Stressor: Fine Sediment (%)

Species: Coho Salmon

Life Stage/Season: Fry/Parr Rearing

Citation

Beechie, T. J., C. Nicol, C. Fogel, J. Jorgensen, J. Thompson, G. Seixas, J. Chamberlin, J. Hall, B. Timpane-Padgham, P. Kiffney, S. Kubo, and J. Keaton. 2021. Modeling Effects of Habitat Change and Restoration Alternatives on Salmon in the Chehalis River Basin Using a Salmonid Life-Cycle Model. U.S. Department of Commerce, NOAA Contract Report NMFS-NWFSC-CR-2021-01.

Stressor-Response Relationship

Rationale

Jensen et al. (2009) summarized published values of incubation productivity (survivorship) for four salmonid species (Chinook, Coho, Chum, and Steelhead) and created a logistic regression function to relate percent fines in streams to incubation productivity. Jensen et al. (2009) presented data for all four salmonid species. However, there was significant overlap among species, and there appeared to be little justification for using different functional relationships for each species. Therefore, they applied the published β_0 and β_1 estimates to define a functional relationship (presented here) applicable to all four salmonid species. Sedimentation (% fines) is treated as a productivity multiplier. Egg survivorship decreases in locations with a high percentage of fines as the dominant substrate. Impact mechanisms unspecified but likely to occur include direct suffocation or barriers to fry emergence from spawning gravels. The percentage of fines in spawning substrates should (ideally) be estimated from field surveys, but a generic function is provided to produce a rough estimate of fines for unsurveyed areas based on road densities (estimates are expected to have limited transferability across systems).

Function

Derived relationship between fry/parr rearing habitat (density-independent incubation productivity in redds) and generalized % fine sediment in spawning gravels. The % fine sediment in spawning gravels is predicted by road density for areas with a slope to bankfull width index > 0.05; where it is assumed that areas with a slope to bankfull width index < 0.05 have very high fine sediment levels which aren't significantly influenced by road density (Beechie et al., 2021; data from Mobrand Biometrics, Inc. 2003).

Type:

Empirical (Real data)

Original Function:
Where slope to bankfull width index is > 0.05:

$$fine\ sed\ = 5.74 + 2.05 * road\ density$$

$$p_{incub}\ = \frac{1}{1 + e^{-1.989+0.185*fine\ sed}}$$

fine sed is the percent fine sediment <0.85mm.

road density is the hectares of current roads per hectare of drainage area.

p_{incub} is incubation productivity from 0-1. This is then scaled to 0-100% to represent mean system capacity (%). An offset of +12% is added to standardize the function such that the maximum value is 100%.

Known Covariates or Stressor Interactions

Covariate(s)

Applicable for areas with a slope to bankfull width index > 0.05. The slope to bankfull width index calculated as bankfull width times reach slope (rise/run).

Interaction Type

Threshold

Considerations

See rubric in Appendix A for explanations of the data classifiers below.

Data Source: Mechanistic (theory based), and empirical relationship from Jensen (2009) between road density and fines.

Data Type: Empirical relationship

Data Quality: Strong relationship between fine sediment (%) and incubation productivity; however, very weak correlation between fine sediment and road density. Field estimates of fine sediment are recommended rather than GIS proxies.

Confidence in SR function: Moderate uncertainty

Notes and User Recommendations

Jensen et al. (2009) note that data availability may constrain the accuracy and applicability of the SR results. Few studies were available to develop the SR curve, and most of those studies were based on controlled laboratory data.

Stressor-Response Curve

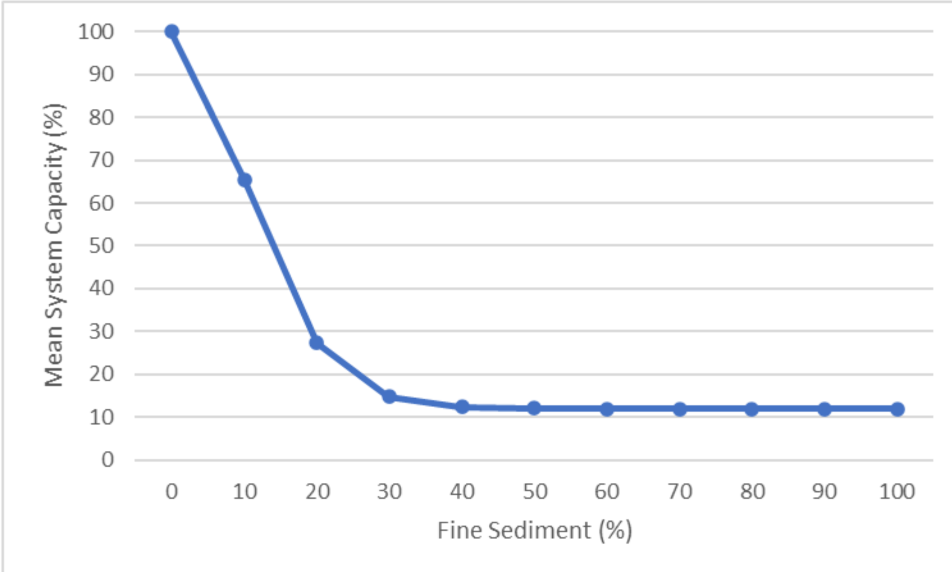


Figure 1: Stressor-response relationship between percent fine sediment and incubation productivity (0-1), interpreted as system capacity in the model. Data are from Beechie et al. (2021).

Stressor-Response Table

Table 1: Discrete stressor-response relationship between raw stressor values and the mean system capacity (0-100%; scaled incubation productivity). The standard deviation of the mean system capacity is defined by the user and represents the inherent stochasticity or noise in the relationship. The set lower limit and upper limit of the mean system capacity are also presented. Mean system capacity (0-100%) is a standardized measure of wild adult recruits produced by the previous spawner cohort.

Sediment	Mean System Capacity (%)	SD	Lower Limit	Upper Limit
0	100	0	0	100
10	65.46941575	0	0	100
20	27.30340562	0	0	100
30	14.76255473	0	0	100
40	12.44473039	0	0	100
50	12.07019123	0	0	100
60	12.0110432	0	0	100
70	12.00173656	0	0	100
80	12.00027306	0	0	100
90	12.00004293	0	0	100
100	12.00000675	0	0	100

Additional References

Jensen, D. W., E. A. Steel, A. H. Fullerton, and G. R. Pess. 2009. Impact of fine sediment on incubation survival of Pacific salmon: a meta-analysis of published studies. Reviews in Fisheries Science 17(3):348-359.

Mobrand Biometrics, Inc. 2003. Assessment of Salmon and Steelhead Performance in the Chehalis River Basin in Relation to Habitat Conditions and Strategic Priorities for Conservation and Recovery Actions. Mobrand Biometrics, Inc. Vashon, WA.

Stressor: Stream Temperature (°C)

Species: Coho Salmon

Life Stage/Season: Summer Rearing (All Freshwater Life Stages)

Citation

Beechie, T. J., C. Nicol, C. Fogel, J. Jorgensen, J. Thompson, G. Seixas, J. Chamberlin, J. Hall, B. Timpane-Padgham, P. Kiffney, S. Kubo, and J. Keaton. 2021. Modeling Effects of Habitat Change and Restoration Alternatives on Salmon in the Chehalis River Basin Using a Salmonid Life-Cycle Model. U.S. Department of Commerce, NOAA Contract Report NMFS-NWFSC-CR-2021-01.

Stressor-Response Relationship

Rationale

Coho salmon have different thermal tolerances than Chinook and Steelhead and thus have been independently modelled by Beechie et al. (2021). Increasing stream temperature decreases Coho Salmon abundance and productivity via changes in summer rearing capacity and productivity. This function was previously used in Beechie et al. (2021) in the Chehalis River in Oregon as a productivity (survivorship) multiplier for Age-1+ stage classes. Stressor magnitude values are provided as the 7-day average daily maximum (7-DADM) stream temperature.

Function

Derived relationship between fry/parr summer rearing capacity and productivity and 7-day average daily maximum stream temperature. At stream temperatures < 18°C, there is no effect on summer rearing capacity/productivity. From 18°C to 24°C summer rearing capacity decreases linearly from 1 to 0. Summer rearing capacity is zero for stream temperatures equal to or greater than 24°C.

Type:
Empirical (Real data)

Original Function:

$T < 18°C, 1$

$18°C \leq T < 24°C, 1 - 0.17 * (T - 18)$

$T \geq 24°C, 0$

Where T is temperature in °C. The productivity/capacity multiplier is 0 at 24°C and above, and 1 at temperatures < 18°C.

Known Covariates or Stressor Interactions

Covariate(s)

Covariates embedded within stream temperature model (e.g., drainage area, channel slope, basin characteristics). Equivalent stream temperature models in British Columbia include estimates of MWAT from methods provided in Moore et al (2013).

Considerations

See rubric in Appendix A for explanations of the data classifiers below.

Data Source: Stream temperature was derived using a stream temperature model (Beechie et al., 2021 Appendix A). Equivalent stream temperature models in British Columbia include estimates of MWAT from methods provided in Moore et al (2013).

Data Type: Combination of Empirical Data & Theory/Mechanistic Model

Data Quality: Function is based primarily on field data from ASEP (2014) Appendix C. Data collection was conducted in the Chehalis Basin in 2013-2014.

Confidence in SR function: Moderate uncertainty of a generalized thermal window. Strength, direction, and relative magnitude are well known, but there is less certainty with respect to absolute values. The SR function is based on a small amount of data from a single empirical study. Pacific Salmon and Steelhead are known to have a high degree of plasticity in the relationships between stream temperature across different systems. Local periodicity (timing) of critical rearing periods, watershed attributes, and the general availability of cold-water refuge may have large implications on the magnitude of local effects.

Notes and User Recommendations

None.

Stressor-Response Curve

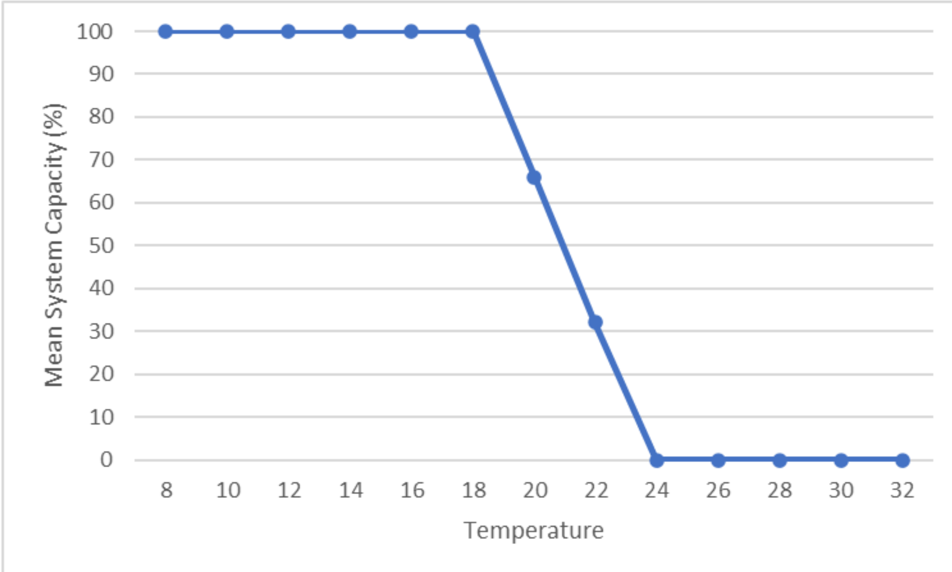


Figure 1: Stressor-response relationship between 7-day average daily maximum stream temperature (°C) and the derived summer rearing productivity multiplier (0-1), interpreted as system capacity in the model. Data are from Beechie et al. (2021).

