of all stocks of Columbia River origin. Some fisheries are terminal for some stocks and preterminal for others. For example, the Columbia River sport fishery is considered terminal for Columbia River stocks, but preterminal for the Oregon coastal stocks, which it also harvests.

On startup, the model reads in a two dimensional array of boolean characters, called *TermPt(s,f)* for "Terminal Pointer", to identify stock/fishery combinations for which all ages are to be considered terminal. Terminal fisheries and the stocks they harvest by geographic region are listed in Table 4.2.

All troll fisheries are considered preterminal for all ages of all stocks they harvest. Net fisheries are more complicated. Some ocean net fisheries harvest both immature and mature ages from the same stock. For example, the nearshore ocean waters where some net fisheries operate are habitat for immature ages and for mature ages returning to spawn. At startup, the model sets the age at which all harvests by net fisheries are to be considered mature. The variable is called the *TermNetAge* and is usually set at age four.

In summary, the model uses three variables to determine whether a stock/age/fishery harvest is preterminal or terminal: *TermPt*, *OcnNetFlg*, and *TermNetAge*. Table 4.3 summarizes the relationship between these variables for a given stock/fishery combination.

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Table 4.2 Stock/fishery interactions considered terminal for all ages.

Region	**Terminal Fisheries**	**Stocks**
Fraser River	Fraser Net	Fraser River Early Fraser River Late
West Coast Vancouver Island	WCVI Net WCVI Sport	WCVI Hatchery WCVI Natural
Puget Sound	Puget Sound North Net Puget Sound South Net	Nooksack Fall Puget Sound Fingerling Puget Sound Natural Puget Sound Yearling Nooksack Spring Skagit Wild Stillaguamish Wild Snohomish Wild
Washington Coast	Washington Coast Net	Wash Coastal Hatchery Wash Coastal Wild
Columbia River	Columbia River Net Columbia River Sport	Upriver Brights Spring Creek Hatchery Lower Bonneville Hatchery Fall Cowlitz Hatchery Lewis River Wild Willamette River Spring Cowlitz Hatchery Columbia River Spring Lyons Ferry

Table 4.3 Preterminal/terminal harvest criteria.

	OcnNetFlg = **FALSE**	*OcnNetFlg* = **TRUE**
TermPT = FALSE (Preterminal)	All ages preterminal	Ages < *TermNetAge* are preterminal Ages >= *TermNetAge* are terminal
TermPT = TRUE (Terminal)	All ages terminal	All ages terminal

Legal Harvests

Harvests of legal sized fish are computed as follows:

$$MDLCohortCat(s, a, f) = Run(s, a)HR(s, a, f)FP(s, f)PV(a, f) \quad (4.18)$$

where

- *MDLCohortCat(s,a,f)* = preterminal or terminal catch of stock *s*, age *a*, in fishery *f*
- *Run(s,a)* = coastwide ocean abundance, *OcnRun(s,a),* or coastwide terminal run, *TermRun(s,a),* for stock *s*, age *a*
- *HR(s,a,f)* = harvest rate for stock *s*, age *a*, in fishery *f*
- *FP(s,f)* = fishery policy scalar for stock *s* in fishery *f*
- *PV(a,f)* = proportion vulnerable for age *a* in fishery *f* (i.e., proportion of age *a* fish that are recruited to the gear and are above the legal size limit in fishery *f*).

Note that when preterminal harvests are computed, the stock/age/fishery specific exploitation rates are applied to the coastwide ocean abundance of the cohort, not the regional abundance. When terminal harvests are computed, the stock/age/fishery specific harvest rates are applied to the coastwide terminal run of the cohort. Terminal runs are computed by subtracting preterminal legal catches and incidental mortalities from the coastwide ocean abundance and then multiplying times the maturation rate.

Note that the *PV*s are age and fishery specific, but not stock specific. The *FP*s are fishery policy scalars and are unique to each stock, fishery, and year. They are used to simulate the effects of changes in fishery policies that disproportionately impact different stocks relative to the base period (e.g., changing the timing of the fishing period may impact stocks differently). For example, a value of *FP(2,3)* = 0.5 indicates that the harvest rates for all ages of stock 2 in fishery 3 are 50% of the corresponding base period harvest rates. Other stocks harvested by fishery 3 may be impacted differently.

Estimating Proportion Vulnerable

The following description is taken from CTC (1988).

The calculation of incidental mortalities associated with size limit restrictions depends critically upon the estimation of the proportion of each stock that is vulnerable (PV) in a particular fishery by age. Available data are not sufficient to permit estimation of stock-specific PVs. Therefore, age-size distributions for large fishing areas were calculated from available data. CWT recoveries turned out to be the best source of this type of age-length data. This is because these data belong to a large (and easily available) data set that can be identified accurately as to age and catch location. A description of the procedure used to estimate the proportion vulnerable by age follows.

Due to the absence of sufficient, direct observational data on the size distribution of fish encountered by a particular fishery, age-length data from

CWT tag recoveries were examined from troll and seine fisheries from Canada and some U.S. fisheries. Seine data were preferred because they are potentially the least size-selective of the fisheries. Troll CWT data were also examined. Canadian sport recoveries were not useful since most returns are from voluntary sources without sampling and consistent measuring procedures. Year-to-year variability seemed to be less than area-to-area variability; data across years were combined as well as some minor areas to produce specific age-size distributions. Seine data from Canadian fisheries appeared to lacking representative fish in the larger size classes while the troll data lacked fish in the smaller size classes (due to size limits). The two data sets were pooled to give large combined data sets for each region (e.g., West Coast Vancouver Island). Only the Alaska seine data were used to estimate the size distribution of chinook salmon encountered by the alaska troll fishery.

