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

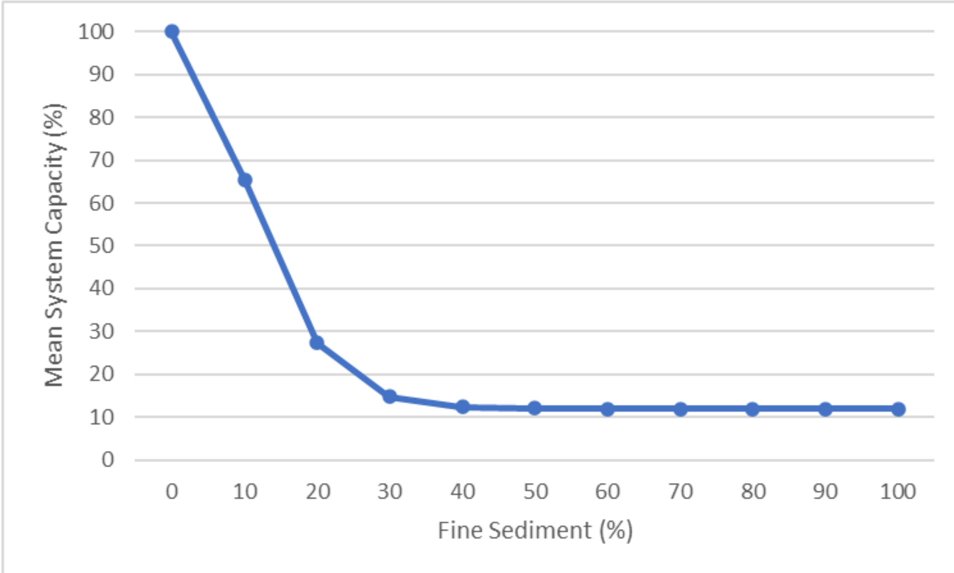


Figure 1: Stressor-response relationship between percent fine sediment and incubation productivity (0-1), interpreted as system capacity in the model. Data are from Beechie et al. (2021).

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

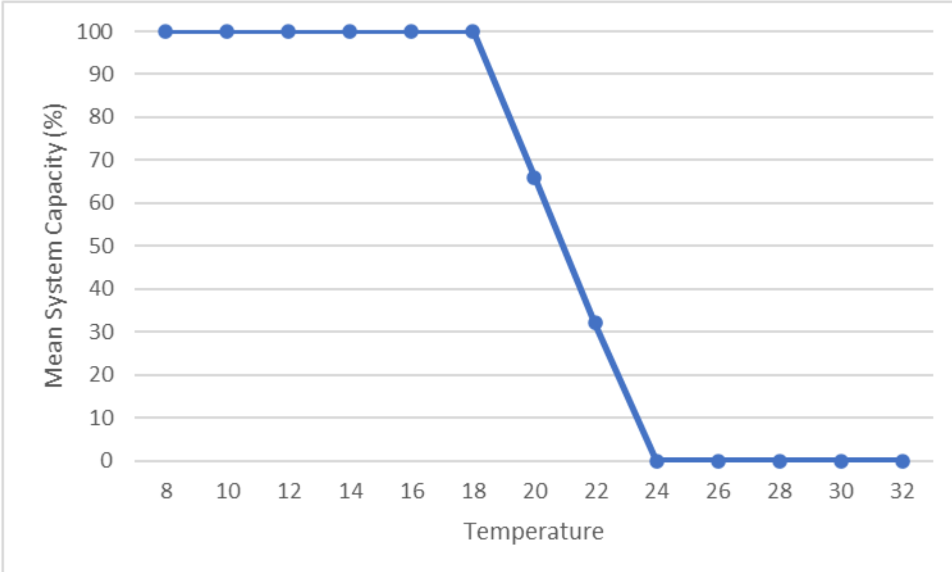


Figure 1: Stressor-response relationship between 7-day average daily maximum stream temperature (°C) and the derived summer rearing productivity multiplier (0-1), interpreted as system capacity in the model. Data are from Beechie et al. (2021).

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

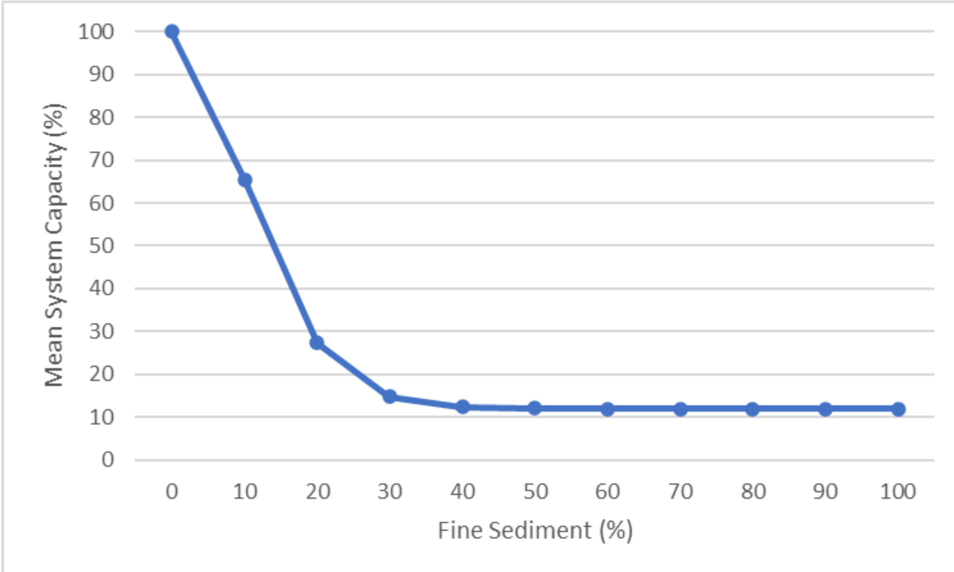


Figure 1: Stressor-response relationship between percent fine sediment and incubation productivity (0-1), interpreted as system capacity in the model. Data are from Beechie et al. (2021).

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

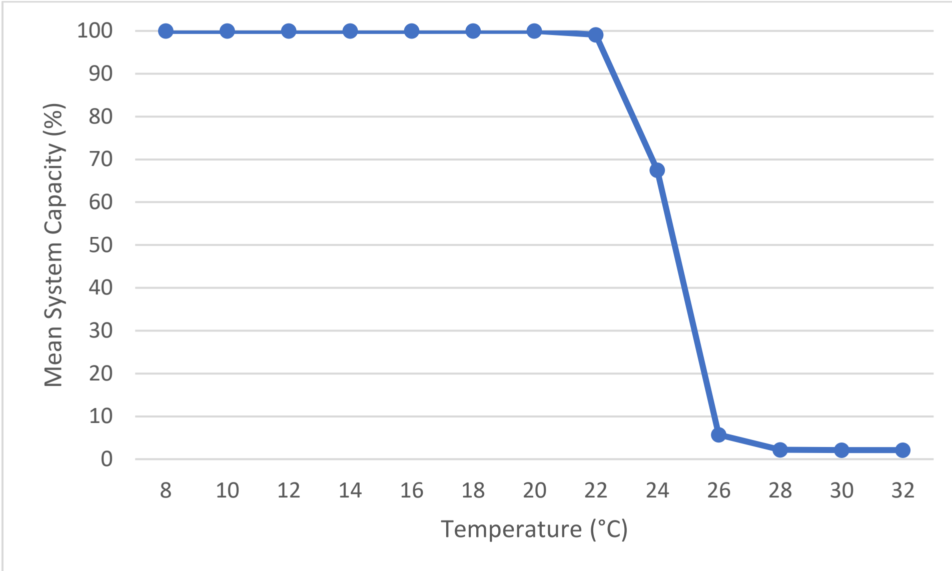


Figure 1: Stressor-response relationship between 7-day average daily maximum stream temperature (°C) and the derived summer rearing productivity multiplier (0-1), interpreted as system capacity in the model. Data are from Beechie et al. (2021).

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.