Stressor-Response Table

Table 1: The table shows the discrete stressor-response relationship between raw stressor values and the mean system capacity (0-100%). The standard deviation of the mean system capacity is defined by the user and represents the inherent stochasticity or noise in the relationship. The set lower limit and upper limit of the mean system capacity are also presented. Data are from Beechie et al. (2021).

Temperature (°C)	Mean System Capacity (%)	SD	Lower Limit	Upper Limit
8	100	0	0	1
10	100	0	0	1
12	100	0	0	1
14	100	0	0	1
16	100	0	0	1
18	100	0	0	1
20	66	0	0	1
22	32	0	0	1
24	0	0	0	1
26	0	0	0	1
28	0	0	0	1
30	0	0	0	1
32	0	0	0	1

Stressor: Fine Sediment (%)

Species: Steelhead

Life Stage/Season: Fry/Parr Rearing

Citation

Beechie, T. J., C. Nicol, C. Fogel, J. Jorgensen, J. Thompson, G. Seixas, J. Chamberlin, J. Hall, B. Timpane-Padgham, P. Kiffney, S. Kubo, and J. Keaton. 2021. Modeling Effects of Habitat Change and Restoration Alternatives on Salmon in the Chehalis River Basin Using a Salmonid Life-Cycle Model. U.S. Department of Commerce, NOAA Contract Report NMFS-NWFSC-CR-2021-01.

Stressor-Response Relationship

Rationale

Jensen et al. (2009) summarized published values of incubation productivity (survivorship) for four salmonid species (Chinook, Coho, Chum, and Steelhead) and created a logistic regression function to relate percent fines in streams to incubation productivity. Jensen et al. (2009) presented data for all four salmonid species. However, there was significant overlap among species, and there appeared to be little justification for using different functional relationships for each species. Therefore, they applied the published β_0 and β_1 estimates to define a functional relationship (presented here) applicable to all four salmonid species. Sedimentation (% fines) is treated as a productivity multiplier. Egg survivorship decreases in locations with a high percentage of fines as the dominant substrate. Impact mechanisms unspecified but likely to occur include direct suffocation or barriers to fry emergence from spawning gravels. The percentage of fines in spawning substrates should (ideally) be estimated from field surveys, but a generic function is provided to produce a rough estimate of fines for unsurveyed areas based on road densities (estimates are expected to have limited transferability across systems).

Function

Derived relationship between fry/parr rearing habitat (density-independent incubation productivity in redds) and generalized % fine sediment in spawning gravels. The % fine sediment in spawning gravels is predicted by road density for areas with a slope to bankfull width index > 0.05; where it is assumed that areas with a slope to bankfull width index < 0.05 have very high fine sediment levels which aren't significantly influenced by road density (Beechie et al., 2021; data from Mobrand Biometrics, Inc. 2003).

Type:

Empirical (Real data)

Original Function:

Where slope to bankfull width index is > 0.05:

$$fine\ sed = 5.74 + 2.05 * road\ density$$

$$p_{incub} = \frac{1}{1 + e^{-1.989+0.185*fine\ sed}}$$

fine sed is the percent fine sediment <0.85mm.

road density is the hectares of current roads per hectare of drainage area.

p_{incub} is incubation productivity from 0-1. This is then scaled to 0-100% to represent mean system capacity (%). An offset of +12% is added to standardize the function such that the maximum value is 100%.

Known Covariates or Stressor Interactions

Covariate(s)

Applicable for areas with a slope to bankfull width index > 0.05. The slope to bankfull width index calculated as bankfull width times reach slope (rise/run).

Interaction Type

Threshold

Considerations

See rubric in Appendix A for explanations of the data classifiers below.

Data Source: Mechanistic (theory based), and empirical relationship from Jensen (2009) between road density and fines.

Data Type: Empirical relationship

Data Quality: Strong relationship between fine sediment (%) and incubation productivity; however, very weak correlation between fine sediment and road density. Field estimates of fine sediment are recommended rather than GIS proxies.

Confidence in SR function: Moderate uncertainty

Notes and User Recommendations

Jensen et al. (2009) note that data availability may constrain the accuracy and applicability of the SR results. Few studies were available to develop the SR curve, and most of those studies were based on controlled laboratory data.

Stressor-Response Curve

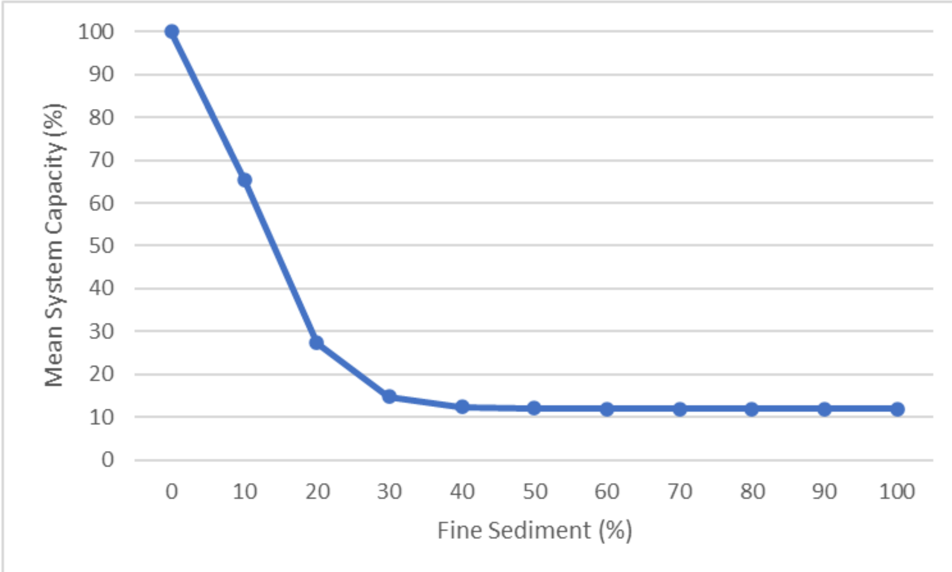


Figure 1: Stressor-response relationship between percent fine sediment and incubation productivity (0-1), interpreted as system capacity in the model. Data are from Beechie et al. (2021).

Stressor-Response Table

Table 1: Discrete stressor-response relationship between raw stressor values and the mean system capacity (0-100%; scaled incubation productivity). The standard deviation of the mean system capacity is defined by the user and represents the inherent stochasticity or noise in the relationship. The set lower limit and upper limit of the mean system capacity are also presented. Mean system capacity (0-100%) is a standardized measure of wild adult recruits produced by the previous spawner cohort.

Sediment	Mean System Capacity (%)	SD	Lower Limit	Upper Limit
0	100	0	0	100
10	65.46941575	0	0	100
20	27.30340562	0	0	100
30	14.76255473	0	0	100
40	12.44473039	0	0	100
50	12.07019123	0	0	100
60	12.0110432	0	0	100
70	12.00173656	0	0	100
80	12.00027306	0	0	100
90	12.00004293	0	0	100
100	12.00000675	0	0	100

Additional References

Jensen, D. W., Steel E. A., Fullerton A. H., & Pess G. R. 2009. Impact of fine sediment on incubation survival of Pacific salmon: a meta-analysis of published studies. Reviews in Fisheries Science, 17(3), 348-359.

Mobrand Biometrics, Inc. 2003. Assessment of Salmon and Steelhead Performance in the Chehalis River Basin in Relation to Habitat Conditions and Strategic Priorities for Conservation and Recovery Actions. Mobrand Biometrics, Inc. Vashon, WA.

Stressor: Stream Temperature (°C)

Species: Steelhead

Life Stage/Season: Summer Rearing (All Freshwater Life Stages)

Citation

Beechie, T. J., C. Nicol, C. Fogel, J. Jorgensen, J. Thompson, G. Seixas, J. Chamberlin, J. Hall, B. Timpane-Padgham, P. Kiffney, S. Kubo, and J. Keaton. 2021. Modeling Effects of Habitat Change and Restoration Alternatives on Salmon in the Chehalis River Basin Using a Salmonid Life-Cycle Model. U.S. Department of Commerce, NOAA Contract Report NMFS-NWFSC-CR-2021-01.

Stressor-Response Relationship

Rationale

Steelhead have unique thermal tolerance profiles and performance windows for summer stream temperatures during the rearing period. Physiological stress is experienced when temperatures exceed upper limits. This SR function defines a generalized upper limit for the summer stream temperature profile for Steelhead. The function was previously used in Beechie et al. (2021) in the Chehalis River in Oregon as a productivity (survivorship) multiplier for Age-1+ stage classes. Stressor magnitude values are provided as the 7-day average daily maximum (7-DADM) stream temperature.

Function

For Steelhead, Beechie et al. (2021) use an experimentally derived relationship between juvenile Rainbow Trout survival and stream temperature (Bear et al. 2007). Bear et al., (2007) exposed juvenile Rainbow Trout (110- 150 mm in length) to temperatures ranging from 8°C to 30°C in two-degree increments, and recorded mortality for each trial.

Type:
Empirical (Real data).

Original Function:

$$p = \frac{97.88}{1 + e^{-\left(\frac{T-24.3522}{-0.5033}\right)}}$$

Where T is the 7-day average daily maximum stream temperature (in °C) from temperature models, and p is a productivity multiplier from 0-1. The productivity multiplier is used to adjust survivorship from baseline values (*e.g., if the baseline survivorship was 0.2 and the temperature effect is 0.7 then the resulting survivorship is 0.2*0.7 = 0.14*).

Known Covariates or Stressor Interactions

Covariate(s)

Covariates embedded within stream temperature model (e.g., drainage area, channel slope, basin characteristics). Equivalent stream temperature models in British Columbia include estimates of MWAT from methods provided in Moore et al (2013).

Considerations

See rubric in Appendix A for explanations of the data classifiers below.

Data Source: The function is applied to annual transitions (survivorship estimates) of all freshwater age classes (Age-1+, excluding fry). The original study derived empirical relationships between younger age classes; however, application to older age classes is theoretical. Data are based on a functional relationship with Rainbow Trout.