The estimated PVs were then adjusted using the PSC Chinook Model to estimate the encounter rates (non-retained/retained) for particular fisheries. These were then compared to field data collected in those fisheries (where available). The PVs were adjusted iteratively until they corresponded as closely as possible to the observed data.

The estimated PVs from the PSC model (by fishery) were then sorted by calendar year (and age) and became input data into the cohort analysis procedure. Size limit changes are represented by changes in the proportion vulnerable at age in the appropriate year.

Shaker Mortality

Many chinook salmon fisheries have size limits. Any captured chinook salmon whose length is below the size limit must be released, or “shaken” off the gear, hence the term “shakers.” Some of the shakers survive, but others die due to the stress of being captured and released. The shaker mortality rate (i.e., the fraction of shakers that die) is gear dependent. Troll and sport gears cause relatively low shaker mortality, since the fish are captured individually and in many cases can be released without serious injury. Net fisheries cause higher shaker mortalities, because the capture process is more stressful.

Modeling stock/age/fishery specific shaker mortalities involves two estimation problems: (1) estimating the number fish from each stock/age cohort that are shaken in a given fishery, and (2) estimating the mortality rate for shaken fish. Since there are no landing records for shaken fish, both problems are difficult.

There are no estimates for age specific shaker mortality rates for chinook salmon, although the subject is currently being studied. Until improved estimates become available, the model sets the shaker mortality rates for troll and sport fisheries at 0.30 and for net fisheries at 0.90. These values are in the range of accepted values agreed to by the full Chinook Technical Committee in 1986. Note that these rates are not age specific, and thus affect all ages equally.

Shaker Calculations

Calculating shaker mortalities consists of six steps. The procedure is identical for calculating both preterminal and terminal shaker mortalities. The steps are outlined below and further illustrated in Table 4.4.

Step 1

Compute the relative contribution of each stock in each fishery**,** called *StkWgt(s,f)*, as follows:

$$StkWgt(s, f) = \frac{FP(s, f)\sum_a MDLCohortCat(s, a, f)}{\sum_s FP(s, f)\sum_a MDLCohortCat(s, a, f)} \quad . \tag{4.19}$$

Note that the numerator is the catch of stock *s* by fishery *f* and the denominator is the total catch by fishery *f*. Note also that if all catches by fishery *f* are multiplied by a common scaling factor, call it *R*, the *StkWgt(s,f)* term is unchanged. This fact is useful in examining catch ceiling and fixed escapement management algorithms which require adjusting all catches by a fishery to meet management objectives.

Step 2

Compute *TotPNV(f)* and *TotPV(f)* for each fishery, as follows:

$$TotPNV(f) = \sum_s \sum_a N(s, a)PNV(a, f)StkWgt(s, f) \tag{4.20}$$

$$TotPV(f) = \sum_s \sum_a N(s, a)PV(a, f)StkWgt(s, f) \tag{4.21}$$

Note that these variables represent the total number of sublegal ***(****TotPNV(f)*) and legal ***(****TotPV(f)*) fish recruited to the gear in fishery *f*.

Step 3

Compute the encounter rate *EncRte(f)* for each fishery.

$$EncRte(f) = \frac{TotPNV(f)}{TotPV(f)} \tag{4.22}$$

Step 4

Compute *FracNV(s,a,f)* for each stock, age, and fishery.

$$FracNV(s, a, f) = \frac{StkWgt(s, f)N(s, a)PNV(a, f)}{TotPNV(f)} \tag{4.23}$$

Step 5

Compute the total shakers *TotShak(f)* for each fishery. Total shakers in fishery *f* is the product of the total catch by fishery *f* (the summation terms in the equation below) times the encounter rate times the shaker mortality rate.

TotShak(f) =

$$ShakMortRte(f)EncRte(f)\sum_{s} FP(s, f)\sum_{a} MDLCohortCat(s, a, f) \tag{4.24}$$

Note that if all the catches in a given fishery are multiplied by a common scaling factor, *TotShak(f)* is also multiplied by that factor.

Step 6

Compute shaker mortalities *Shakers(s,a,f)* for all stocks, ages, and fisheries by distributing total shakers across all cohorts.

$$Shakers(s, a, f) = FracNV(s, a, f)TotShak(f) \tag{4.25}$$

Table 4.4 Spreadsheet illustration of sample shaker calculations for a hypothetical fishery harvesting three stocks.

Stk	Age	Run	HR	PNV	Catch	StkWgt *Run	TotPV	TotPNV	FracNV	Shakers
1	2	20000	0.01	0.95	10	6233	312	5921	0.371	584
1	3	10000	0.06	0.50	300	3116	1558	1558	0.098	154
1	4	5000	0.10	0.10	450	1558	1402	156	0.010	15
1	5	1000	0.20	0.00	200	312	312	0	0.000	0
				Total	960					
		StkWgt(1) = 960/3081 =			0.312					
2	2	12000	0.10	0.95	60	4784	239	4544	0.284	448
2	3	8000	0.05	0.50	200	3189	1595	1595	0.100	157
2	4	4000	0.13	0.10	468	1595	1435	159	0.010	16
2	5	2000	0.25	0.00	500	797	797	0	0.000	0
				Total	1228					
		StkWgt(2) = 1228/3081 =			0.399					
3	2	5000	0.15	0.95	38	1449	72	1376	0.086	136
3	3	4000	0.12	0.50	240	1159	579	579	0.036	57
3	4	3000	0.15	0.10	405	869	782	87	0.005	9
3	5	1000	0.21	0.00	210	290	290	0	0.000	0
				Total	893					
		StkWgt(3) = 893/3081 =			0.290					
		Total over all stocks			3081		9374	15976	1.000	1575