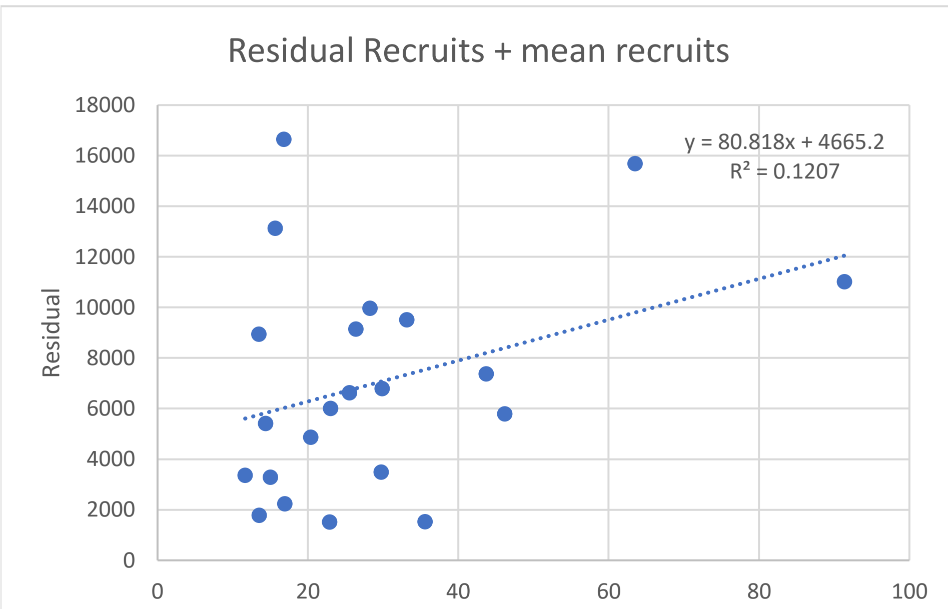
Confidence in SR function: Warkentin et al. (2022) found a weak (R^2 = 0.1207) relationship between residual recruits and mean August flow during spawning (m^3s^{-1}).

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)

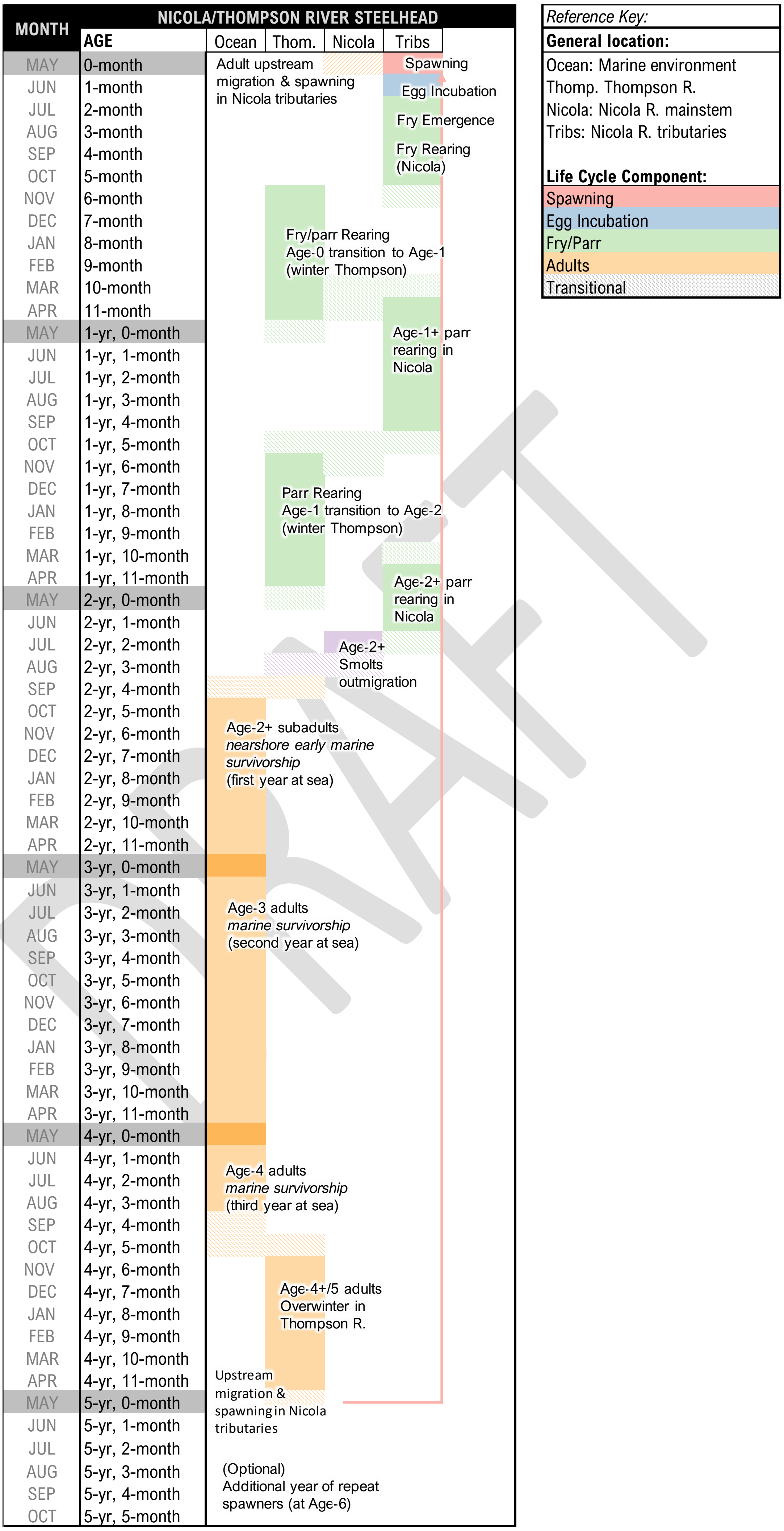
The following summary provides a general overview of the Steelhead life cycle for Nicola/Thompson River populations. Timing of key events is compiled from various sources with preference given to references specific to Nicola Steelhead (Sebastian 1981; McGregor 1986; Korman 2018; Godwin and Krkosek 2022). 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.