Data Type: Combination of Empirical Data & Theory/Mechanistic Model

Data Quality: Unknown

Confidence in SR function: Strength, direction and relative magnitude are well known, but less certain about absolute values. The SR function is based on a small amount of data from a single empirical study. Pacific Salmon and Steelhead are known to have a high degree of plasticity in the relationships between stream temperature across different systems. Local periodicity (timing) of critical rearing periods, watershed attributes, and the general availability of cold-water refuge may have large implications on the magnitude of local effects.

Notes and User Recommendations

Local periodicity (timing) of critical rearing periods, watershed attributes, and the general availability of cold-water refuge may have large implications on the magnitude of local effects.

Stressor-Response Curve

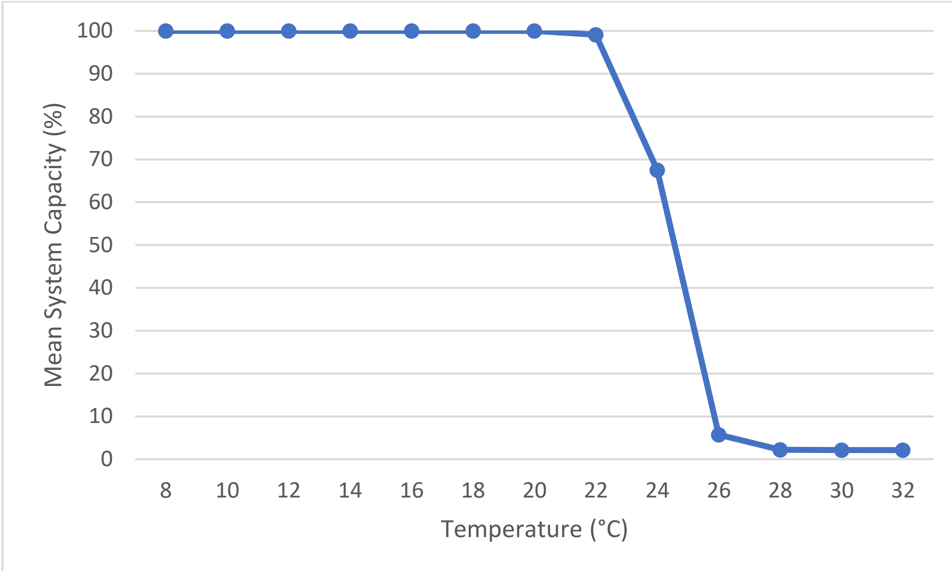


Figure 1: Stressor-response relationship between 7-day average daily maximum stream temperature (°C) and the derived summer rearing productivity multiplier (0-1), interpreted as system capacity in the model. Data are from Beechie et al. (2021).

Stressor-Response Table

Table 1: Discrete stressor-response relationship between raw stressor values and the mean system capacity (0-100%; scaled version of the productivity multiplier). The standard deviation of the mean system capacity is defined by the user and represents the inherent stochasticity or noise in the relationship. The set lower limit and upper limit of the mean system capacity are also presented. Mean system capacity (0-100%) is a standardized measure of wild adult recruits produced by the previous spawner cohort. Data are from Beechie et al. (2021).

Temperature	Mean System Capacity (%)	SD	Lower Limit	Upper Limit
8	100	0	0	100
10	100	0	0	100
12	100	0	0	100
14	99.99999989	0	0	100
16	99.99999392	0	0	100
18	99.99967684	0	0	100
20	99.98281573	0	0	100
22	99.09435509	0	0	100
24	67.51747599	0	0	100
26	5.690103118	0	0	100
28	2.189617868	0	0	100
30	2.121309894	0	0	100
32	2.120024629	0	0	100

Additional References

Bear, E. A., McMahon T. T., & Zale A. V. 2007. Comparative thermal requirements for westslope cutthroat trout and rainbow trout: Implications for species interactions and development of thermal protection standards. Transactions of the American Fisheries Society, 136(4), 1113-1121. doi: 10.1577/T06-072.1.

Moore, R. D., Nelitz, M., & Parkinson, E. 2013. Empirical modelling of maximum weekly average stream temperature in British Columbia, Canada, to support assessment of fish habitat suitability. Canadian Water Resources Journal, 38(2), 135-147.

Stressor: August Mean Flow (m^3s^{-1})

Species: Chinook Salmon

Life Stage/Season: Spawning

Citation

Warkentin, L., Parken, C.K., Bailey, R., and Moore, J.W. 2022. Low summer river flows associated with low productivity of Chinook salmon in a watershed with shifting hydrology. Ecol. Solut. Evid. ***3****: e12124.*

Stressor-Response Relationship

Rationale

Chinook salmon in the Nicola River are hypothesized to exhibit higher productivity (young of the year recruits) with increased discharge during the summer low flow period (August). This increase in productivity is attributable to increases in both spawning and recruitment.

Function

Relationship between mean August flow during spawning and the residual recruits (from the stock-recruit curve). The mean August flow during spawning is measured during the brood year when spawners are moving upstream and waiting to spawn. This relationship was derived using a linear regression, with data collected between 1992-2013.

Type:
Empirical (Real data)

Original Function:
$y = 80.818x + 4665.2$

Where y is the number of recruits (residual recruits + mean recruits) and x is the mean August flow during spawning (m^3s^{-1}).

Known Covariates or Stressor Interactions

Covariate(s)

Covariates embedded within the August flow model (e.g., stream temperatures may increase during low flows, affecting spawning and recruitment).

Considerations

See rubric in Appendix A for explanations of the data classifiers below.

Data Source: Data were collected by the Department of Fisheries and Oceans Canada (DFO) from cohorts spawned between 1992-2013.

Data Type: Empirical Data

Data Quality: Function is based on empirical data from 22 Chinook cohorts in the Nicola River, which were spawned between 1992-2013.

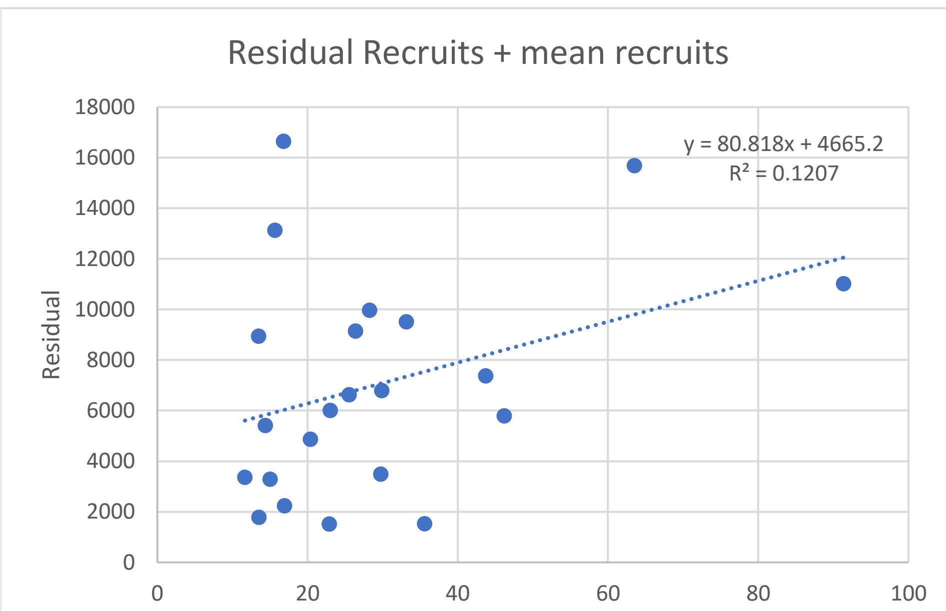
Confidence in SR function: Warkentin et al. (2022) found a weak (R^2 = 0.1207) relationship between residual recruits and mean August flow during spawning (m^3s^{-1}).

Notes and User Recommendations

None.

Stressor-Response Curve

Figure 1: Raw stressor-response relationship between mean August flow during spawning (m^3s^{-1}) and the number of recruits (residual recruits + mean recruits) model. Data are from Warkentin et al. (2022).



Stressor-Response Table

Table 1: The table shows the discrete stressor-response relationship between raw stressor values and the mean system capacity (0-100%). The standard deviation of the mean system capacity is defined by the user and represents the inherent stochasticity or noise in the relationship. The set lower limit and upper limit of the mean system capacity are also presented. Data are from Warkentin et al. (2022).

Mean August Flow (m^3s^{-1})	Recruits	SD	Lower Limit	Upper Limit
0	4665.2	0	0	12747

10	5473.38	0	0	12747
20	6281.56	0	0	12747
30	7089.74	0	0	12747
40	7897.92	0	0	12747
50	8706.1	0	0	12747
60	9514.28	0	0	12747
70	10322.46	0	0	12747
80	11130.64	0	0	12747
90	11938.82	0	0	12747
100	12747	0	0	12747

Species Profiles

Steelhead

Oncorhynchus mykiss

The following species profile for Steelhead (*Oncorhynchus mykiss*) was developed from relevant reference literature from the Nicola Basin in British Columbia. While some parameters may be transferable to Steelhead in other systems, many components of this profile are specific to the dominant structure of Steelhead in the Nicola Basin. Steelhead have some of the most diverse life histories strategies of all anadromous fish in the Pacific Northwest (Godwin and Krkosek 2022). Nicola Basin Steelhead are part of the Thompson River Steelhead Run (Sebastian 1981; McGregor 1986; Levy 2014). Within the Thompson River, approximately fourteen different Steelhead life history patterns have been identified (McGregor 1986). Trying to fully capture all of these complex life cycle variants within a single matrix population modelling framework is impractical. We therefore attempt to represent the most prevalent life history pattern of Steelhead observed in the Nicola Basin. Future extensions could include the representation of alternative life history patterns represented as different species profile variants. These variants could be run in parallel in the CEM-PRA/Joe Model tool.

Thompson River Steelhead (TRS) migrate upstream as adults from the marine environment into the Fraser River and then to the Thompson River in the fall (Sebastian 1981; McGregor 1986; Rosenau and Angelo 2003). Returning adults will overwinter in the Thompson River before moving into tributaries within the Nicola Basin to spawn. Fry and parr will rear in freshwater environments for 2-3 years before transitioning to smolts and out-migrating to the ocean (Sebastian 1981; McGregor 1986). During the time in freshwater important tributary-to-mainstem seasonal migrations occur between winter and summer rearing areas. Adult rearing in the marine environment can extend for 2-3 years. Adult Steelhead will return to spawn at ages of 5-6. Steelhead can spawn more than once (iteroparity) and then live up to many years (4 - 11) but for the purpose of this modelling exercise we assume that most mature adults have an average generation time of 5 years and reach a maximum age of 6 years (see Korman et al 2018).

The majority of Steelhead in the Thompson River smolt at age 2.2+ with some 3.2+ and 2.3+ and a small number of 3.3+ (McGregor 1986). The portion of adults returning to spawn is predominantly composed of Age-5 adults (83%), followed by Age-6 adults (13%) with a small quantity of Age-4 adults (3%) (Korman et al 2018). The prevalence of repeat spawning is believed to be much lower (~ 3%, MELP and DFO 1998) than coastal populations (e.g., 12% Beechie et al 2021).