Encounter Rate = 15976/9374 = 1.70
Sample FracNV(1,2) = 5921/15976 = 0.371
Total Encounters = 3081*1.70 = 5250
Total Shakers = 5250*0.30 = 1575
Sample Shakers(1,2) = 1575*0.371 = 584

Chinook Non-Retention Mortality

Several of the model fisheries that are subject to chinook catch ceilings, or quotas, also catch other species of salmon (coho, sockeye, pink, and chum). As chinook abundances increase or catch ceilings are reduced, the time required to catch the ceiling would be expected to be shortened. In order to provide continued access to other species, it is assumed that managers would permit the fishery to continue, but retention of chinook salmon would be prohibited. Such fisheries are called chinook non-retention, or CNR, fisheries, and are listed below:

- Alaska troll
- Northern BC troll
- Central BC troll
- West Coast Vancouver Island troll
- Strait of Georgia troll
- Alaska net
- Strait of Georgia sport.

In each CNR fishery, the selectivity of the fishing gear for legal and sublegal size chinook salmon may decrease in response to changes in fleet behavior. These selectivities never approach zero however, and some of the chinook salmon caught and released would die, resulting in CNR mortalities. The model assumes that the shaker mortality rate in the legal fishery also applies to the CNR fishery. Note that since chinook of all sizes must be released in CNR fisheries, there are both legal and sublegal CNR mortalities. Thus, an important model assumption is that within each CNR fishery, all chinook have the same shaker mortality rate, regardless of size.

The model provides three alternative methods of computing CNR mortalities. The following sections describes the computations in detail.

CNR Mortality Computation Overview

The amount of fishing time during which chinook retention is prohibited depends on the abundance of other species. At this time, the model does not incorporate abundances and management regimes for other salmon species. However, it does use data from CNR fisheries to estimate CNR mortalities when available.

During the calibration period, the model estimates CNR mortalities by using either (1) direct observations of legal and sublegal chinook encounter rates in CNR fisheries or (2) season lengths for directed and CNR fisheries. When forecasting beyond the calibration period, the model uses relative harvest rates compared to base period harvest rates (during which there were no, or relatively few, CNR mortalities) to estimate CNR mortalities.

Although there are some observations on chinook encounters in CNR fisheries, there are no data on how those encounters are distributed among stock/age cohorts. In the absence of such data, each CNR method assumes that the ratios between the CNR mortalities (legal and sublegal) and mortalities in the legal fisheries (legal and sublegal) are equal for all stock/age cohorts in a fishery, as follows:

$$\frac{CNRSublegalCat(s, a, f)}{Shakers(s, a, f)} = CNRSublegalRatio(f) \tag{4.26}$$

$$\frac{CNRLegalCat(s, a, f)}{MDLCohortCat(s, a, f)} = CNRLegalRatio(f) \tag{4.27}$$

where

- *CNRSublegalCat(s,a,f)* = sublegal CNR mortalities for stock *s*, age *a*, in fishery *f*
- *Shakers(s,a,f)* = shaker mortalities for stock *s*, age *a*, in fishery *f* computed by the model
- *CNRLegalCat(s,a,f)* = legal CNR mortalities for stock *s*, age *a*, in fishery *f*
- *MDLCohortCat(s,a,f)* = legal preterminal or terminal catch of stock *s*, age *a*, in fishery *f* computed by the model, depending on whether preterminal or terminal CNR mortalities are being computed.

Once the ratios are determined, the sublegal ratio is multiplied by the shakers to get the sublegal CNR mortalities and the legal ratio is multiplied by the legal catch and the shaker mortality rate to get the legal CNR mortalities (remember, the *Shakers()*s already have the shaker mortality rate applied whereas the *MDLCohortCat()*s do not). Again, note the assumption that the shaker mortality rate applies to all sizes. Rearranging terms, we have:

$$CNRSublegalCat(s, a, f) =$$

$$CNRSublegalRatio(f)Shakers(s, a, f) \tag{4.28}$$

$$CNRLegalCat(s, a, f) =$$

$$CNRLegalRatio(f)MDLCohortCat(s, a, f)ShakMortRte(f) \tag{4.29}$$

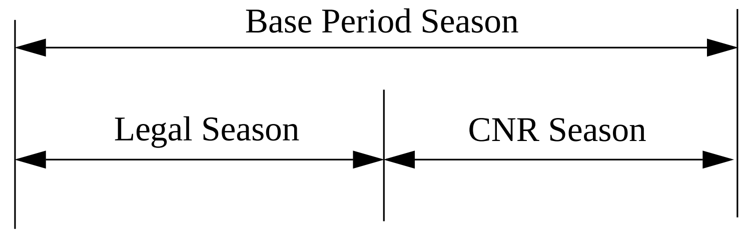
Each method uses a different technique for computing the legal and sublegal ratios. Fig. 4.9 illustrates the types of data used by each CNR computation method.