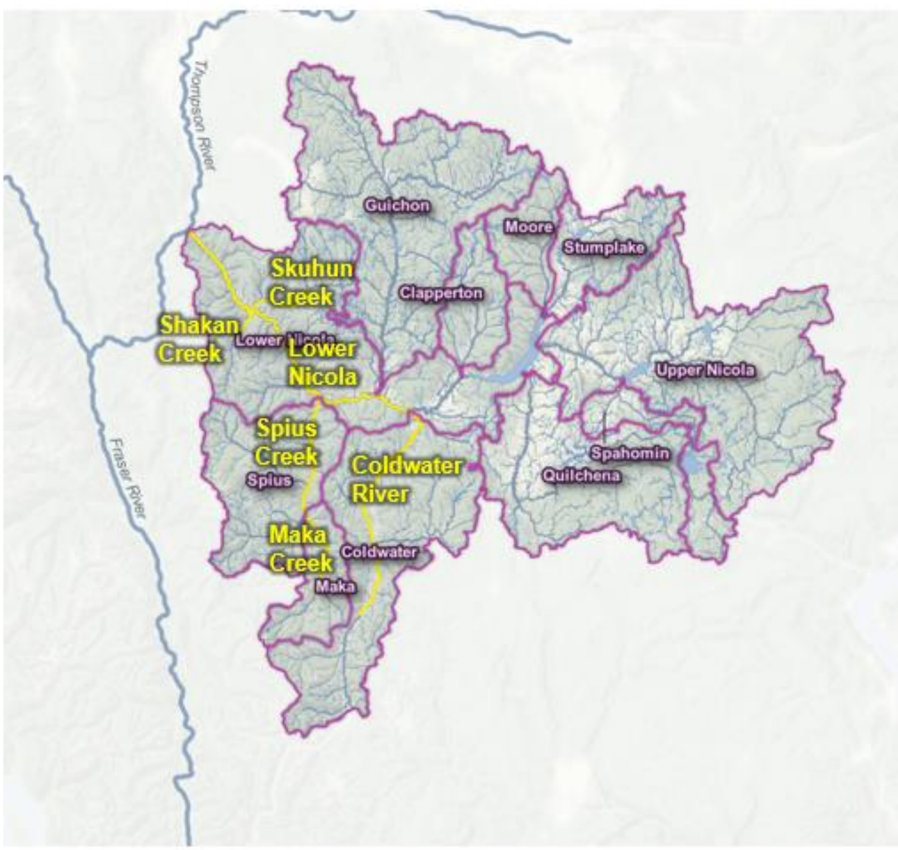


Habitat and Locations

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

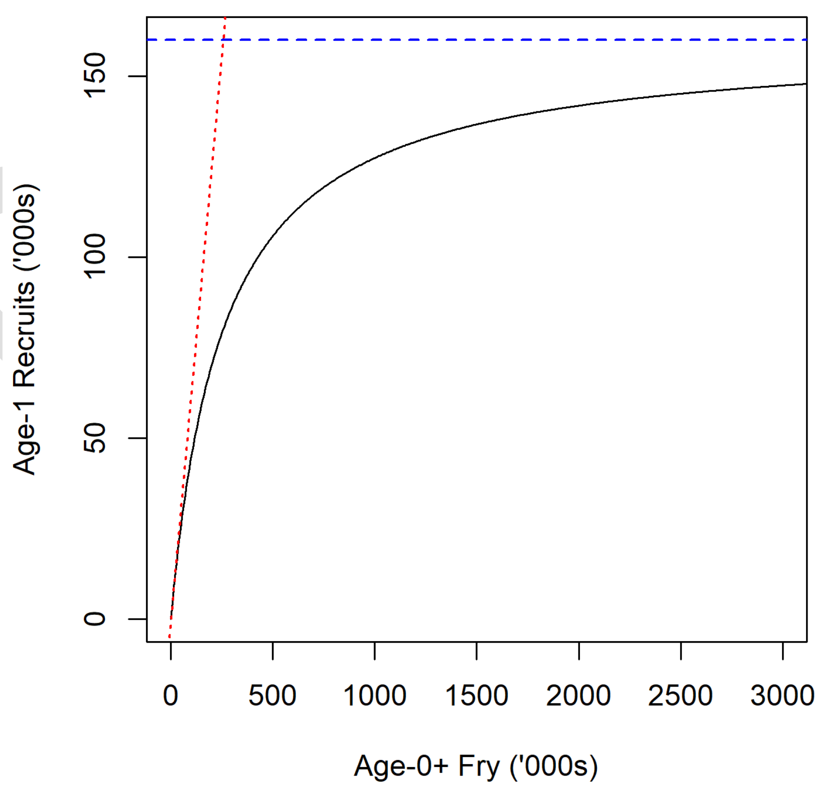


Capacity Estimates

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).

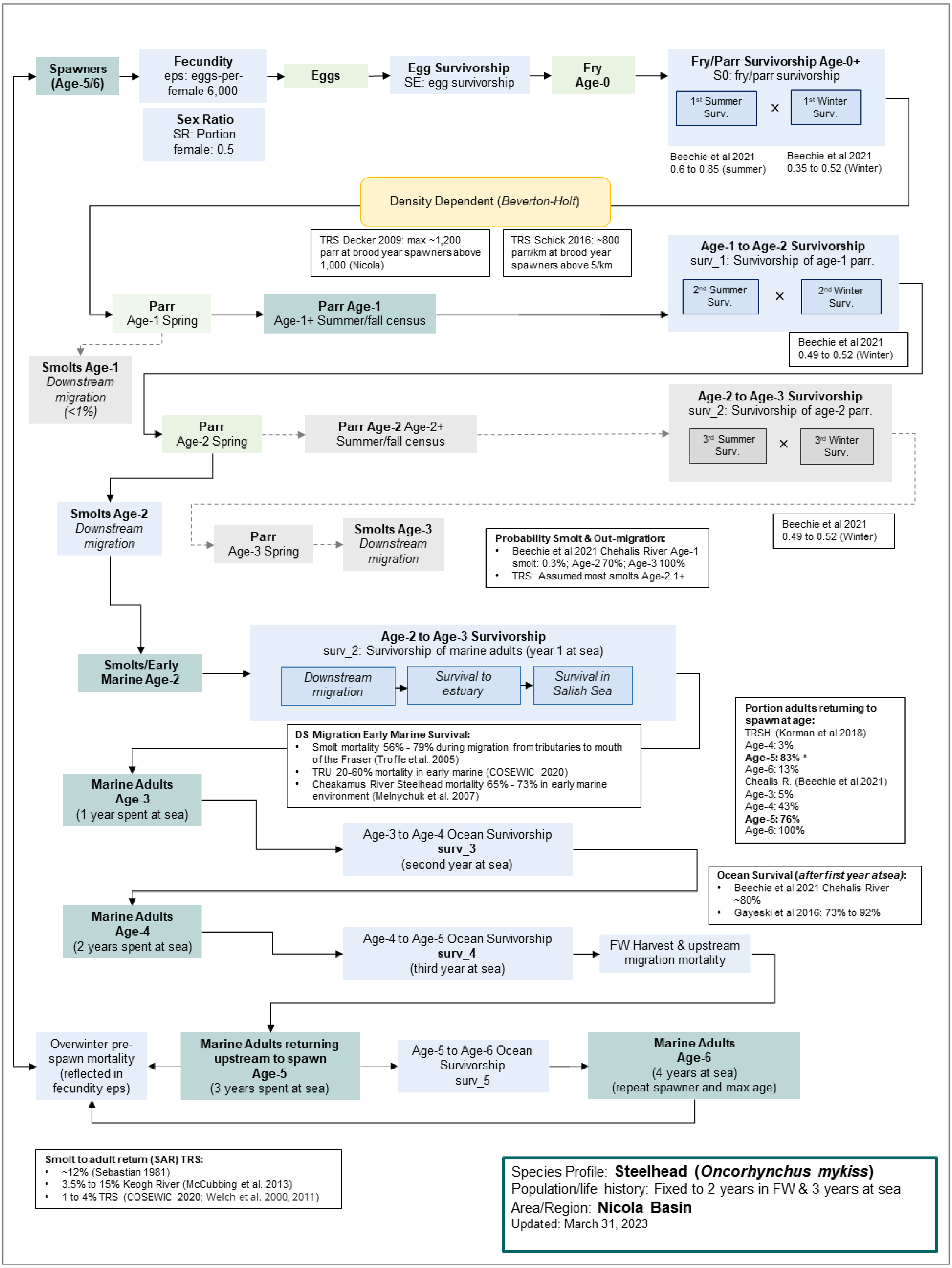
Figure 3. Beverton-Holt function governing density-dependent growth between fry (Age-0) and parr (Age-1) individuals. Capacity set to 160,000 Age-1 parr



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-independent 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).

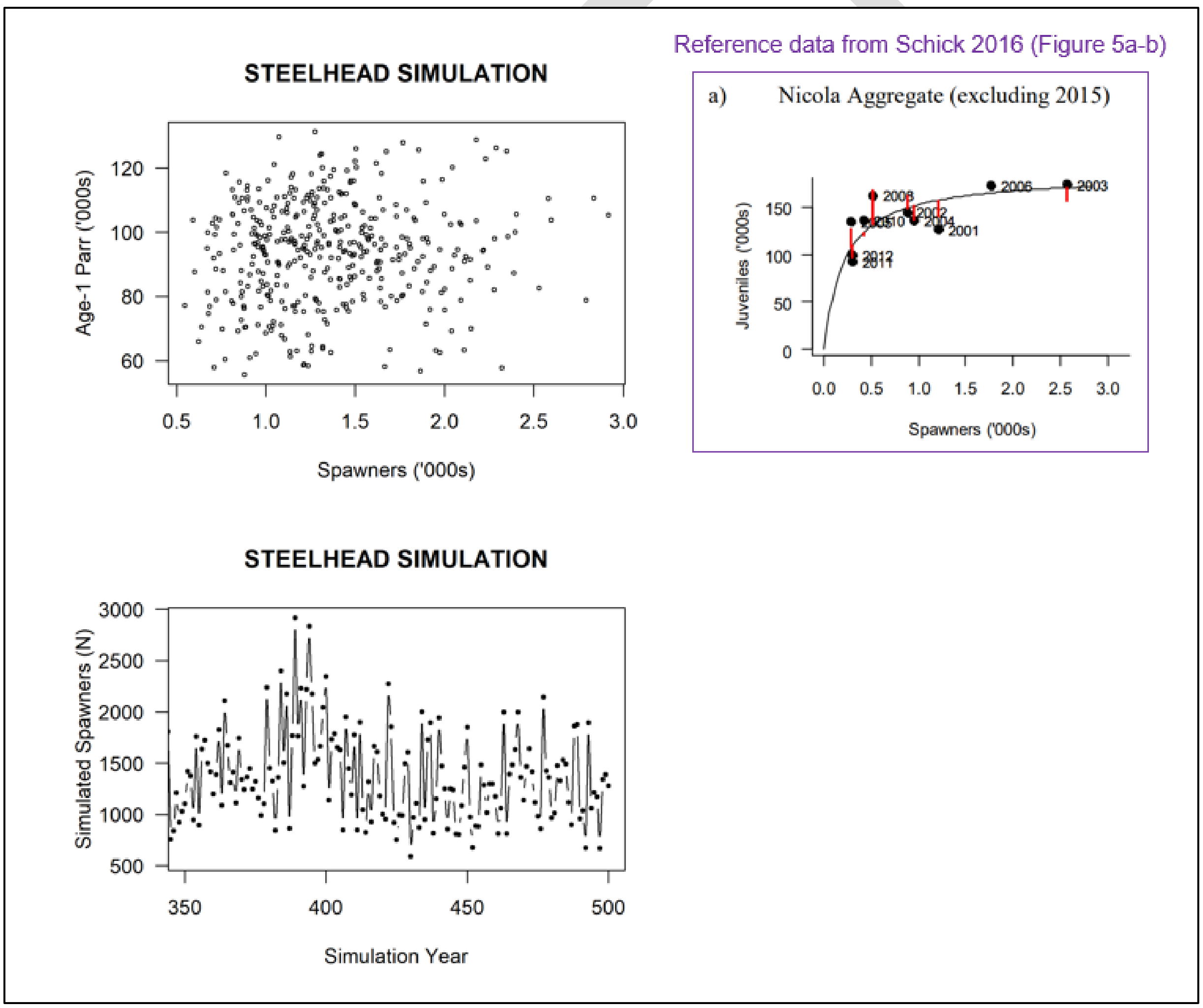
Table 3. Eigen Analysis of the Projection Matrix for Nicola Steelhead