The dominant life history pattern represented here for the Nicola Steelhead species profile assumes that most juveniles smolt after spending two years in freshwater (2.2+) and that adult rearing in the marine environment lasts for three years with adult spawners returning at Age-5 with some Age-6 repeat spawners. Simplifying the Steelhead species profile to a single dominant life history pattern for the CEM-PRA tool is necessary for implementation, but these simplifications may also have important consequences on our understanding of vulnerability and exposure to stressors. A key evolutionary advantage of the diversity of life history strategies observed in Steelhead is believed to be (in part) a bet hedging strategy to mitigate risk and exposure to adverse conditions in the diverse range of environments the fish encounter over their life cycle

(Sebastian 1981; MCGregor 1986; Korman et al 2018). Therefore, it would be valuable to run simulations for other species profiles as ‘Steelhead variants’ in future iterations of this work.

Periodicity (Seasonality)

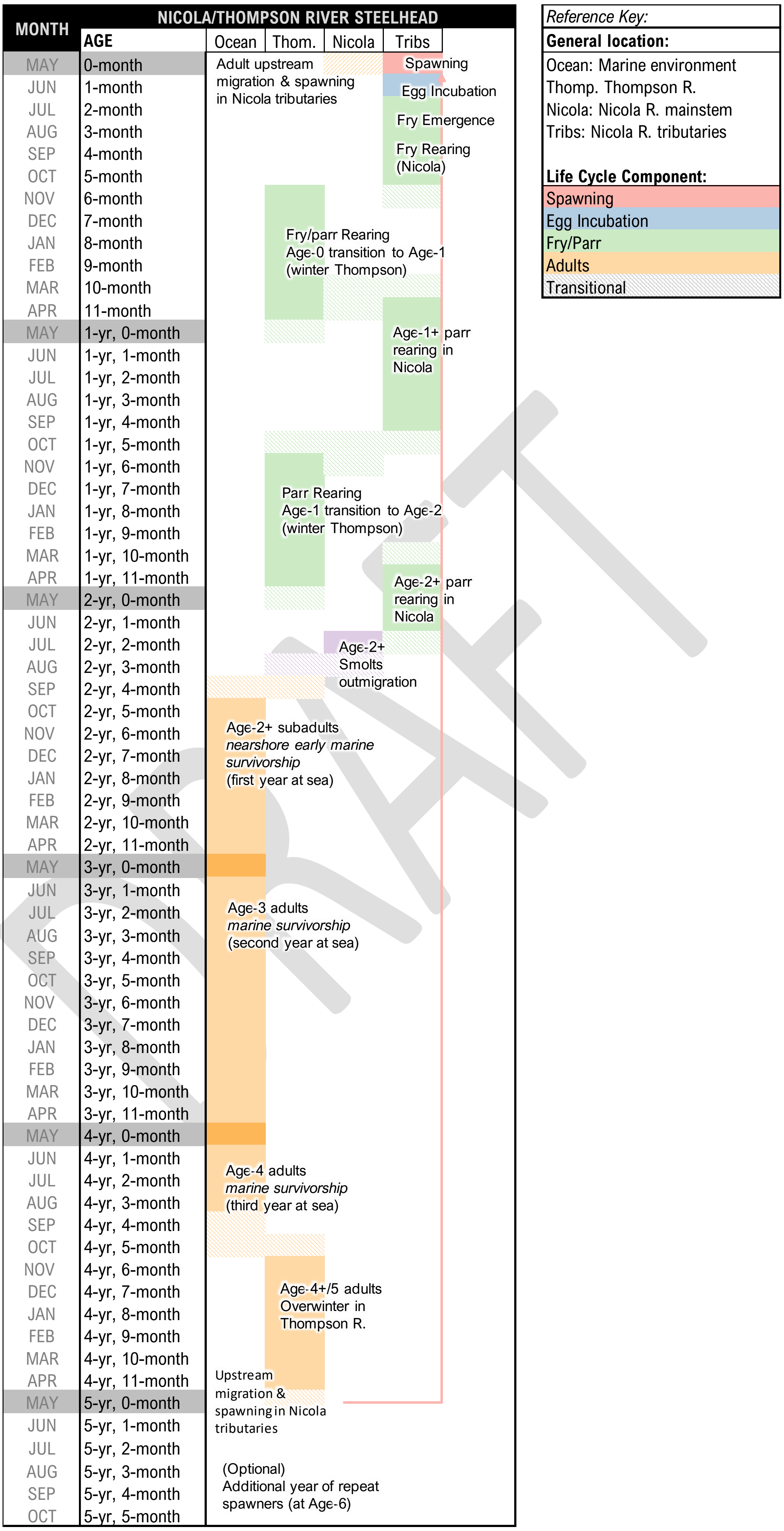
The following summary provides a general overview of the Steelhead life cycle for Nicola/Thompson River populations. Timing of key events is compiled from various sources with preference given to references specific to Nicola Steelhead (Sebastian 1981; McGregor 1986; Korman 2018; Godwin and Krkosek 2022). Understanding fish periodicity and the timing of key events is critical to appropriately link stressor-response functions and stressor magnitude data to local populations in space and time. For example, exposure to suboptimal overwinter rearing conditions in the Thompson River is critical to population productivity to all locations in the Nicola. However, stream temperatures over the summer rearing period will have localized effect to fry/parr in each tributary of the Nicola.

Generalized Steelhead Periodicity in the Nicola Basin:

- **Fall/September:** Upstream migration of adults (Ocean → Fraser River → Thompson River) and pre-spawn overwintering (Sebastian 1981; Rosenau and Angelo, 2003)
- **April to early-June:** Adult spawners enter tributaries of the Nicola Basin (Sebastian 1981)
- **early-May to mid-June:** Primary spawning window (Sebastian 1981; Rosenau and Angelo, 2003)
- **May to late-July:** Egg incubation in gravel of natal tributaries (Sebastian 1981)
- **Late-July:** Fry emergence (Sebastian 1981)
- **July-September**: Fry summer rearing in Nicola tributaries
- **First fall**: Most Age-0+ fry/parr will migrate from tributaries of the Nicola to mainstem reaches of the Thompson River (between Spences Bridge to Kamloops Lake) in the fall of their first year for overwintering.
- **Second Spring/Summer:** Age-1+ parr will migrate from the Thompson River back into Nicola tributaries for a second spring/summer/fall year of rearing.
- **Second fall/winter:** Age-1+ parr will then migrate (again) from tributaries in the Nicola to mainstem reaches of the Thompson River for their second winter.
- **June - third spring:** Age-2 (2-year-old) parr emerging from the winter will be characterized as out-migrating smolts. These 2-year-old fish will then begin their downstream migration in their third spring (early June).
- **Smolt outmigration:** (Nicola Tributaries → Thompson → Fraser River → Pacific Ocean). Nearshore rearing in coastal estuaries of the marine environment. Larger individuals will exit Salish Sea into the Pacific Ocean through the Strait of Juan de Fuca (COSEWIC 2018).
- **Marine rearing:** Steelhead will (predominantly) spend a total of three years in the marine environment with adults returning to spawn in the fall of their third year at sea (Korman et al 2018).

Figure 1 shows a draft periodicity table for Nicola Basin Steelhead with 2 years of freshwater rearing and three years at sea with spawning at Age-5. Constructing a periodicity table like this is a valuable exercise to help appropriately map out the life cycle and create linkages between stressors to key life cycle components in space and time.

Figure 1. Periodicity table of Nicola Basin Steelhead showing one of the dominant life history variants with two years of freshwater rearing and three years at sea.

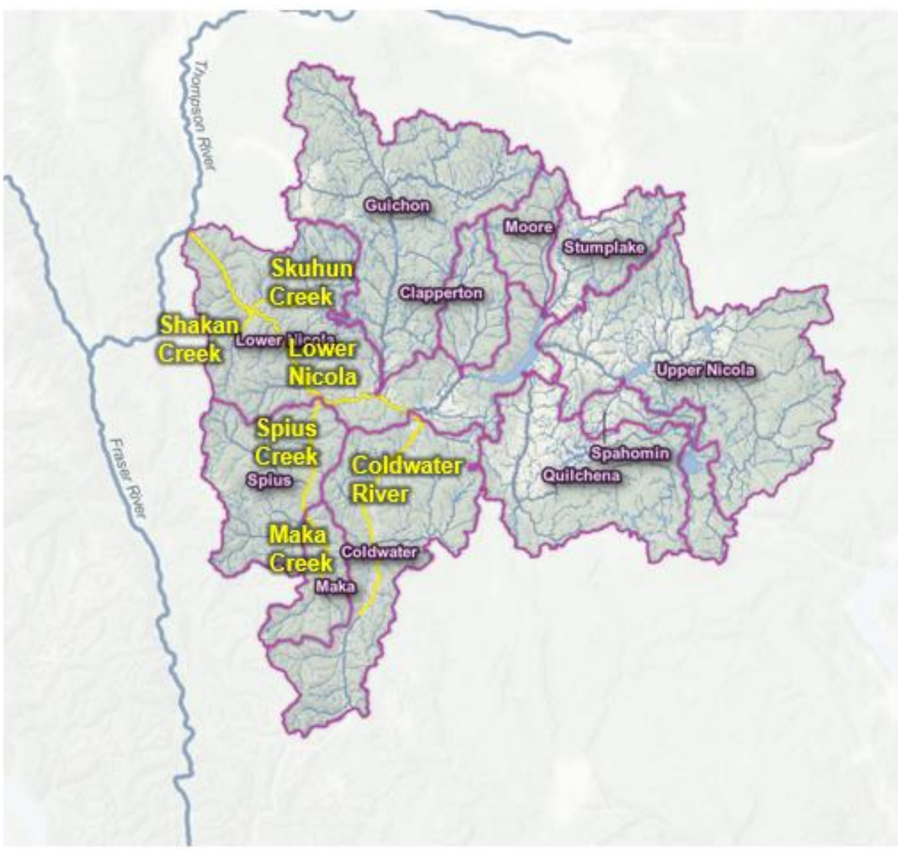


Habitat and Locations

Steelhead occupy tributaries and mainstem reaches of the lower Nicola. Major (current & historic) Steelhead spawning streams within the Nicola Basin include Spius Creek, Nuaitch Creek, Shakan Creek, Skuhun Creek and the Coldwater River (Sebastian 1981). Tributary habitat is critical for summer rearing and smolt production while adults are found more frequently in larger mainstem systems downstream (Sebastian 1981; Rosenau and Angelo 2003).

As discussed in previous sections season fish movement of parr plays an important component in regards to exposure to stressors. After emergence fry will rear in their natal tributaries, but then migrate downstream to the Thompson River (between Spences Bridge and Kamloops Lake) for overwintering (Levy 2014). These migratory patterns are important because exposure to different stressor-response relationships in the CEM-PRA/Joe Model tool will be seasonal. Therefore, scenarios that target overwintering survivorship or capacity of juveniles should a.) consider stressor-magnitude estimates linked to target reaches of the Thompson River and b.) apply stressor-response curves to all locations of the Nicola Basin. Based on available reference literature, key locations to represent in the CEM-PRA/Joe Model for Nicola Steelhead are shown in yellow in Figure 2. The Thompson River could also be added as a special seasonal location.