The *RelHR*s in Fig. 4.9 are generated by the model, as described in the Ceiling Management section. They are the ratios that adjust the catches in ceilinged fisheries to match the specified catch ceilings (remember that all CNR fisheries are ceilinged fisheries).

Equations (4.30) and (4.31) show the assumed relationships on which the actual calculations are based.

$$\frac{1 - RelHR}{RelHR} = \frac{LegalSeasonLen}{CNRSeasonLen} = \frac{RPTSublegalEnc}{(EncRte)(RptCatch)} \tag{4.30}$$

$$\frac{1 - RelHR}{RelHR} = \frac{LegalSeasonLen}{CNRSeasonLen} = \frac{RPTLegalEnc}{RptCatch} \tag{4.31}$$



Estimation Method	Model Variables		Data Source
	Shakers *MDLCohortCat*	*CNRSublegalCat* = ? *CNRLegalCat* = ?	
Reported Encounter	*Shakers* = ? *RptCatch*	*RptSublegalEnc* *RptLegalEnc*	Auxiliary
Season Length	*LegalSeasonLen*	*CNRSeasonLen*	Auxiliary
Harvest Ratio	*RelHR*	1 - *RelHR*	Model

Fig. 4.9 Variables and data sources used in calculating CNR mortalities.

Harvest Ratio Method

This method estimates CNR mortality through *RelHR(f)* factors generated by the model for each ceilinged fishery *f*. These factors represent the ratio between harvest rates associated with a catch ceiling and base period rates. Consequently, *RelHR(f)*s can be considered as surrogate indicators for season length in fishery *f*. If the harvest ratio method is selected, the model estimates CNR mortality of legals and sublegals by multiplying mortalities associated with the catch ceiling by the selectivity scalars and mortality rates appropriate for the gear involved. This method is generally applied when no other data are available or when projecting regimes into the future. Ratios are calculated as follows:

$$CNRSublegalRatio(f) = CNRSublegalSel(f)\frac{1 - RelHR(f)}{RelHR(f)} \tag{4.32}$$

$$CNRLegalRatio(f) = CNRLegalSel(f)\frac{1 - RelHR(f)}{RelHR(f)} \tag{4.33}$$

The *CNRSublegalSel(f)*s and *CNRLegalSel(f)*s are selectivity scalars used to compensate for changes in fleet behavior during CNR restrictions. Scalar values are all relative to 1.0 (no change). For example, setting *CNRLegalSel(f)* = 0.34 indicates a 66% reduction in impacts on legal-sized chinook during CNR fisheries compared to fisheries allowing chinook retention.

Season Length Method

This method uses the ratio of the regular season length to the CNR season length to estimate CNR mortalities.

$$CNRSublegalRatio(f) = CNRSublegalSel(f)\frac{CNRSeasonLen(f)}{LegalSeasonLen(f)} \tag{4.34}$$

$$CNRLegalRatio(f) = CNRLegalSel(f)\frac{CNRSeasonLen(f)}{LegalSeasonLen(f)} \tag{4.35}$$

where

- *CNRSeasonLen(f)* = length of the CNR fishery season (in days) for fishery *f*
- *LegalSeasonLen(f)* = length of the legal fishery season (in days) for fishery *f*.

Reported Encounter Method

This method requires direct observations of encounters of legal and sublegal (shaker) chinook during CNR fisheries and knowledge of the chinook catch during the directed fishery. From these observations one can compute the ratios of legal chinook encountered during CNR fisheries to the catch during the directed fishery. Same for the sublegal ratio. The predicted directed chinook catch from the model is then multiplied by these ratios to get predicted legal and sublegal CNR mortalities.

$$CNRSublegalRatio(f) = \frac{RptSublegalEnc(f)}{EncRte(f)RptCatch(f)} \tag{4.36}$$

$$CNRLegalRatio(f) = \frac{RptLegalEnc(f)}{RptCatch(f)} \tag{4.37}$$

where

- *RptSublegalEnc(f)* = reported encounters of sublegal-sized chinook (numbers of fish) in fishery *f* when it is illegal to retain chinook
- *RptLegalEnc(f)* = reported encounters of legal-sized chinook (numbers of fish) in fishery *f* when it is illegal to retain chinook.

4.5 - Catch Ceiling Management

Overview

The primary management tool of the Pacific Salmon Commission is the use of catch ceilings. A catch ceiling consists of an upper limit on the numerical catch for a fishery, or group of fisheries, for a specified time period. For example, the 1991 catch ceiling (upper limit) for the combined Southeast Alaska troll, net, and sport fisheries was 273,000 chinook. Note the following:

- catch ceilings are not established for individual stocks
- catch ceilings may include fisheries that are considered preterminal for some stocks but terminal for other stocks.

The PSC Chinook Model only allows catch ceilings to be applied to individual fisheries. Fisheries that have ceiling management are identified during data input (Table 4.5).

Table 4.5 Fisheries with ceiling management.

Fishery	Harvest Types
Alaska Troll	Preterminal
Northern B.C. Troll	Preterminal
Central B.C. Troll	Preterminal
WCVI Troll	Preterminal
Washington/Oregon Troll	Preterminal
Strait of Georgia Troll	Preterminal
Alaska Net	Preterminal and Terminal
Northern B.C. Net	Preterminal and Terminal
Central B.C. Net	Preterminal and Terminal
Alaska Sport	Preterminal
North/Central B.C. Sport	Preterminal
Washington Ocean Sport	Preterminal
Strait of Georgia Sport	Preterminal

For each ceilinged fishery, ceilings are specified for each year of the simulation. During each simulation year, if the sum of the computed individual stock catches using input harvest rates (as modified by any fishery policy factors) does not exceed the ceiling amount, the ceiling has no effect (i.e., the stock abundance is such that the ceiling will not be reached given the specified stock exploitation rates). The model also allows ceilings to be “forced,” or modeled as a fixed catch. A forced ceiling is called a “quota” and is taken every year regardless of the stock abundance. Most catch ceilings are modeled as quotas.