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

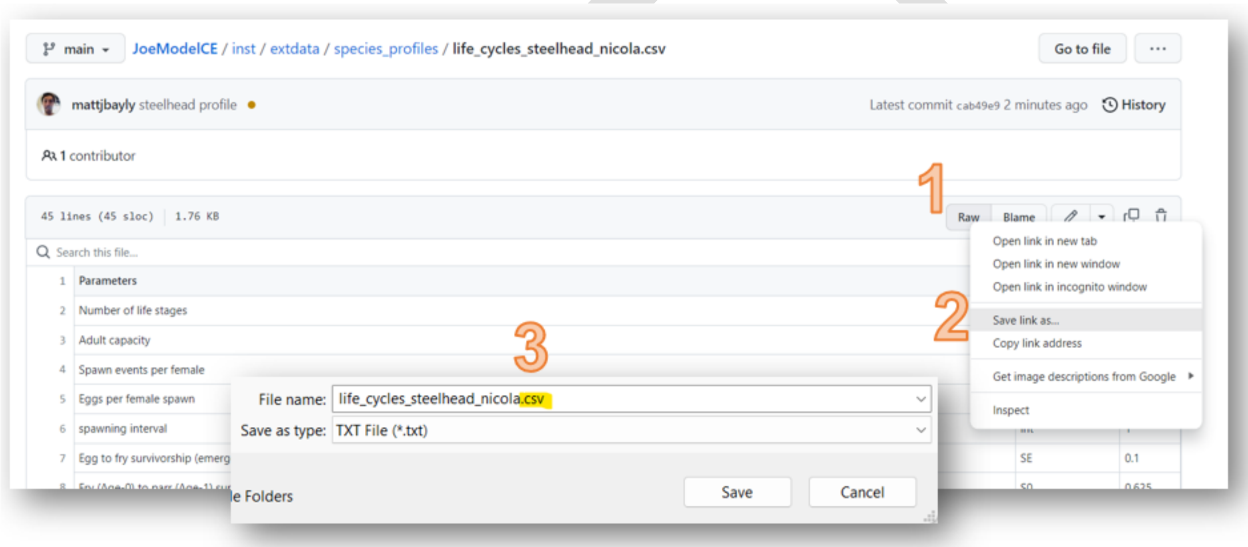
watershed characteristics and condition. Oceanographic survival is also coupled with marine harvest (incidental or fishery-related) and predation (pinnipeds). Stressor-response curves linked to adult survivorship could be created to represent marine survival. The stressor-magnitude value would (presumably) 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).

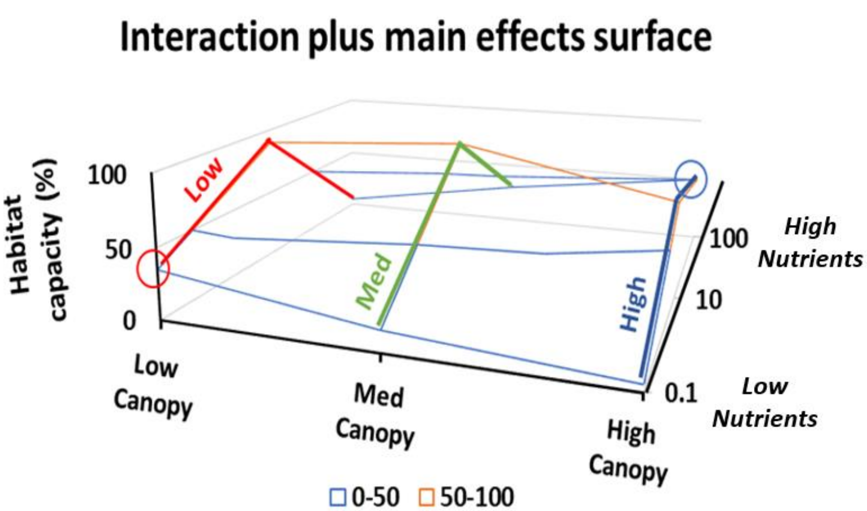
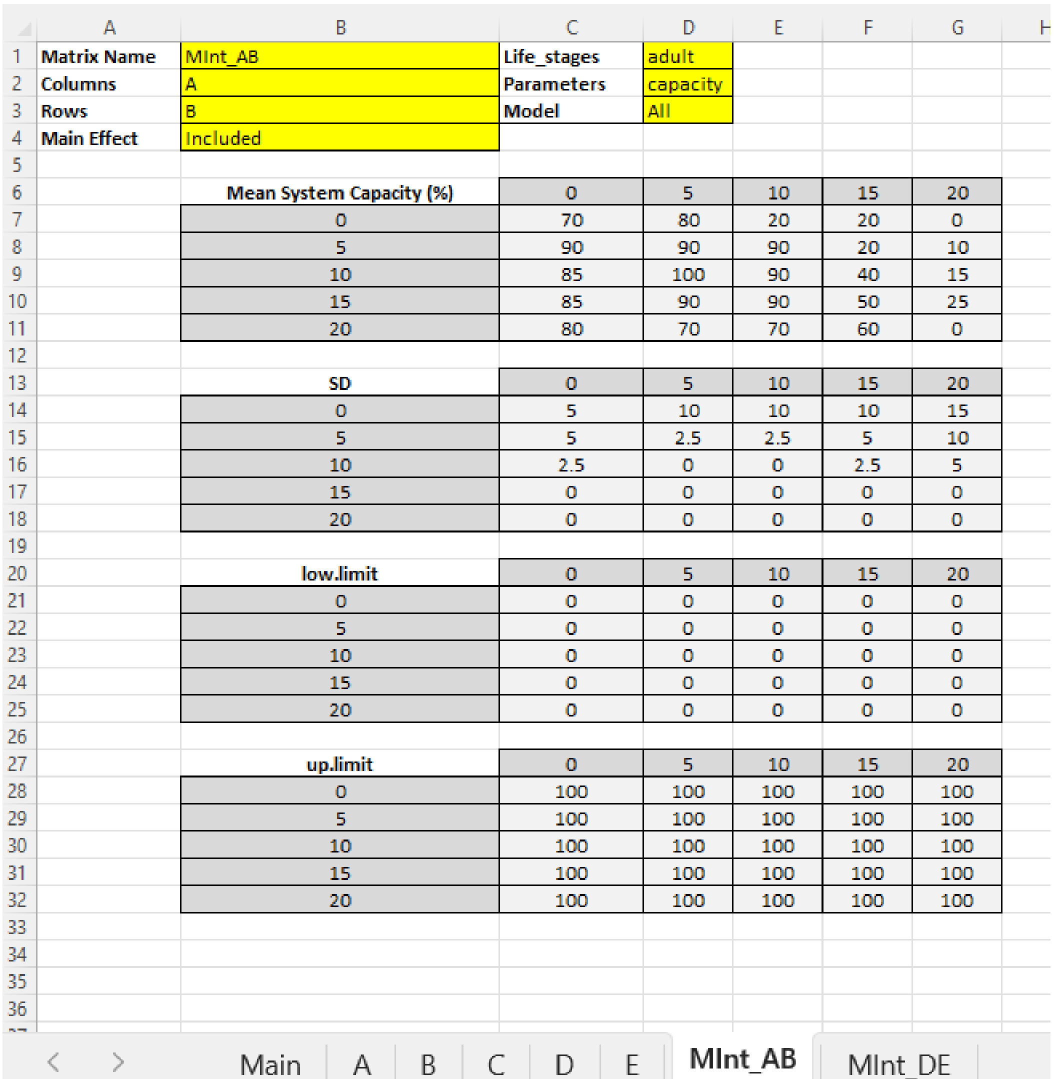


Figure 1. Example interaction surface for the CEMPRA 2-factor interaction matrix between trout capacity canopy cover and nutrients.