Figure 2. Proposed CEM-PRA/Joe Model Locations for Nicola Steelhead

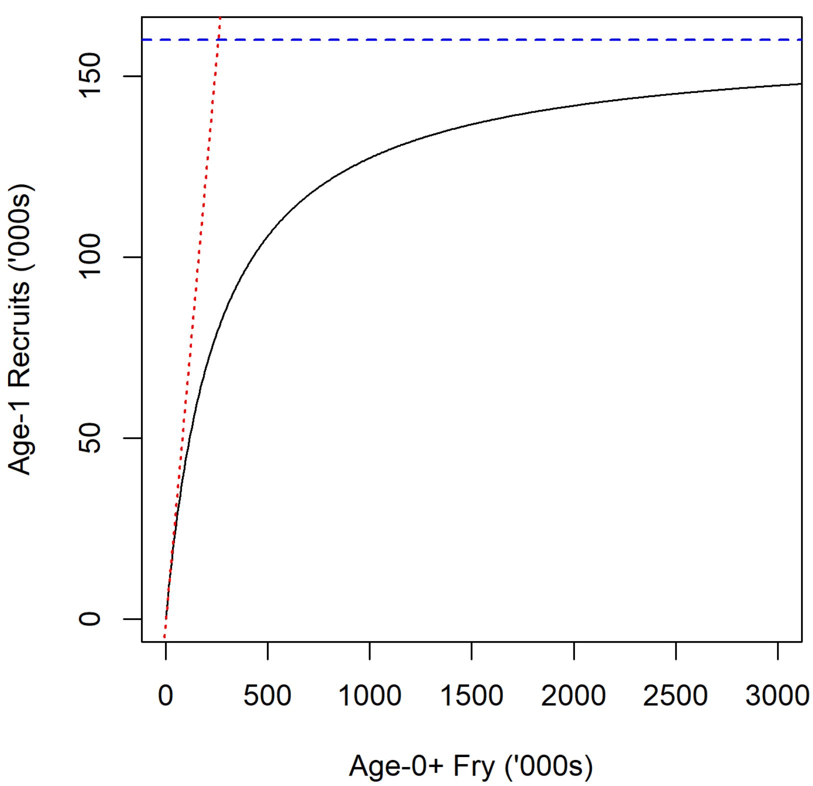


Capacity Estimates

Carrying capacity can be implemented in the CEM-PRA/Joe Model as either a.) an adult threshold carrying capacity with stage-specific compensation ratios or b.) location and stage-specific carrying capacities with possible Beverton-Holt density-dependent growth functions. In this application of the tool, density-dependent growth is modelled as a carrying capacity threshold for the fry (Age-0) to parr (Age-1) transition following a Beverton-Holt density-dependence function. This demographic bottleneck is consistent with relevant reference literature for Nicola Steelhead and is consistent with trends documented within various regional studies (Sebastian 1981; Rosenau and Angelo 2003; Decker et al. 2009; Levy and Parkinson 2014; Korman et al 2018).

Implementing this density-dependence function to recruitment (along with other parameters) means that the production of Age-1 (parr) recruits is largely insensitive to additional spawners beyond a given threshold (roughly ~500 to 1,500 adult Steelhead in the Nicola). There are no other density-dependent constraints implemented in the Nicola Steelhead CEM-PRA/Joe Model species profile. Therefore, factors such as spawning habitat availability will not be identified as limiting unless they are linked to productivity (survivorship) vital rates (as opposed to stage-specific capacities). See Figure 3 for Beverton-Holt relationship with parr capacity following Schick 2016 for Nicola Steelhead).

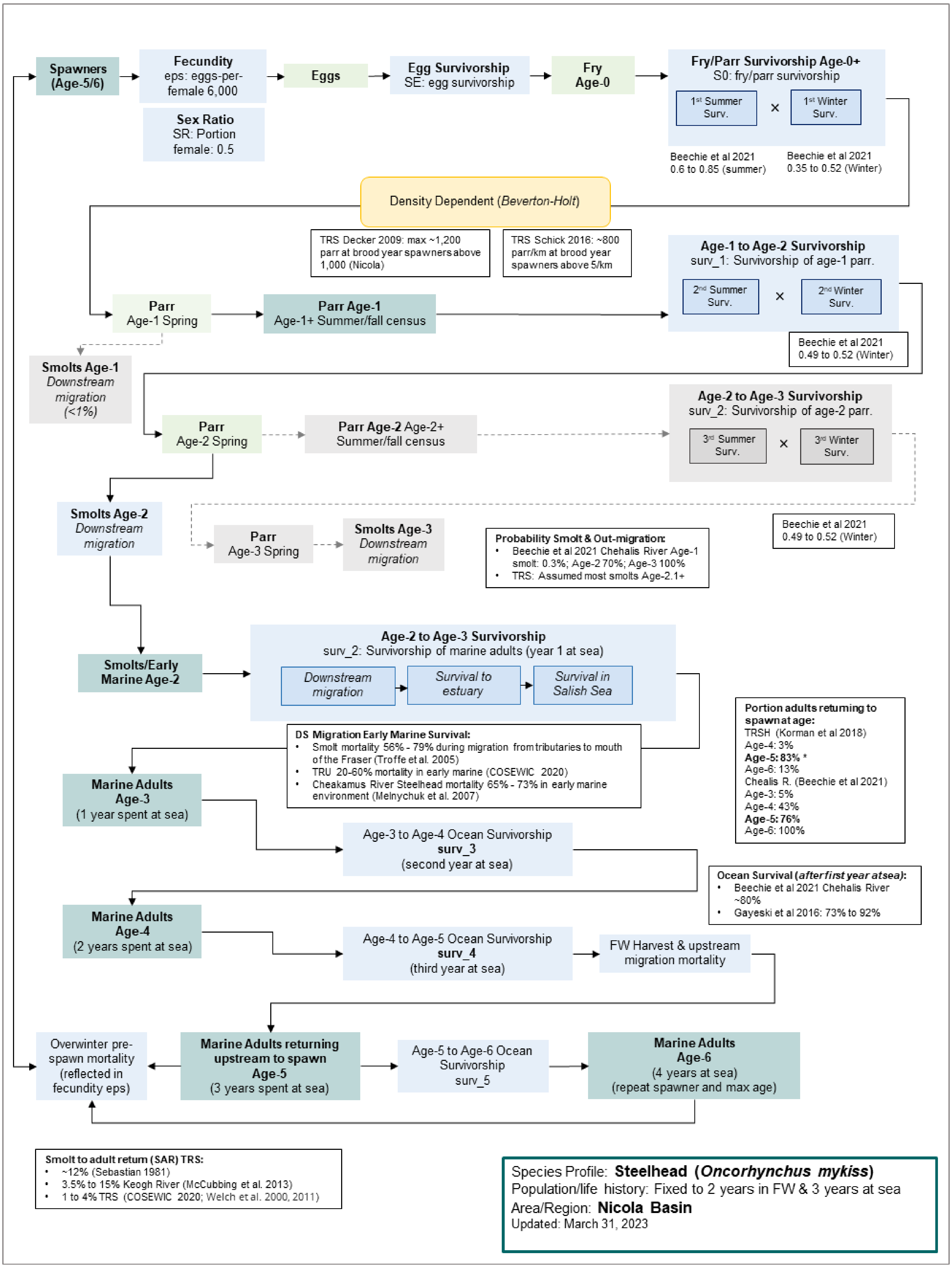
Figure 3. Beverton-Holt function governing density-dependent growth between fry (Age-0) and parr (Age-1) individuals. Capacity set to 160,000 Age-1 parr



Regardless of these hypothetical capacity estimates, numerous limiting factors in both the marine and freshwater environments prevent real world Steelhead populations in the Nicola from reaching these capacities. The current status of the Thompson River Steelhead population is characterized as "*Extreme Conservation Concern*". 2022 estimates of adult spawners were only ~104 (Bison 2022). A decline of approximately 97% from historic highs of ~3,510 individuals in 1985. A near-continuous downward trend has been observed for the last three decades (Korman et al 2018). Therefore, the evolution of stressor-response functions and scenario alternatives in the CEM-PRA/Joe Model tool should likely focus on increasing productivity (survivorship).

Life Cycle Diagram for Nicola Steelhead

Figure 4. Draft life cycle diagram for Nicola Steelhead showing model components (in dark green), substages (in light green), transitions (in blue), density-dependent transitions (in orange) and alternate life cycle variables (in grey)



Life Cycle Parameter for Nicola Steelhead

Life cycle parameters were developed for Nicola Steelhead based on available reference literature. One or more reference was available for each parameter. For each parameter we reviewed references and made a recommendation for a value (or range) to use in the species profile. This recommendation was based on the regional relevancy of the reference. References were prioritized if they a.) represented Nicola Steelhead, b.) represented interior Steelhead (as opposed to populations from small coastal streams), c.) provided reliable estimates with large sample sizes and/or extended monitoring periods.

(eps): Eggs Per Female Spawner:

Estimate	Source	Note
12,600	COSEWIC 2020	Thompson River Steelhead, but reference likely characterising maximum fecundity.
6,000	Beechie et al 2021	Range: 5,400 first time spawners to 8,000 large mature re-spawn fecundity. Large regional literature review.
4,924	Gayeski et al 2016	Puget Sound Coastal Steelhead
4,923	Quinn 2005	Coastal Steelhead? Source unclear.
6,000	***Recommended value:*** *based on regional review and scope of reference literature in Beechie et al 2021*	

(SE): Egg to fry survivorship (emergence) of Age-0 individuals.

Estimate	Source	Note
0.1	Moore and Olmsted 1985	Range: 0.08 - 0.12 (Thompson Nicola)
0.4	Beechie et al 2021	Coastal Steelhead in Chehalis River (0 to 0.9: large range per system).
0.2	Gayeski et al 2016	Puget Sound Coastal Steelhead
0.29	Quinn 2005	Coastal Steelhead? Source unclear.
0.1	***Recommended value:*** *based on regional review and scope of reference literature relevant to Thomson Nicola (Moore and Olmsted 1985)*	

(S0): Fry-to-fry survivorship (Age-0 to Age-1) density-<u>independent</u> portion.

Estimate	Source	Note
0.625	Levy et al 2014	Intercept of fry-to-parr BH-DD relationship. Derived attribute estimating Thompson-Nicola Steelhead DI survivorship of fry-to-parr.
0.3	Gayeski et al 2016	Range: 0.3 to 0.4 (Coastal Steelhead Puget Sound, not adjusted for DI survivorship)
0.14	Quinn 2005	Unclear on source and likely represents coupled DD-DI survivorship.
0.625	***Recommended value:*** *hard to find relevant references that estimate fry-to-parr survivorship in the absence of density-dependence constraints. Estimate derived alpha from DD functions.*	

(SR): Sex ration (portion female) at birth.