CRiSP Harvest uses a slightly different algorithm from the PSC model, but the net effect is the same. The CRiSP Harvest algorithm is described here, with significant differences from the PSC version noted.

Setting Catch Ceilings

For catch ceiling management, the simulation period is divided into two time segments. The base period includes the years 1979 to 1984 (i.e., years prior to enactment of the PST). The simulation period includes year 1985 and beyond.

Catch ceilings are established in two steps. During data entry, base period (1979-1984) catches for each fishery (from the *.CEI file) are summed and averaged. Catches for the remaining years are divided by the average to get scalar values relating observed catches to average base period catches. During model execution, preterminal and terminal catches for each fishery are summed and averaged. At the end of the base period, the scalars computed during data entry are multiplied by the average preterminal and terminal model catches to get the catch ceilings for the remainder of the simulation period. Thus, the model catches during the ceiling management period are not equal to the catches given in the *.CEI file, but have the same relative value compared to the base period catches. Table 4.6 illustrates how the catch ceilings are computed.

Table 4.6 Computation of catch ceilings. For example, in 1985 the ceiling scalar = 212,827/272,500; the model preterm ceiling = 216,667*.781; the model terminal ceiling = 64,833*.781.

Year	**Observed Catch (*.CEI file)**		**Model PreTerm Catch**	**Model Terminal Catch**	**Model Total Catch**
1979	338,000		250,000	75,000	325,000
1980	300,000		235,000	70,000	305,000
1981	248,000		198,000	65,000	263,000
1982	242,000		202,000	64,000	266,000

Table 4.6 Computation of catch ceilings. For example, in 1985 the ceiling scalar = 212,827/272,500; the model preterm ceiling = 216,667*.781; the model terminal ceiling = 64,833*.781.

Year	**Observed Catch (*.CEI file)**		**Model PreTerm Catch**	**Model Terminal Catch**	**Model Total Catch**
1983	271,000		235,000	55,000	290,000
1984	236,000		180,000	60,000	240,000
Average Base Period	272,500		216,667	64,833	281,500
Year	Observed Catch	Ceiling Scalars	Model PreTerm Ceiling	Model Terminal Ceiling	Model Total Ceiling
1985	212,827	.781	169,217	50,635	219,852
1986	229,980	.844	182,867	54,719	237,586
1987	230,901	.847	183,517	54,915	238,432
1988	216,427	.794	172,034	51,477	223,511
1989	220,966	.811	175,717	52,580	228,297

The algorithm used to keep model catches for each fishery below ceilings (or equal to quotas, if forcing is specified) depends on whether or not any ceilinged fisheries have both preterminal and terminal harvests. If a fishery has only preterminal harvests, the model simulates the effects of ceiling management policies by calculating catches in two passes. The first pass calculates catch as if no ceiling were present. The ratio of the ceiling divided by the total catch of all stocks in the fishery is then calculated. This ratio is the basis for adjustment during the second pass. If the ratio is less than one (i.e., the ceiling is less than the computed catch), the catch is reduced by multiplying the age-specific catch of each stock by the ratio. If the ratio is greater than one and the user specifies quota management, the catch is increased to meet the quota; if the ratio is greater than one and ceiling management is specified, no adjustment to catch is made.

Fisheries that are “terminal” for one or more stocks must use an iterative procedure to compute the appropriate adjustment ratios. This is because preterminal catches are computed prior to the calculation of mature run sizes and terminal catches. For each fishery, the procedure is as follows:

- Compute ocean catches and mature run sizes
- Compute terminal catches by age and stock, using any specified fishery policies
- Compute a cumulative ratio as the previous ratio (= 1 on the first iteration) multiplied by the ratio between the ceiling and the total catch for all stocks
- Process the ceiling according to the same procedure described for ocean fisheries
- Repeat the procedure until the computed catch using the cumulative ratio factor is within .999 of the specified ceiling level.

In instances where a fishery is (1) terminal for a particular stock and (2) the terminal run size after fishing exceeds the specified spawning escapement goal, any catch ceilings specified for that fishery will not include the harvest of fish in excess of the spawning escapement goal.

4.6 - In-River Management

As described in the previous section, the primary management tool of the Pacific Salmon Commission is the establishment of catch ceilings for fisheries harvesting stocks originating from both the US and Canada. These fisheries are mostly preterminal fisheries, and thus are first in line in the long gauntlet of fisheries harvesting each stock. The total harvest on a stock is fine-tuned via in-river management of the last fisheries to harvest each stock.

The most common strategy for in-river management is fixed escapement. An escapement goal is established for one or more stocks and catches are adjusted to meet the escapement goal. The original PSC Chinook Model did not include this type of management option. It was added to the CRiSP Harvest model to better simulate management of Columbia River fisheries which are governed by the court ordered Columbia River Fish Management Plan (*US vs Oregon*).