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

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:

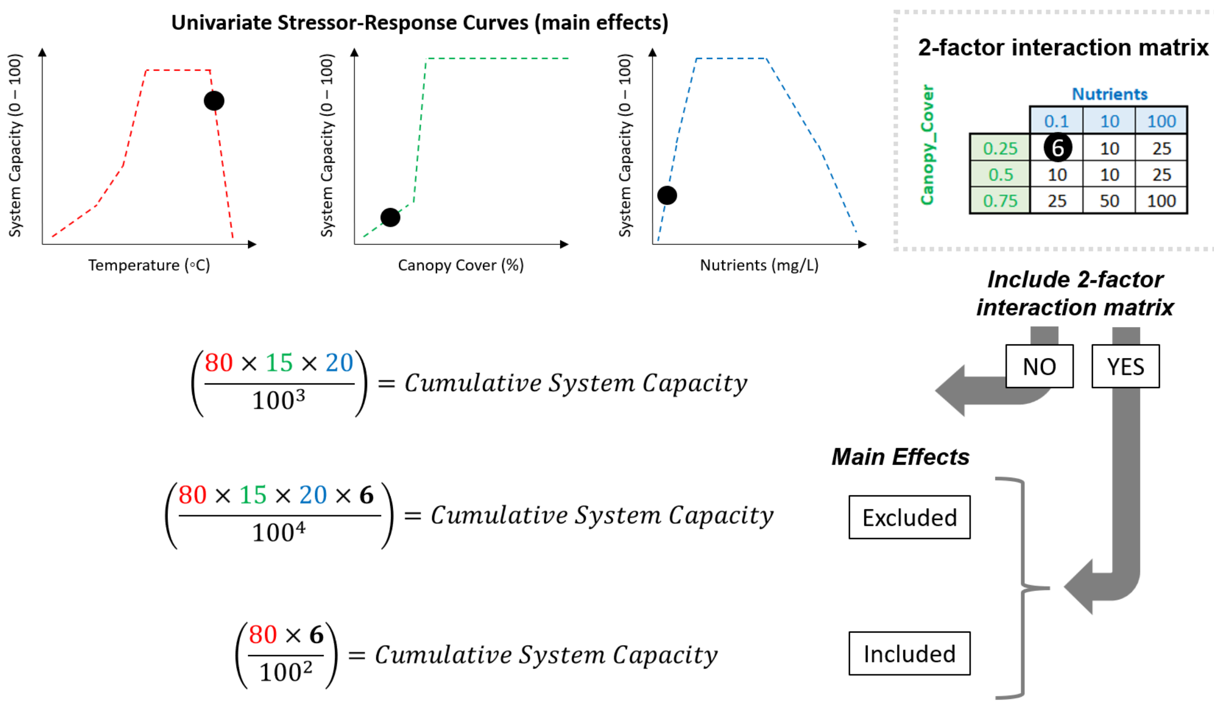


Figure 3. Difference between main effects being included or excluded from 2-factor interaction matrix summary. The Interaction factor for main effects Excluded (X) will be different (in this case lower) than for main effects Included.

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.

1 Appendix E: Socio-economic Evaluation of Restoration Actions

The Joe Model and Life Cycle Model components of the CEMPRA tool primarily focus on status, condition, and relative risk rating(s) among assessment units, scenarios, and stressors, providing insights when formulating management priorities for a watershed or study system. However, First Nations, industry, governing bodies, and conservation initiatives/collaboratives seeking to mitigate stressors within a framework of potential restoration actions need to understand the comparative costs of competing management interventions. To address this need, the socio-economic component of the CEMPRA tool generates an overview of the costs and effectiveness of user-defined management strategies associated with stressor reduction. The socio-economic component attempts to provide a high-level cost-benefit analysis of restoration alternatives, and is designed to facilitate decision-making by quantifying the economic implications of competing restoration strategies.

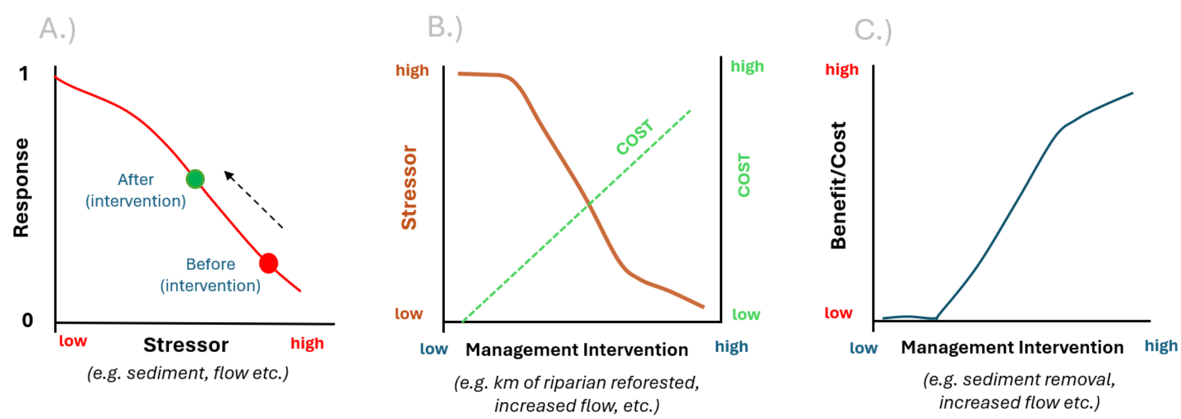


Figure 1. Overview of the linked relationships underlying the socio-economic evaluation of restoration actions in the CEMPRA tool showing a.) reduction in stressor level from a hypothetical management action, following a pre-defined stressor-response function; b.) cost associated with the management action/intervention (intervention-cost function); and c.) the resulting cost-benefit analysis that provides insights into relative trade-offs between restoration actions, stressor reduction, and associated cost.

The socio-economic component of the CEMPRA tool is illustrated in Figure 1. First, working groups consider potential reductions in a stressor from a hypothetical management action (green point in Fig. 1a, brown line in Fig. 1b). For example, in certain circumstances, riparian planting can be applied to reduce stream temperatures (a possible stressor). Next, working groups consider how increasing levels of each restoration action will incur increasing costs (e.g., $/km of stream planted; green line in Fig. 1b). Finally, groups input user-defined restoration scenarios. The tool then runs the scenarios (with or without stochasticity) to calculate the relative change in the Joe Model system capacity scores as well as their associated costs. Comparisons are made between scenarios regarding their ability to reduce stressor levels relative to their respective cost (i.e., relative to a high-level cost-benefit analysis of alternative management actions).

Like the associated stressor-response functions, predictions from the socio-economic modelling component will only be as reliable as the cost and stressor-reduction estimates that users define for a given management interventions, and in many cases, these may amount to structured back-of-the-envelope cost-benefit assessments of hypothetical restoration actions. In these cases, the ranking and prioritization of restoration actions within CEMPRA will not be complete or comprehensive. In these situations, the intent of the tool is to allow users to set potential bounds on the costs and respective benefits of different management options, in a structured framework that allows clarity of assumptions for both simple and complex restoration planning. The socio-economic component is provided as a supplementary decision support tool that forces users to be transparent about the predicted costs and benefits of different management actions, and to confront and define the level of confidence in both costs and benefits; as such it is intended to be informative rather than prescriptive.

The socio-economic component was developed primarily in the context of the restoration of stream ecosystems. Although it may be possible to extend this framework to other systems, the examples that we provide are focused on streams. We emphasize that the socio-economic module is intended to complement the other capabilities of the modelling tool, and is intended as a decision support tool rather than a complete resource for the planning, design, or implementation of a restoration program. It is assumed that users are familiar with the overarching principles of stream restoration and holistic frameworks for restoration planning and prioritization. We recommend guidance from the following resources:

- Roni, P., & Beechie, T. (Eds.). (2012). Stream and Watershed Restoration: A Guide to Restoring Riverine Processes and Habitats. John Wiley & Sons.
- Yochum, S. E., & Reynolds, L. V. (2018). Guidance for stream restoration. US Department of Agriculture, Forest Service, National Stream & Aquatic Ecology Center.
- Gann GD, McDonald T, Walder B, Aronson J, Nelson CR, Jonson J, Hallett JG, Eisenberg C, Guariguata MR, Liu J, Hua F, Echeverria C, Gonzales, EK, Shaw N, Decleer K, Dixon KW. (2019). International principles and standards for the practice of ecological restoration. Second edition. Restoration Ecology S1-S46.
- Yochum, Steven E., Reynolds, Lindsay V. (2020). Guidance for Stream Restoration. US Department of Agriculture, Forest Service; US Department of Interior, Bureau of Land Management; Forest Service National Stream & Aquatic Ecology Center Technical Note TN-102.5. Fort Collins, Colorado.
- Pacific Salmon Foundation. 2023. Playbook to Guide Landscape Recovery Strategies and Priorities for Salmon Habitat Following Major Wildfires. Technical report prepared by EDI Environmental Dynamics Inc. for the Pacific Salmon Foundation. EDI Project ID: 21P0581 (Feb 2024 DRAFT).