Estimate	Source	Note
0.5	Beechie et al 2021	Default assumption
0.5	Gayeski et al 2016	Default assumption
0.5	*No evidence (across studies) to suggest that long-term equilibrium portions are significantly difference than 0.5 for Nicola Steelhead. Revisit if considering size at maturity.*	

(surv_1): Survival of Age-1 parr from spring to Age-2 (2-year-old) parr in the spring.

Estimate	Source	Note
0.49	Beechie et al 2021	Range: 0.49 - 0.52
0.49	*(**Revisit**): Limited regional references available to estimate over the target transition period.*	

(surv_2): Survival of Age-2 parr from the spring of their second (2-year-old individuals) through outmigration to the ocean, smoltification and first 6-month at sea as immature adults.

Estimate	Source	Note
0.2	Troffe et al 2005	Reference unvalidated, but cited in COSEWIC 2018 for TRS. Possible stage-period mismatch
0.14	Beechie et al 2021	Bay/delta productivity, back-calculated from SAR estimates. Possible stage-period mismatch.
0.06	Gayeski et al 2016	Transition/stage period matches current application, but likely that outmigration mortality lower in Thompson River than Puget Sound reference.
0.06	*(**Revisit**): Valuable to revisit estimate, potentially back-calculate from SAR ratios and other regional references.*	

(surv_3): Survival of Age-3 marine adults from 6 months at sea to 18 months at sea

Estimate	Source	Note
0.8	Beechie et al 2021	Estimated from SAR ratios
0.73	Gayeski et al 2016	Estimated from SAR ratios
0.75	*(**Revisit**): Estimate between references. Valuable to revisit estimate, potentially back-calculate from SAR ratios and other regional references. Assume (for simplicity) at-sea survivorship not substantially different from source population.*	

(surv_4): Survival of Age-4 from 18 months at sea to 24 months at sea and upstream migration through the Fraser and Thompson Rivers.

Estimate	Source	Note
0.8	Beechie et al 2021	Estimated from SAR ratios
0.74	Gayeski et al 2016	Estimated from SAR ratios; Range: 0.74 - 0.93

0.75	*(**Revisit**): Estimate between references. Valuable to revisit estimate, potentially back-calculate from SAR ratios and other regional references. Assume at-sea survivorship not substantially different from source population. Upstream migration mortality likely underestimated for Nicola Steelhead.*

(surv_5): Survival of Age-5 (5-year-old fish) from post-spawning to Age-6 repeat spawners

Estimate	Source	Note
0.028	MELP 1998	Assume very small percentage of repeat spawners for Thompson River Steelhead
0.05	COSWEIC 2020	Estimated small percentage of repeat spawners for Thompson River Steelhead
0.75	Gayeski et al 2016	Estimated from SAR ratios; Range: 0.75 - 0.93
0.03	*(**Revisit**): Estimate based on regional repeat spawners. May want to keep survivorship high but decrease maturity of Age-6+ fish*	

(mat_4): Maturity of Age-4 fish

Estimate	Source	Note
0.03	Korman et al 2018	Thompson River Steelhead
0.03	*(**Recommendation**): Based on the dominant life history strategy being represented in this species profile.*	

(mat_5): Maturity of Age-5 fish

Estimate	Source	Note
0.83	Korman et al 2018	Thompson River Steelhead
0.83	*(**Recommendation**): Based on the dominant life history strategy being represented in this species profile.*	

(mat_6): Maturity of Age-6 fish

Estimate	Source	Note
0.13	Korman et al 2018	Thompson River Steelhead
0.13	*(**Recommendation**): Based on the dominant life history strategy being represented in this species profile. Assume these fish are repeat spawners*	

The following list of default parameters were chosen based on basic biology of the species or inferred (determined by) on parameters in above table.

Default Parameters:

- **Number of life stages (Nstage):** The number of life stages is set to 6.
- **Spawn events per female (events):** Assume that there is only 1 major spawning event per year.
- **Spawning interval (int):** Assume 1 such that mature adult spawners spawn every year and do not skip years.

- **Survival of repat spawners (surv_6):** Assume very low percentage of repeat spawners and no Age-7+ fish in the system. Set survivorship of Age-6 to zero.
- **Stage 1 years (year_1):** 1 one year in this stage
- **Stage 2 years (year_2):** 1 one year in this stage
- **Stage 3 years (year_3):** 1 one year in this stage
- **stage 4 years (year_4):** 1 one year in this stage
- **stage 5 years (year_5):** 1 one year in this stage
- **stage 6 years (year_6):** 1 one year in this stage
- **Compensation Ratios:** *Set all compensation ratios to 1 (no density dependence through compensation ratios. Beverton-Holt Stage specific density dependence is being used to control density-dependent growth).*
- **Maturity Age-1 (mat_1):** 0, Age/Stage-1 fish are not mature.
- **Maturity Age-2 (mat_2):** 0, Age/Stage-2 fish are not mature.
- **Maturity Age-3 (mat_3):** 0, Age/Stage-3 fish are not mature.
- **Variance in eggs per female (eps_sd):** 1000 (based on approximate range of estimates between reference literature for eps)
- **Correlation in egg fecundity through time (egg_rho):** 0.1 default value in CEM-PRA tool
- **Coefficient of variation in stage-specific mortality (M.cv):** 0.1 default value in CEM-PRA tool
- **Correlation in mortality through time (M.rho):** 0.1 default value in CEM-PRA tool
- **Fry (Age-0) to parr (Age-1+) density dependent (DD) survivorship function following a classical Beverton-Holt (BD) Relationship (bh_stage_1):** 1 – implemented.
- **BH DD 2 (bh_stage_2):** 0, not implemented.
- **BH DD 3 (bh_stage_3):** 0, not implemented.
- **BH DD 4 (bh_stage_4):** 0, not implemented.
- **BH DD 5 (bh_stage_5):** 0, not implemented.
- **BH DD 6 (bh_stage_6):** 0, not implemented.

Population Model Components

Matrix Components

This section provides a summary of the stage-structured matrix population model elements for Nicola Steelhead.

Pre-birth pulse census: The stage-structured matrix population model is setup as a pre-birth pulse census (see Caswell 2000). The design of stage-structured matrix models does not allow for the initial number of eggs and fry to be represented as independent matrix elements (cells). In a pre-birth pulse census, we assume that the demographic census takes place immediately before spawning, meaning that yearlings of the previous spawning year have undergone a full-time step (Age-0/Stage-0 to Age-1/Stage-1). Yearlings (Age-0: egg & fry) must survive the entire census period to subsequent the census. Therefore, the Age-0 transitions (egg-to-fry survivorship: SE and fry-to-parr survivorship: S0) are accounted for within the fecundity element (cells) of the transition matrix (Table 1).

In Table 1 we see how the fecundity terms (row 1, columns 2:6) account for stage-specific maturity (mat), spawning events per year (events: 1), eggs-per-spawner (eps), sex ratio (sR: 0.5), spawning intervals per year (int: 1), the survivorship of eggs (SE) and the survivorship of fry-to-parr (Age-0 to Age-1). Stage 0 is therefore characterized as adult spawning along with egg and fry survivorship all expressed in the fecundity element of the matrix. Stage 1 is characterized as parr (Age-1) censused approximately in the spring. Stage 2 are 2-year-old parr that have spent two full years in the freshwater rearing environment and are ready to out-migrate as smolts. Stage 3 represent marine adults after outmigration and approximately half a year spent at sea. Stage 4 represent adults (Age-4) after completing their second year at sea. Stage 5 represent 5-year-old adults after completing a portion of their third year at sea and migrating upstream to the spawning grounds. Stage 6 represents repeat spawners (Age-6+).

In Table 1 s1 – s6 (surv_1 to surv_6) represent stage specific survivorship transitions. Since individuals spend no more than one year in each stage n1 to n6 will always equal 1.

Table 1. Symbolic representation of the projection matrix for Nicola Steelhead

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6
Stage 1	s1 * (1 - s1^(n1 - 1))/(1 - s1^n1)	(mat2 * events * eps * sE * s0 * sR)/int	(mat3 * events * eps * sE * s0 * sR)/int	(mat4 * events * eps * sE * s0 * sR)/int	(mat5 * events * eps * sE * s0 * sR)/int	(mat6 * events * eps * sE * s0 * sR)/int
Stage 2	s1 - s1 * (1 - s1^(n1 - 1))/(1 - s1^n1)	s2 * (1 - s2^(n2 - 1))/(1 - s2^n2)	0	0	0	0
Stage 3	0	s2 - s2 * (1 - s2^(n2 - 1))/(1 - s2^n2)	s3 * (1 - s3^(n3 - 1))/(1 - s3^n3)	0	0	0
Stage 4	0	0	s3 - s3 * (1 - s3^(n3 - 1))/(1 - s3^n3)	s4 * (1 - s4^(n4 - 1))/(1 - s4^n4)	0	0
Stage 5	0	0	0	s4 - s4 * (1 - s4^(n4 - 1))/(1 - s4^n4)	s5 * (1 - s5^(n5 - 1))/(1 - s5^n5)	0
Stage 6	0	0	0	0	s5 - s5 * (1 - s5^(n5 - 1))/(1 - s5^n5)	s6 * (1 - s6^(n6 - 1))/(1 - s6^n6)

Table 2 shows the life cycle parameters (described in the previous) section compiled with the symbolic representation of the transition matrix (Table 1) to generate a numeric representation of the transition matrix.

Table 2. Stage-structured transition matrix for Nicola Steelhead under density-independent growth conditions

Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6

Stage 1	0	0	0	5.6	155.6	24.4
Stage 2	0.5	0	0	0	0	0
Stage 3	0	0.06	0	0	0	0
Stage 4	0	0	0.75	0	0	0
Stage 5	0	0	0	0.75	0	0
Stage 6	0	0	0	0	0.03	0

The numeric representation of the transition matrix (Table 2) does not account for density-dependent growth (see next section for simulations); however, it does allow for numerous properties of the population to be described (Table 3: eigen analysis under density-independent growth).