For fall chinook salmon, the Columbia River Fish Management Plan (FMP) established the following spawning escapement goals: “40,000 naturally spawning Columbia River upriver bright (URB) adults above McNary Dam. The goal for the developing Snake River fall chinook program shall be addressed in the Snake River (mainstem) Subbasin plan. Bonneville Pool hatchery (BPH) brood stock necessary to meet hatchery program production requirements.” The present goal is a combined escapement of 45,000 fall chinook salmon above McNary dam.

The PSC Chinook Model has two fisheries that target Columbia River stocks—Col R Sport and Col R Net. The Col R Sport fishery operates primarily at the river mouth and harvests significant numbers of fish from stocks outside the Columbia River, including Georgia Strait stocks. The Col R Net fishery harvests no fish that spawn outside the Columbia River basin. Both fisheries were originally modeled as fixed harvest rate fisheries in which stock/age/fishery specific harvest rates are fixed within each year, but can be modified from year to year by changing the stock/fishery specific fishery policy (FP) scalars. Under this method, escapements vary from year to year. The problem with this approach is that there is no dynamic mechanism for adjusting harvest rates to meet a fixed escapement goal.

A more realistic modeling approach would establish escapement goals for each year and adjust catches to meet those goals. The net affect is that the harvest rates on each stock will change dynamically from year to year as relative stock abundances change. This is especially important for analyzing recovery options for the listed Snake River Fall Chinook stock, as simulated by the LYF stock. Both the Col R Sport and Net fisheries harvest both the URB and LYF stocks. Thus, if the URB stock increases over time and a fixed escapement policy is implemented, the harvest rate on the weaker LYF stock will increase over time. This type of dynamic behavior cannot be modeled with a stock/ fishery specific fixed harvest rate policy.

A second type of in-river management is combined fixed harvest rate strategy. Under this type of policy, a constant fraction of the combined cohorts (from one or more stocks) entering the river are harvested each year. Under this type of policy, the harvest rate on each cohort changes each year as the relative abundance of the cohorts changes. In terms of the computation algorithms, this type of policy is nearly identical to that of fixed escapement. Once one knows the total number of fish available for in-river harvest and the desired combined harvest rate, one also knows the desired combined fixed escapement level.

In CRiSP Harvest, fisheries managed under a fixed escapement and fixed harvest rate policies are treated as a special type of terminal fishery called a river fishery. A control statement in the *.OPT file indicates if any fisheries are to be designated river fisheries and provides the name of a *.RIV file that gives specific information about the desired policies.

Nonlinear Harvesting Formula

Our overall goal was to modify the original PSC Chinook Model such that during the simulation period, the harvest rates in the Columbia River Sport and Net fisheries were adjusted dynamically to meet an escapement goal at McNary Dam. We also wanted to preserve the concept that in-river harvest rates would be applied to the terminal runs, just as other terminal catches are. That is, we did not want the harvest rates to be applied to the “true terminal run” returning just to the river (i.e., terminal run minus ocean terminal catches). And to the extent possible, we wanted to maintain the shaping options defined by the harvest rates, FP scalars, and the PNVs contained in the input files.

These goals proved to be impossible because scaling all river catches (by stock, age, and fishery) up or down by an equal factor often resulted in catches exceeding the fish available. For example, a strong terminal run (i.e., much larger than the escapement goal) might require a two- or three-fold increase in the input harvest rate to meet the escapement goal. Such a large increase in the catch of a weak stock often resulted in a harvest rate greater than 1.0, which is impossible. Thus, we were forced to use a non-linear harvesting function that prevented harvests from exceeding the available fish.

Recall that in non-river fisheries the preterminal and terminal legal harvests are computed as follows:

$$Catch_{s,a,f} = Run_{s,a} \cdot HR_{s,a,f} \cdot FP_{s,f} \cdot PV_{a,f} \tag{4.38}$$

where

- $Catch_{s,a,f}$ = preterminal or terminal catch of stock s, age a, in fishery f

- $Run_{s,a}$ = coastwide ocean abundance or coastwide terminal run for stock *s*, age *a*
- $HR_{s,a,f}$ = harvest rate for stock *s*, age *a*, in fishery *f*
- $FP_{s,f}$ = fishery policy scalar for stock *s* in fishery *f*
- $PV_{a,f}$ = proportion vulnerable for age *a* in fishery *f* (i.e., proportion of age *a* fish that are recruited to the gear and are above the legal size limit in fishery *f*).

Note that this type of catch equation is a simple linear relationship of the form:

$$Catch = Run \cdot P \tag{4.39}$$

where P is the proportion of the run that is harvested.

A more realistic type of catch equation is the following:

$$Catch = Run \cdot (1 - e^{-q \cdot E}) \tag{4.40}$$

where *q* is called the “Poisson Catchability Coefficient” and *E* is the amount of fishing effort (Robson and Skalski 1993). In this formulation, catch can never exceed the run size. Note that if we have an estimate of *P* for some level of effort (e.g., input values for *HR*, *FP*, and *PV*), we can solve for the product *qE*.

$$q \cdot E = -\ln(1 - P) \tag{4.41}$$

If we want to simulate the effects of adjusting effort, we simply replace *qE* with *qERatio*, where *Ratio* is the relative increase or decrease in effort.

Fig. 4.10 illustrates the differences between eq (4.39) and eq (4.40). For low harvest rates and relative efforts less than one, the equations are very similar. However, for larger harvest rates and as relative effort is increased, the non-linear representation provides a more realistic simulation of increased harvesting because it does not permit the entire stock to be harvested.