1.1 Designing Restoration Action Scenarios

The socio-economic component of CEMPRA largely consists of a template workbook with pre-defined functions to automate calculations. However, it is up the user to define the restoration scenarios that are most applicable to their study system and to populate scenarios with attributes for cost-benefit applications. Part of the value of the socio-economic module is that it forces the user to be explicit and empirical about the expected costs and benefits of expected interventions.

Prior to running restoration scenarios in the socio-economic module, an initial brainstorming session should take place. The purpose of this session is to shortlist the most appropriate restoration actions for evaluation. Working groups should broadly consider target management actions, determine if they are appropriate for modelling or whether they should be evaluated outside of the CEMPRA tool, define an appropriate spatial unit for calculations (see details below) and then think about and define the direct linkages between restoration actions and stressor reductions.

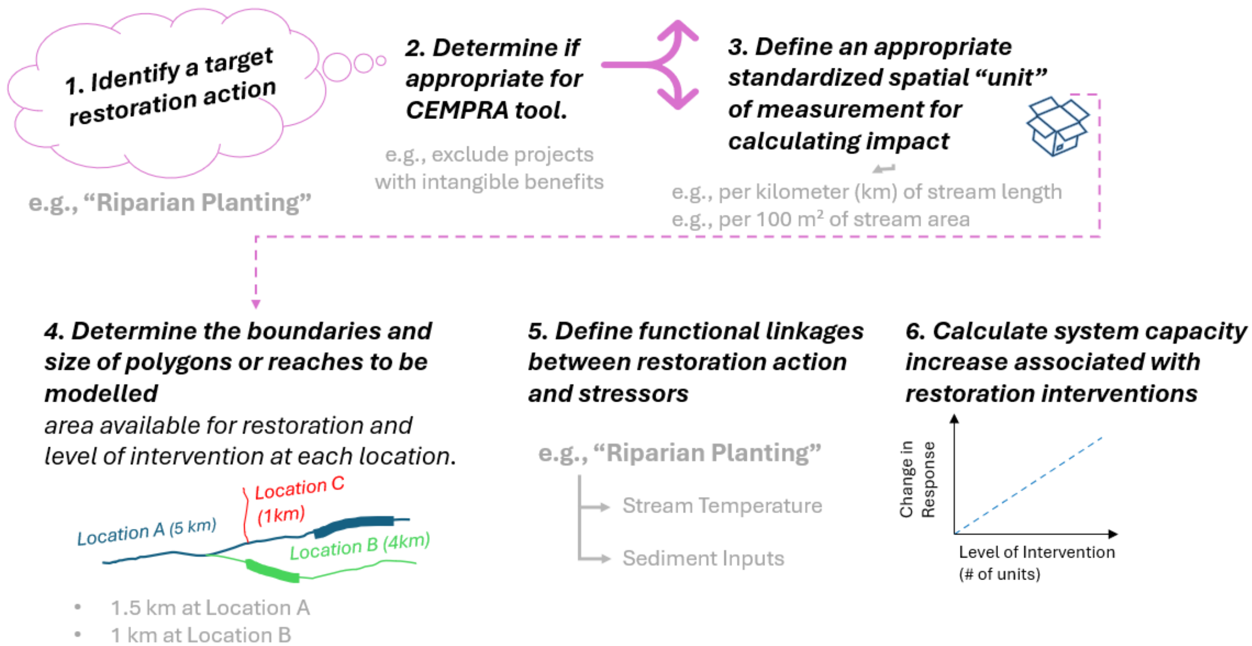


Figure 2 Sequence of steps for identifying the costs and consequences of each restoration action type evaluated in the socio-economic component of CEMPRA.

The sequence of steps for defining the cost and effects of recovery interventions before running scenarios in the socio-economic component of the tool is outlined in Figure 2.

1. **Identify target restoration actions**: Working through the costs and benefits of restoration action types one at a time is recommended. Examples of restoration action types may include off-channel habitat creation, riparian planting, barrier removal, gravel augmentation, the addition of large woody debris, the installation of beaver dam analogues, etc.

2. **Determine if the target restoration action is appropriate for this tool:** Various action types may be more or less suitable for evaluation in the socio-economic module. The tool works best with concrete actions that can be explicitly quantified in terms of system capacity, and unsuited to evaluate actions that provide abstract or intangible benefits. It will likely be difficult to apply to management actions that are highly complex, overly context-dependent, or can only be qualitatively described at a high level. For example, hatchery interventions may be a valuable action type for a target watershed/population, but it may be challenging to evaluate within the module because of the difficulty including very real impacts on genetic diversity or hybridization with wild stocks. Similarly, actions like public education, large barrier/dam removals, etc., while essential components of restoration planning, may be inappropriate.
3. **Define an appropriate standardized unit of measurement for calculating the impact of each action type**: For each type of intervention, users must define a representative unit for calculating impact. Spatial units may be defined as linear distances (e.g., kilometres of stream restored), areas (e.g., m^2), etc. The intent is to perform cost-benefit calculations per measurement unit for each action type. For example, an appropriate spatial unit for riparian planting could be a linear distance (e.g., per kilometre of stream planted), or an area (buffer width x length) depending on application. Off-channel habitat development, on the other hand, could be expressed in terms of the area of habitat created (e.g., m^2). Point features such as beaver dam analogues (BDAs) and/or LWD placements might be expressed in terms of total area, or as an absolute value (i.e., number of BDAs) and then converted into a linear density (e.g., number of units per kilometre of stream).
4. **Define the boundaries and size of each location (e.g., spatial polygon or linear reach):** The system (e.g., stream or watershed) must be divided into spatial units (e.g., polygons or reaches) that collectively make up the target system (e.g., stream or watershed). Users must also define the relative size of each spatial unit (referred to hereafter as a "location") for appropriate weighting. For example, consider evaluating three locations (defined as stream reaches or subbasins). Assume location A contains 5 km of stream, location B contains 4 km, and location C contains 1 km. If a restoration program did 1 km of riparian planting at each location, we would expect that the relative impact would be greater for location C relative to location A (ignoring their interconnectivity in a hydrologic network). Similarly, if we were to consider the relative benefit of a program that created off-channel habitat, we would want to know the relative habitat area of each location, to allow calculation of the relative decrease in the stressor represented by off-channel habitat loss (Figure 3). The goal here is to convert each of the restoration interventions into location-specific stressor reduction estimates to perform cost-benefit calculations (e.g., kilometres of stream planted per total kilometres of stream at Location X (%), area of off-channel habitat created relative to the total habitat area at Location X (%), number of BDAs per kilometre, number of pieces of LWD per 100 m of stream, volume (m^3) of LWD per length of stream etc.).