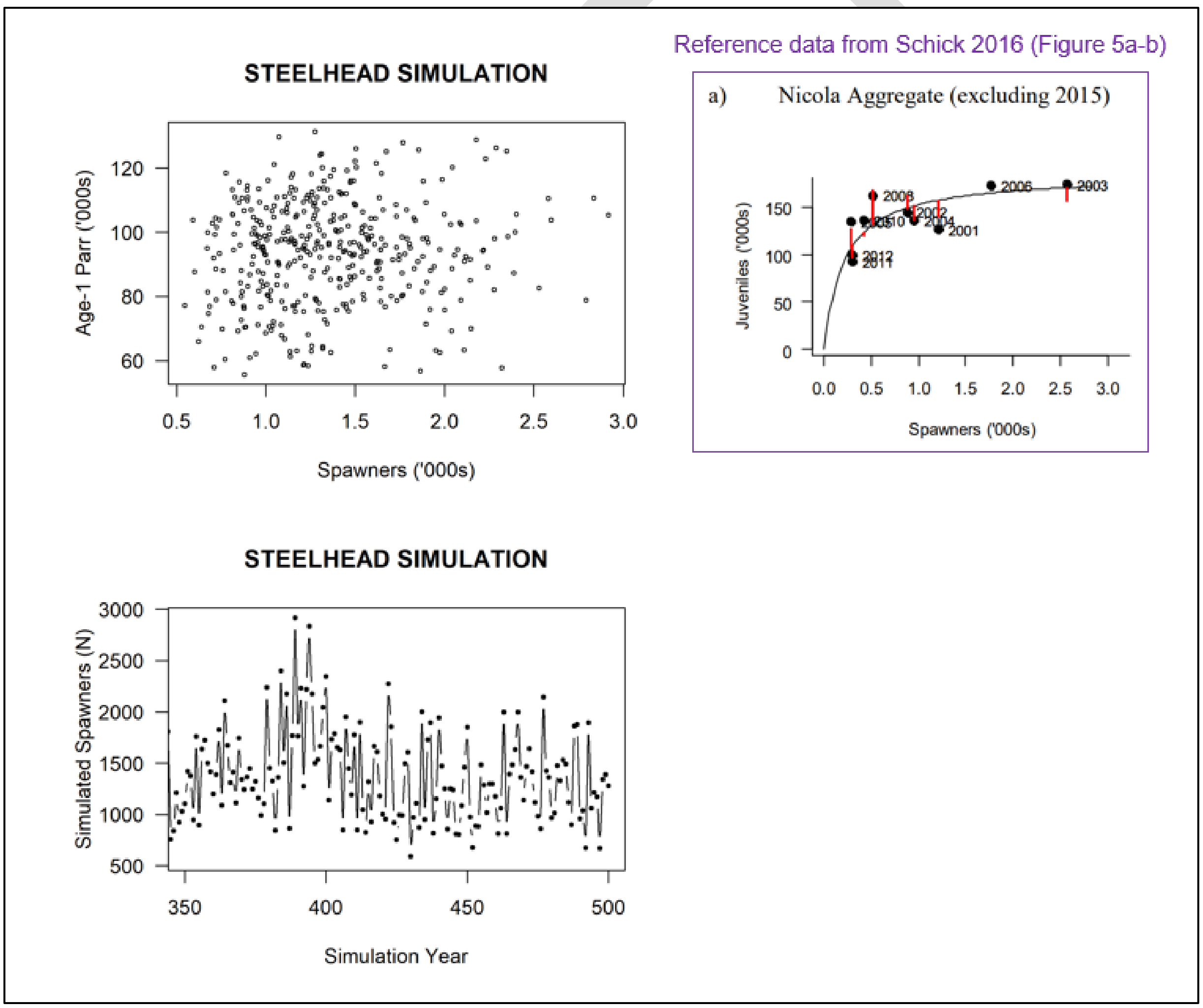
Table 3. Eigen Analysis of the Projection Matrix for Nicola Steelhead

Parameter	Value		Discussion			
Lambda (λ): finite rate of growth	1.23		The value is above 1 so the population will continue to grow exponentially.			
Generation time	4.95		The average generation time is approximately 5 years			
Stable Stage Distribution						
Stage distribution at DI equilibrium	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6
	0.69	0.28	0.013	0.008	0.005	0.0001

Sample Simulations

Simulations offer the best opportunity to really understand how the modelled population will behave under density-dependent growth constraints (Schaub and Kéry 2021). Figure 5 shows sample simulations for Nicola Steelhead. The panel on the upper left shows the simulated Age-1 parr (y-axis) and the simulated spawners (x-axis). Each dot represents a sample simulation year and batch replicate. The simulated population can then be compared against real-world reference data (Figure 5, upper right panel) from Schick (2016) to understand how closely the simulated population matches sample estimates from individual years, both in mean values and interannual variability. Overall, we see generally positive performance of the CEM-PRA/Joe Model tool to predict adult spawners in the Nicola within the range of 500 – 3,000 individuals under stochastic equilibrium conditions.

Figure 5. Nicola Steelhead simulations in the CEM-PRA/Joe Model under the default species profile



Key Stressors and Scenarios

In the Nicola Basin, key stressors include interacting pathways between water availability, instream habitat quality, the prevalence and quality of riparian habitat, availability and access to side-channels and wetlands, stream temperatures and sedimentation (Levy and Parkinson 2014; COSEWIC 2018; Pearsall et al 2022). The complex life history of Steelhead and seasonal and/or stage-specific usage of different locations requires researchers to carefully consider linkages between stressor-response functions and vital rates in the CEM-PRA/Joe Model tool. The following list, while not exhaustive, highlights some considerations for key stressors:

- **Stream Temperatures:** Upper limits to summer stream temperature constraints are well documented as limiting factor for numerous Salmonids species in the Nicola Basin. High stream temperatures can be lethal in mainstem segments in July/August. High stream temperatures are also coupled with other stressors such as low DO and low stream flows. Cooler water temperatures may also be limiting (potentially reducing size at age of fry/parr) but only in target tributaries (e.g., upper sections of the Coldwater River vs Spius Creek, Levy 2014). If stream temperatures are used as a stressor variable in simulations with the CEM-PRA tool, we recommend using a metric that captures sustained summer stream temperatures such as the maximum 7-day (weekly) averaged stream temperature (MWAT) to allow for linkages with available stressor-response curves to fry and parr.
- **Sediment and Fines**: Sediments and fines are also important stressors in the Nicola. Many systems are already characterized as having high turbidity, but the timing and composition of sediment inputs may contribute to fines covering the stream bed and dominating interstitial spaces. Potential concerns include bank instability and exacerbated siltation due to upland disturbances and agricultural activities.
- **Summer Low Flows**: Water management activities along the Nicola mainstem (a regulated system) or low flow in tributes can reduce habitat availability, stranding, limit connectivity to off-channel habitat and upstream reaches, increase temperatures and reduce DO. Low flows could be considered as a candidate stressor to model in the CEM-PRA tool. Stressor-response linkages could be made to parr capacity and survivorship of freshwater life stages (fry/parr). It would be valuable to differentiate between low flows due to water management activities (along the Nicola mainstem) and natural low flows in tributaries. These could be represented as different stressors (e.g., low-flows natural; low-flows management). Pre-existing instream flow guidelines could be used to generate a stressor response curve between low flows for the Nicola mainstem (e.g., Nicola River at the Spius Creek Confluence. Steelhead flows: Optimal > 5.5 m^3/s; fair between 5.5 – 3 m^3/s; critical < 3 m^3/s, see Alexander et al 2021).
- **Thompson River Overwinter Survival**: Given the complex life history and seasonal migratory patterns of Nicola Steelhead between tributaries of the Nicola (summer rearing) and the Thompson River mainstem (winter rearing) it would be valuable to attempt to capture stressors that attenuate or exacerbate overwinter survivorship of fry/parr. These stressors could be characterized and modelled in the CEM-PRA tool such that all tributaries of the Nicola share the same stressor-magnitude value, but conditions are modelled/represented based on winter rearing habitat within the Thompson River.
- **Reduced Ocean Survival:** Climate and oceanographic conditions of the North Pacific are believed to have reduced smolt-to-adult returns (SAR) for numerous Steelhead populations across the Pacific Northwest (Johnston 2013; Levy 2014). Evidence for this is consistent with long-term population trends across the coast and interior, regardless of

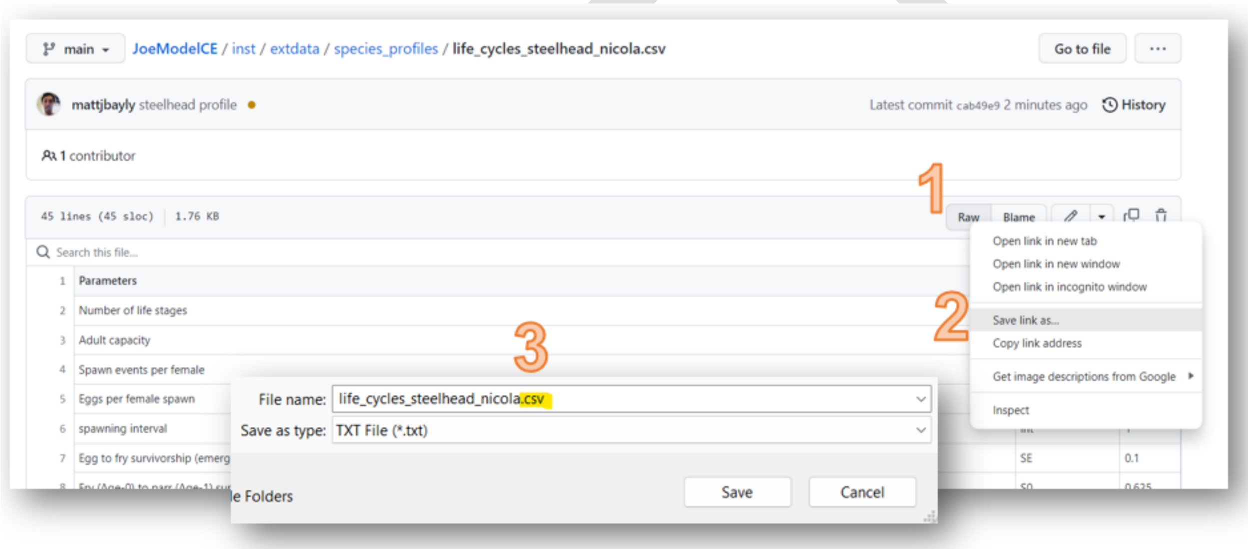
watershed characteristics and condition. Oceanographic survival is also coupled with marine harvest (incidental or fishery-related) and predation (pinnipeds). Stressor-response curves linked to adult survivorship could be created to represent marine survival. The stressor-magnitude value would (presumably) be the same across all tributaries of the Nicola, but relative comparisons could be made between scenarios that include a high degree of stochasticity from marine survivorship relative to other stressors.

Species Profile Input File

Download the life cycles input file for Nicola Steelhead:

https://github.com/essatech/JoeModelCE/blob/main/inst/extdata/species_profiles/life_cycles_steelhead_nicola.csv

To download the draft species profile for Nicola Steelhead go to the GitHUB link right click ‘Raw’ then ‘Save link as..’ then edit the file name so that it ends with ‘.csv’



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Appendix C: Multi-Stressor Interaction Matrix

Customizable Two-Factor Interaction Matrix

Customizable 2-factor interaction matrices may be (optionally) included by users to specify non-additive interactions between stressor variables (e.g., antagonistic, synergistic, etc.). If included, these matrices define the mean system capacity at different combination levels between two stressors. This can be especially important to capture conditional effects, attenuating or exacerbating factors, and/or compound variance and uncertainties. The 2-factor interaction matrices can also be a convenient mechanism to explore hypothetical and experimental scenarios.

The 2-factor interaction matrices are defined in the Stressor-Response Excel workbook. Template matrices are available in the R-Shiny application and sample datasets (*see upload data tab).* The data input format of the 2-factor interaction matrix is designed to be relatively flexible and accommodate both simple and more complex use cases. Similar to the single stressor-response functions, the 2-factor matrix is constructed by the user using data or expert opinion, depending on data availability.