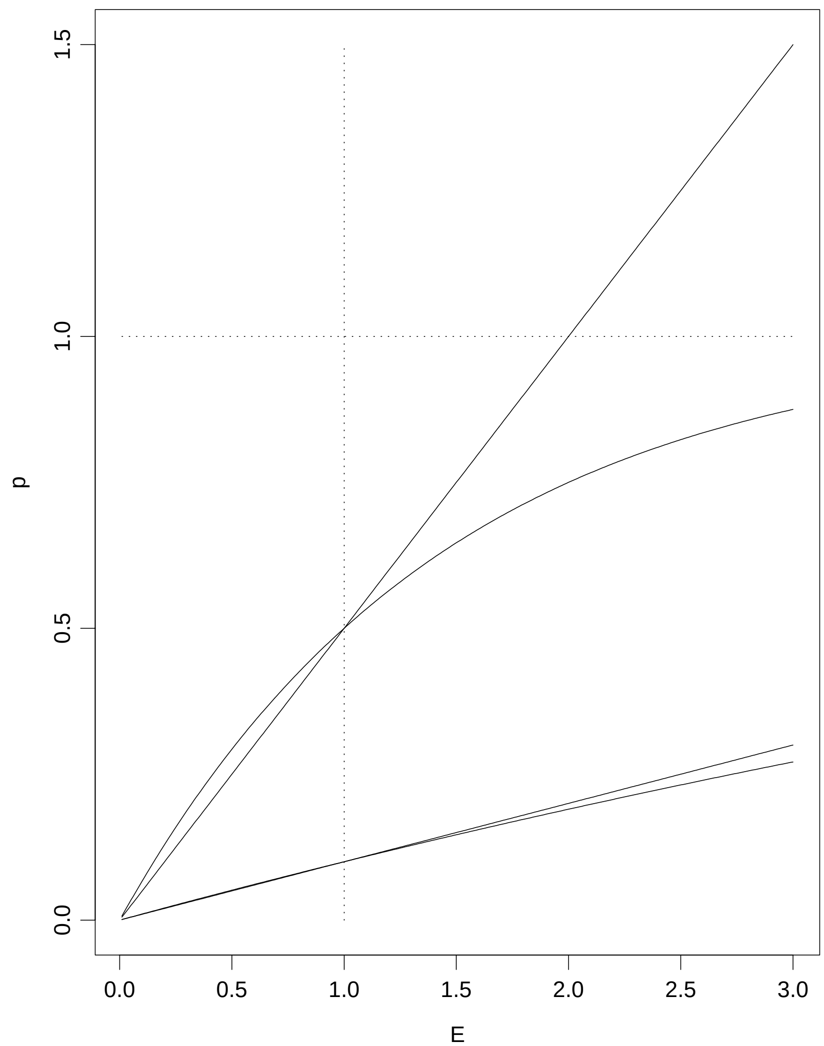


Fig. 4.10 Illustration of the relationship between relative fishing effort level compared to the base period (E) and the fraction of the stock harvested (p) for two cohorts with base period harvest rates of 10% and 50%. Straight and curved lines represent harvesting using eq (4.39) and eq (4.40), respectively. Note that when the effort level is increased more than two-fold, the linear harvesting equation results in a harvest fraction greater than one for one stock.

Before the fixed escapement and fixed harvest rate algorithms are implemented, a four step procedure is utilized to translate the harvesting equations into non-linear form by computing the input Poisson catchability coefficients.

First, we compute the maximum fraction of the terminal run for each cohort that can be taken by the river fisheries. The fish available for the river fisheries is just the terminal run minus the terminal mortalities (legal harvests plus incidental mortalities) in non-river fisheries, sometimes called the true terminal run. Thus, the maximum fraction that can be harvested is:

$$MaxP_{s,a} = \frac{TrueTermRun_{s,a}}{TermRun_{s,a}} \tag{4.42}$$

where

$$TrueTermRun_{s,a} = TermRun_{s,a} - \sum_{f \neq riv} TermMort_{s,a,f} \tag{4.43}$$

If either $TrueTermRun_{s,a} < 0$ or $TermRun_{s,a} < 0$, then we set $MaxP_{s,a} = 0$. Note that in eq (4.42) s indexes all stocks that are harvested by the fisheries managed under in-river management but f indexes fisheries not included in in-river management.

Second, we compute the total in-river harvest fraction from input data (*HR*s, *FP*s, and *PV*s):

$$TotP_{s,a} = \sum_{f = riv} P_{s,a,f} \tag{4.44}$$

where

$$P_{s,a,f} = HR_{s,a,f} \cdot FP_{s,f} \cdot PV_{a,f} \tag{4.45}$$

Here, s and f index stocks and fisheries that are harvested and managed under in-river management, respectively

Third, we create a new variable call $PScal_{s,a}$ to adjust the input variables if they are unreasonable. If $TotP_{s,a}$ is less that $MaxP_{s,a}$, then the input values are within reasonable limits, no adjustments are necessary, and we set $PScal_{s,a} = 1$. However, if $TotP_{s,a}$ is greater than $MaxP_{s,a}$, then the input values are too large and must be scaled down by:

$$PScal_{s,a} = \frac{MaxP_{s,a}}{TotP_{s,a}} \tag{4.46}$$

If $TotP_{s,a} = 0$, then we set $PScal_{s,a} = 0$.