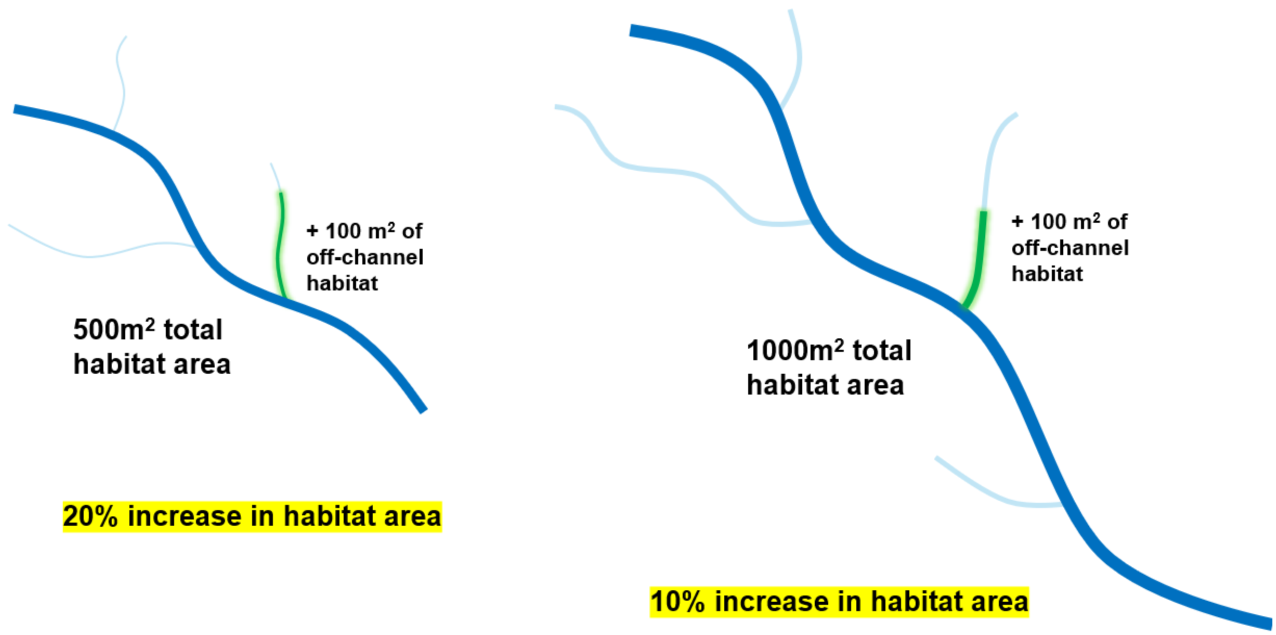


Figure 3. Addition of off-channel habitat scaled by total habitat area pre-restoration.

5. **Define Functional Linkages Between Restoration Actions and Stressors**: Linkages between restoration action types and stressors specify how each intervention can decrease stressor magnitudes and (presumably) increase system capacity. Note that restoration actions may be linked to one or more stressors. For example, riparian planting might decrease summer stream temperatures, but may also reduce sediment or nutrient inputs, thereby linking to multiple stressors.

6. **Calculate System Capacity Increase Associated With Restoration Interventions (on a per unit area basis)**: The final component of data input preparation (not including estimation of costs; see below) involves the creation of custom functions linking the magnitude of management intervention to reduction in the target stressor (*stressor reduction functions*, e.g., defining how stream temperature decreases with the extent of riparian planting). This exercise forces the user to be explicit about the expected response to the management intervention and confront and define any uncertainty. All estimates and calculations are performed on a per-unit-area basis (e.g., m^2). The input workbook design is flexible so that restoration interventions can be linked to stressor magnitude levels or directly to stressor response values. Stressor reduction functions are discussed in further detail in the next section.

*Remember, projections using the socio-economic component of the CEMPRA tool are only as reliable as the data that go into them. Using restoration benefit and cost estimates from the literature will inevitably entail considerable error, and projection error will likely increase with the complexity of restoration scenarios. Users need to remember that any uncertainty in cost and stressor reduction functions for management interventions will be additive to **existing** uncertainties associated with underlying SR functions and stressor magnitude estimates in different spatial polygons. Inferences should be tempered accordingly, and when uncertainty is high, projections should be recognized as back-of-the-envelope calculations or hypotheses.*

1.2 Estimating Costs of Management Actions

The socio-economic module of CEMPRA ***requires*** cost estimates for each restoration action type on a per-unit basis. Again, this process forces the user to be explicit about the anticipated costs of restoration interventions, as well as their potential effectiveness. Cost estimates can be included as a dollar amount (with uncertainty) or included semi-quantitatively with a customized scoring system (e.g., 1 = low, 2.5 = moderate, 5 = high etc.). Cost estimates are provided on a per-unit basis (e.g., cost per BDA, cost per kilometer of riparian stream bank planting, or cost per m² of off channel-habitat creation, etc.). Location-specific cost modifiers can also be provided for local adjustments from global means, i.e., when site access is particularly bad, off-channel habitat construction costs might be 50% higher than the global mean (cost multiplier of 1.5).

1.3 Socio-economic Input Excel Workbook

The socio-economic input workbook is supplied to CEMPRA as a separate Excel workbook. Each worksheet within the Excel workbook contains information for each type of planned management action, the magnitude of the action (intervention level) at each location, the ability of each action to reduce a stressor and the corresponding stressor-response reduction, and the per-unit cost of each intervention (i.e., all of the key attributes described above).

A sample Socio-Economic Excel workbook can be found here:
https://essa.shinyapps.io/CEMPRAShiny/_w_c5a9a69b/demo/socio_economic_input.xlsx

Worksheets:

- **Management Actions:** Provides an overview of the management interventions that have been shortlisted for evaluation. This workbook is used to define action-specific attributes such as the cost measurement unit and cost per unit for each management action type.
- **Location Implementation**: This workbook defines the magnitude of the proposed management actions for each location. Each line in the workbook provides attributes for each specific management action applied to each specific location (i.e., the level of intervention by tributary or reach, depending on the scale at which locations are defined). The workbook also contains estimates for the relative size of each location (with respect to each management action type).
- **Location Size Attributes**: Cumulative effects modelling with the Joe Model focuses on the relative status and condition among user-defined polygons (e.g., watersheds), but it does not explicitly consider habitat area or the size of each polygon. This worksheet allows users to specify location-specific size and area attributes. Defining these attributes becomes important when evaluating stressor reduction from a given intervention, since the habitat stressor is usually expressed as percent loss or gain relative to the total area of habitat available in a polygon (location).
- **Stressor Reduction**: The stressor reduction workbook defines the relationship between each management action type and stressor levels. Each row in the stressor reduction

workbook must have a unique identifier in the "Stress Reduction Curve ID" column (e.g., SR1, SR2, SR3… etc.) that links the restoration intervention to a particular stressor. Subsequent Excel worksheets should be labelled to match the IDs in this column (e.g., SR1, SR2… etc.). The "SR" "#" worksheets define the functional relationships between each stressor and restoration action.

- **SR1**: Action: "Riparian Planting" and Stressor: "August Stream Temperature".
- **SR2**: Action: "Riparian Planting" and Stressor: "Riparian Habitat Condition".
- **SR3**: Action: "Off Channel Habitat Creation" and Stressor: "Habitat Loss".
- **SR#**: …

1.3.1 Management Actions Excel Worksheet

Management Actions		*Management Cost (defined on a per unit basis)*				*Bulk Discounts Thresholds for Economies of Scale (optional)*			
Management Action Name	**Measurement Unit**	**Mean Cost per Unit**	**SD of Cost per Unit**	**Lower Limit of Cost per Unit**	**Upper Limit of Cost per Unit**	Bulk Discount Units Threshold (Level 1)	Bulk Discount Price Multiplier (Level 1)	Bulk Discount Units Threshold (Level 2)	Bulk Discount Price Multiplier (Level 2)
Beaver Dam Analogues	#	$1,000	$1,000	$250	$15,000	10.00	0.80		
Off Channel Habitat	m^2	$25	$50	$12	$200	1000.00	0.90		
Riparian Planting 2m wide	km	$1,500	$2,000	$1,000	$20,000				
Riparian Planting 10m wide	km	$30,000	$15,000	$5,000	$65,000				

Management Actions | Location Implementation | Location Size Attributes | Stressor Reduction | SR1 | SR2 | SR3 | SR4 | SR

Figure 4a. Example of the CEMPRA socio-economic input worksheet for the 'Management Actions' with four unique action types represented in the simulation.

Create a new row for each unique management action type. For each unique management action, define the following features:

Management Action Core Attributes:

- **Management Action Name:** The unique name for a management action. Ensure that the spelling is consistent across all worksheets. Avoid the use of special characters or symbols.
- **Representative Measurement Unit:** Define the measurement unit for the target restoration action type. The measurement unit should be defined as the most appropriate metric for each management intervention. For example, linear developments (e.g., bank stabilization, riparian planting) might reference units such as meters (m) or kilometres (km) of stream length. Area-based developments (e.g., riparian planting, off-channel habitat development, spawning channels) could reference meters squared (m^2), hectares (ha) or even aggregates (such as 100 m^2) of wetted stream area. Point features that

consist of discrete structures could simply use feature counts (e.g., number of BDAs, LWD, culverts, etc.).