A hypothetical example (Figure *1*) is included to show the interaction between stream canopy cover (low to high) and nutrients (as total Phosphorous). At low nutrients, habitat capacity for trout is highest under low canopy cover, where high light maximizes algal and invertebrate production (red circle). However, at high nutrients (eutrophic conditions), habitat capacity is highest under a closed canopy that suppresses algal growth and associated high temperatures and poor water quality (blue circle).

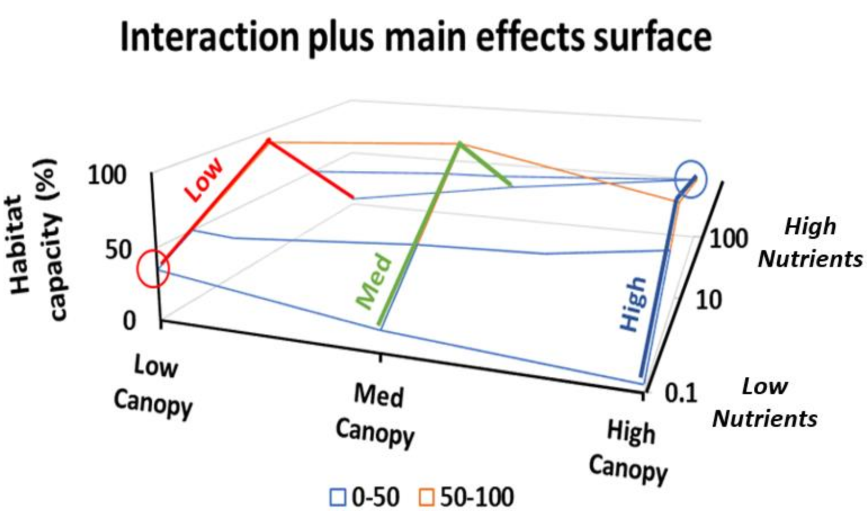

Figure 1. Example interaction surface for the CEMPRA 2-factor interaction matrix between trout capacity canopy cover and nutrients.

Data Preparation

The 2-factor interaction matrices are optionally included as additional tabs in the stressor response workbook. The formatting must follow Figure 2. The worksheet name must begin with “***MInt_***” followed by a unique name (ideally without spaces). In this example we used “MInt_AB”.

	A	B	C	D	E	F	G
1	**Matrix Name**	MInt_AB	**Life_stages**	adult			
2	**Columns**	A	**Parameters**	capacity			
3	**Rows**	B	**Model**	All			
4	**Main Effect**	Included					
5							
6		**Mean System Capacity (%)**	0	5	10	15	20
7		0	70	80	20	20	0
8		5	90	90	90	20	10
9		10	85	100	90	40	15
10		15	85	90	90	50	25
11		20	80	70	70	60	0
12							
13		**SD**	0	5	10	15	20
14		0	5	10	10	10	15
15		5	5	2.5	2.5	5	10
16		10	2.5	0	0	2.5	5
17		15	0	0	0	0	0
18		20	0	0	0	0	0
19							
20		**low.limit**	0	5	10	15	20
21		0	0	0	0	0	0
22		5	0	0	0	0	0
23		10	0	0	0	0	0
24		15	0	0	0	0	0
25		20	0	0	0	0	0
26							
27		**up.limit**	0	5	10	15	20
28		0	100	100	100	100	100
29		5	100	100	100	100	100
30		10	100	100	100	100	100
31		15	100	100	100	100	100
32		20	100	100	100	100	100
33							
34							
35							
36							

Main | A | B | C | D | E | **MInt_AB** | MInt_DE

Figure 2 Example Matrix interaction surface for stressor variables A and B.

The header section of the workbook must include several inputs:

- **Matrix Name (cell B1):** A custom name given to the 2-way interaction (for personal reference purposes). This name should match the worksheet name (e.g., MInt_AB). Try to avoid using spaces or special characters outside of MInt_.

- **Columns (cell B2):** The name of the stressor variable representing the column header values in the system capacity table. In the previous example column header values in the subsequent tables will map onto this stressor. Ensure that the spelling of the stressor matches the spelling throughout the rest of the workbook.
- **Rows (B3)**: The name of the stressor variable representing the row names in the system capacity table. In the previous example row names in the subsequent tables will map onto this stressor. Ensure that the spelling of the stressor matches the spelling throughout the rest of the workbook.
- **Main Effects**: Specify whether the system capacity estimates in the 2-factor interaction matrix account for (include) the main effects. Options for cell B4 can be either “Included” or “Excluded”.

    - **Included**: When cell B4 is set to “Included” the system capacity estimates are intended to represent the entire relationship between the two stressors at their respective levels (main effects and interactive effects combined). If the main effects option is set to “Included” the cumulative system capacity calculation will be adjusted to automatically omit both of the univariate stressor-response relationships (if they have been specified in the stressor-response workbook) and only evaluate their combined effect from the 2-factor interaction matrix. This modification is necessary to avoid double counting the effects of each stressor.

      For example, if the Stressor-Response workbook contained stressor-response worksheets for “Nutrients”, “Canopy_Cover” and an interactive matrix (e.g., “Matrix_1”) for “Nutrients and Canopy_Cover”, then the Joe Model would only evaluate system capacity values from the matrix and discard the univariate effects with the assumption that they are already accounted for in the matrix capacity data (Y = “VarA” + “VarB” + “Nutrients and Canopy_Cover”).

    - **Excluded (experimental – apply with caution)**: Setting cell B4 (Main Effects) to “Excluded” indicates that the interaction surface only describes the interactive effects and that the main effects (defined in the other stressor-response worksheets) must remain in the cumulative system capacity calculation. If the “Excluded” option is selected, the 2-factor interaction matrix ultimately acts as an additional stressor variable to modify the system capacity score. Setting the main effects to “Excluded” is convenient when users wish to quickly evaluate scenarios with and without customized interactive effects.

      Important Note: The implementation of interactive effects and main effects in the CEMPRA tool is different from a conventional logistic regression equation. There is no intercept, context-dependent coefficients, or link function. The interactive effect is simply added into the formula like any other stressor. For example, if the Stressor-Response workbook contained stressor-response worksheets for “Nutrients”, “Canopy_Cover” and an interactive matrix (e.g., “Matrix_1”) for “Nutrients and Canopy_Cover”, then the Joe Model would incorporate all three terms into the equation as stressor-response terms (Y = “VarA” + “VarB” + “Nutrients” + “Canopy Cover” + “Nutrients and Canopy_Cover”.

The difference between the 2-factor interaction matrix calculations with the main effects “Included” and “Excluded” is further illustrated in the following figure:

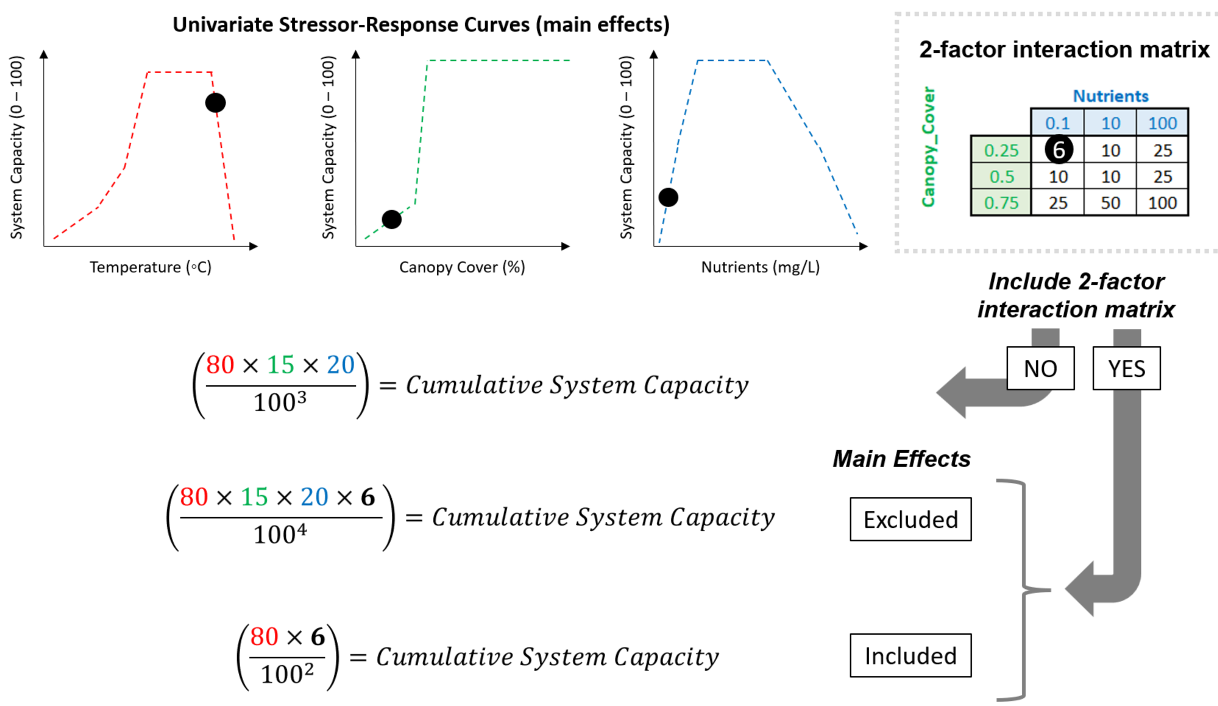

Figure 3. Difference between main effects being included or excluded from 2-factor interaction matrix summary. The Interaction factor for main effects Excluded (X) will be different (in this case lower) than for main effects Included.

The formatting of the matrix worksheet allows for some flexibility (see example below), but the variable inputs in cells B1:B4 must be kept in their original positions. For each stressor variable, the user can define any number of steps (intervals) provided that the stressor column variable (x-axis) starts in cell C6 and extends right (associated with columns – B2), and the stressor row variable (y-axis) starts in cell B7 and extends downward (associated with rows – B3 stressor). See figure Figure 4.

Figure 4. Matrices of different resolutions

If values in the stressor magnitude workbook do not align exactly with stressor values in the column and row heads of the interaction matrix, then the system capacity value will be calculated with linear interpolation. NULL or missing values from the stressor magnitude workbook will omit the HUC or subbasin assessment unit from any calculation of habitat capacity or cumulative effects.

Common Errors and Issues:

- ***Order stressors with values increasing**: Matrix column and row header values must be sorted non-decreasingly and contain no NA values or blank values. For example, 800, 600, 400 should be reordered as 400, 600, 800 in either the row or column headers for each stressor.*
- ***Keep template clean**: Format of template has been altered or additional content is placed in rows or columns to the left or below matrix tables.*
- *Errors in header and meta data*

Population Model

The 2-factor interaction matrix can also be used to define interactions linked to vital rates in the population model. The parameterization and setup for this is identical to how other variables are described in the stressor-response workbook. Ensure that linkages are properly defined in the “Main” coversheet for each of the input stressors being used as rows and columns.