Finally, for each stock, age, and fishery specific river harvest, we compute the Poisson catchability coefficient as

$$q_{s,a,f} = -\ln(1 - (P_{s,a,f} \cdot PScal_{s,a})) \tag{4.47}$$

We set the maximum fraction of a cohort that can be harvested to be about 99% by setting a maximum limit on $q_{s,a,f}$ to be 5.0.

Note that we now have catchability coefficients that will not generate catches that are greater than the true terminal run. However, this does not guarantee that the river catches plus the river shakers will be less than the true terminal run. We account for that possibility later.

Fixed Escapement Algorithm

The computation algorithm is similar to that for multi-phase ceiling management in that catches are computed by an iterative procedure. The fixed escapement algorithm is implemented after all initial terminal catches are taken but before final escapements are computed. If multiple stocks in the same river are being managed via fixed escapements, three types of policies may be implemented: (1) strong stock management in which the river is managed to meet the strongest stock's escapement goal; (2) weak stock management in which the river is managed to meet the weakest stock's escapement goal; or (3) combined stock management in which the escapement goal is based on the sum of all stocks.

Step 1.

Compute the river catches using the formula:

$$RivCatch_{s,a,f} = TermRun_{s,a} \cdot (1 - e^{-(q_{s,a,f} \cdot Ratio)}) \tag{4.48}$$

where *Ratio* is the relative increase or decrease in the river fishing effort required to adjust the river catch to meet the escapement goal. Note that *Ratio* = 1 on the first iteration.

We also compute the river shaker mortalities for each stock, age, and fishery in the usual manner. Note that for each cohort it is possible for the catch plus the shakers to exceed the true terminal run. This is accounted for in Step 3.

Step 2.

We create a new variable for the total river mortalities, called *RivMorts*, which can not exceed the available fish. This is a temporary variable and is only used within this algorithm. For each stock and age we compute

$$RivMorts_{s,a} = min(RivCatch_{s,a} + RivShakers_{s,a}, TrueTermRun_{s,a}) \tag{4.49}$$

where $RivCatch_{s,a}$ and $RivShakers_{s,a}$ are summed over all river fisheries. Thus, $RivMorts_{s,a}$ cannot exceed the total available fish.

Step 3.

Compute another temporary variable called *TempNewScale*. If strong or weak stock management is being implemented, the algorithm computes separate adjustment values for each stock using the following formula:

$$TempNewScal_s = \frac{TrueTermRun_s - \dfrac{EscGoal_s}{MgtIdl_s}}{\sum_{a=3}^{5} \sum_{f=riv} RivMort_{s,a,f}} \tag{4.50}$$

where

$$TrueTermRun_s = \sum_{a=3}^{5} TrueTermRun_{s,a} \tag{4.51}$$

$RivMort_{s,a,f}$ =River catches plus incidental mortalities for stock *s*, age *a*, in river fishery *f*.

$EscGoal_s$ = Escapement goal for stock *s*;

$MgtIdl_s$ = Interdam survival rate for stock *s* after all harvesting mortalities to the point where the escapement goal is measured.

For strong or weak stock management, the largest or smallest *TempNewScal* is used to compute the adjustment ratio to be applied to all catches by the river fisheries, respectively.

If combined stock management is used, *TempNewScale* is computed as follows:

$$TempNewScal = \frac{\left[\sum_s MgtIdl_s \cdot TrueTermRun_s\right] - EscGoal}{\sum_s \left(MgtIdl_s \sum_{a=3}^{5} \sum_{f=riv} RivMort_{s,a,f}\right)} \tag{4.52}$$

Step 4. Compute NewScal

We compute *NewScal* as follows:

$$NewScal = \frac{\ln(1-(TempNewScal \cdot WgtAvgP))}{\ln(1-WgtAvgP)} \tag{4.53}$$

where the *WgtAvgP* terms are the weighted average of the adjusted harvest rates (i.e., *P*PScal* values). The weights are the terminal run sizes divided by the total terminal run for the managed stocks. Thus, if weak or strong stock management is being used, the weights are simply the fraction each age cohort contributes to the strong or weak stock. If combined stock management is being used, the weights are the fraction each stock/age cohort contributes to the total terminal run (ages 3, 4, and 5) for the river managed stocks.

Step 5. Update the adjustment ratio

The final step is to multiply *Ratio* by *NewScal* to get a new ratio. Then go to *Step 1*and repeat until *NewScal* is close to one.

$$Ratio = Ratio \cdot NewScal \tag{4.54}$$

Fixed Combined Harvest Rate Algorithm

For any given stock, if one knows the total number of fish available for in-river harvest and the desired harvest rate, one also knows the desired escapement level. Setting TempNewScal = 1 and rearranging terms in eq (4.54) gives

$$EscGoal_s = MgtIdl_s \cdot (TrueTermRun_s - RivMort_s) \tag{4.55}$$

Thus, we first compute the combined true terminal run (i.e., the number of fish that actually enter the river) for the stocks under in-river management:

$$TrueTermRun = \sum_s TrueTermRun_s \tag{4.56}$$

where *s* indexes stocks under in-river management.

Next we compute the escapement goal that will produce the desired harvest rate goal:

$$EscGoal = TrueTermRun \cdot MgtIDL \cdot (1 - HRGoal) \tag{4.57}$$

Note that the MgtIDL is assumed constant for all stocks being managed under the fixed harvest rate policy in the river. Once the combined escapement goal is determined, the combined fixed escapement algorithm is implemented to determine in-river catches. Note that the harvest rate goal includes both legal catches and associated incidental mortalities.