Management Action Cost Attributes:

- **Mean Cost per Measurement Unit:** Define the mean cost to implement each management action on a per-measurement unit basis. For example, if the measurement unit for riparian planting was 1 kilometre of stream, then the mean cost per unit would be defined as the cost of implementing riparian planting for one kilometre of stream length (although this could also be treated as an area, e.g. length x riparian buffer width).
- **SD of Cost per Unit (*optional*):** Define the uncertainty in the cost estimate (as the standard deviation of cost) for stochastic simulations. Stochastic simulations will sample cost estimates for each location following a normal distribution with the user-defined mean and SD. This is an optional feature - if this cell is left blank then the program will assume no cost uncertainty.
- **Lower Limit of Cost per Unit (*optional*)**: Define the lower limit of cost per unit for stochastic simulations. Regardless of the user-supplied SD value, the cost sample in stochastic simulations will never fall below this value. Note that this is also an optional feature and will only be used if a SD is specified.
- **Upper Limit of Cost per Unit (*optional*)**: Define the upper limit of cost per unit for stochastic simulations. Regardless of the user-supplied SD value, the cost sample in stochastic simulations will never exceed this value. Note that this is also an optional feature and will only be used if a SD is specified.

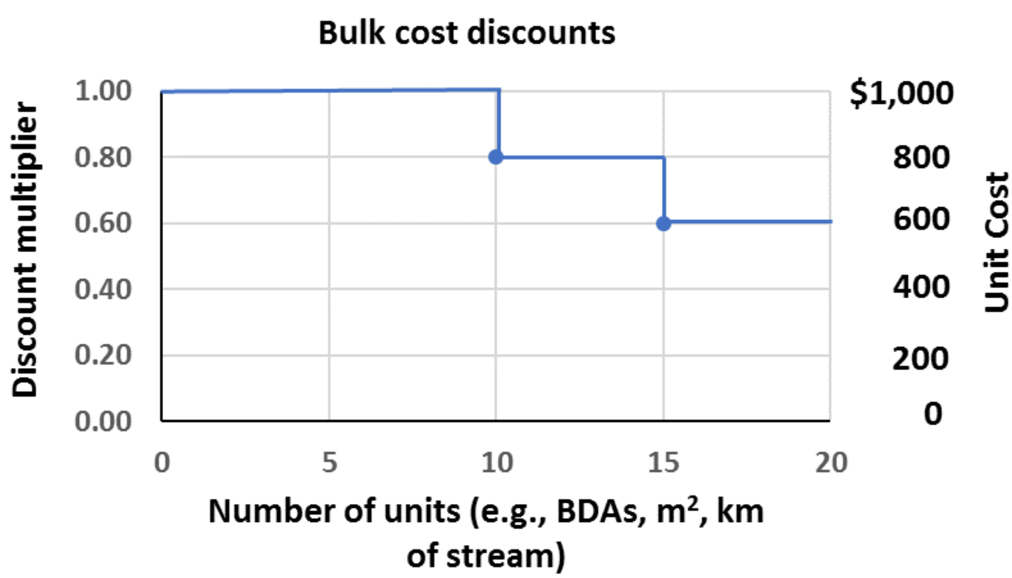


Figure 5b. Illustration of how unit costs can change with economies of scale using the example discount multipliers for BDAs in Fig. 3a. The unit cost for each BDA is discounted by 20% for each multiple of 10 BDAs.

Bulk Discounts Thresholds for Economies of Scale (*optional*)

This feature provides the option to define thresholds for bulk discounts and possible economies of scale (i.e., decreased costs with larger projects; see Fig. 3b). The base mean cost of each management action will reference the value specified in column C. However, suppose the number of units in the "Location Implementation" tab exceeds a bulk discount unit threshold specified. In that case, the bulk discount cost multiplier (0 – 1) will be applied to the mean cost per unit to reduce the unit cost. For example, if BDAs are estimated to cost an average of $500 per unit (without the bulk discount) but are only expected to cost an average of $400 per unit if more than 10 units can be constructed, then the "Bulk Discount Units Threshold (Level 1)" would be set to 10 and the "Bulk Discount Price Multiplier (Level 1)" would be set to 0.8 ($400/$500). The workbook lets working groups specify two tiers for economies of scale: Level 1 and Level 2.

- **Bulk Discount Units Threshold (Level 1):** Unit threshold required to activate Level 1 cost multiplier.
- **Bulk Discount Price Multiplier (Level 1):** Mean cost multiplier once Level 1 threshold is achieved.
- **Bulk Discount Units Threshold (Level 2):** Unit threshold required to activate Level 2 cost multiplier.
- **Bulk Discount Price Multiplier (Level 2):** Mean cost multiplier once Level 2 threshold is achieved.

Management Action Subcategories:

If a management action type consists of two or more subcategories, create multiple rows to represent each unique variation of the target management action (Fig. 3a). For example, riparian planting might be split into two categories: a.) riparian planting within two meters of the stream bank and b.) riparian planting within ten meters of the stream bank. It is recommended (if possible) to represent management action variants as separate rows to simplify subsequent calculations (e.g., Riparian Planting 2m; Riparian Planting 10m).

1.3.2 Location Implementation Worksheet

The Location Implementation Excel worksheet (Fig. 4) defines the level of proposed management actions (i.e., level of intervention) for each restoration action type associated with each spatial unit (location). Each line in the Location Implementation workbook provides attributes for a specific management action type applied ***at a specific location***. The matching "Location Size Attributes" worksheet (Fig. 5) contains estimates of the absolute size of each location (i.e., stream length or habitat area) and is described in detail in the following section.

- **Location ID**: The unique location ID field (or HUC ID field) associated with the stressor magnitude input workbook and locations GIS polygon layer for mapping in CEMPRA.
- **Location Name**: Optional but recommended to include for convenience (e.g., Rock Creek). All computational data lookups use the Location ID field.

- **Management Action Name**: Name of the management action referenced from the Management Actions input worksheet. Ensure spelling/punctuation exactly matches between worksheets. Include separate rows for each management action to be applied at a given location.
- **Representative Measurement Unit**: Optional (column can be left blank). The measurement unit from the Management Actions worksheet for the target restoration action type is repeated here for convenience (and personal reference when filling out the spreadsheet).

Management Action Intervention Attributes: Define the level of restoration at each location (in terms of the measurement of units designated in the Management Actions Worksheet). These columns define the location-specific extent of modelled restoration actions. Mean, SD, and lower/upper limit columns are provided to represent a range of possible values. The SD column can be set to zero to run simulations without stochasticity.

- **Mean Number of Units Restored (i.e., area in m^2, number of BDAs, etc.):** Provide a numeric value using the measurement units that reference the specific restoration action type (e.g., number of BDAs to install, kilometres of stream to implement riparian planting, etc.). Try to define a mean or average value for the given location.
- **SD Number of Units:** Optionally, users can define uncertainty in the level of restoration action to introduce stochasticity into the simulation. Set this value to zero to reference the mean value without stochasticity.
- **Lower Limit for Number of Units**: Define the lower limit for stochastic simulations.
- **Upper Limit of Cost per Unit**: Define the upper limit for stochastic simulations.
- **Location Cost Multiplier (optional):** Optionally define a location cost multiplier for a specific location. This column should only be used if it is believed that a specific restoration action will be more costly (or significantly cheaper) if applied at a specific location (e.g., one with poor vs. good access, on-site building materials, etc.). The column can be left blank if reference unit costs are considered accurate. Any location cost multiplier will be used to adjust the 'Mean Cost per Unit' (in the Management Actions worksheet) at the specific location (similar to the "Bulk discount multiplier"). For example, to reduce cost by 10%, set the location cost multiplier to 0.9 ('Mean Cost per Unit' * 0.9 = a 10% discount, or 90% of the original cost); to increase cost, set the value to something greater than 1 (e.g., a value of 1.2 will increase costs by 20% at a given location).
- **Location Effect Multiplier (optional):** Optionally define a location effect multiplier for a specific location. This column should only be used if it is believed that a specific restoration action will be significantly more or less effective at a given location. We don't expect this to be a common feature. However, if it's decided that a certain management action would only be half as effective at location relative to other locations, then use a value of 0.5. Conversely, if a management action is expected to be twice as effective at a given location, then a value of 2 could be provided. The location effect multiplier will be applied to the mean number of units restored.

Location Attributes:		**Management Action Intervention:** Define the level of restoration at each location (in terms of number of units from the Management Actions Worksheet).						**Other attributes:** location and restoration action modifers	
Location ID	**Location Name**	**Management Action Name**	**Measurement Unit**	**Mean Number of Units Restored**	**SD Number of Units**	**Lower Limit for Number of Units**	**Upper Limit for Number of Units**	**Location Cost Multiplier**	**Location Effect Multiplier**
A	Tributary A	Riparian Planting 2m wide	km	2	0.5	0	2	1	1
B	Stream B	Riparian Planting 2m wide	km	3.5	0.9	0	3.5	1	1
A	Tributary A	BDAs	#	3	5	0	10	1.1	1
A	Tributary A	Off Channel Habitat	m^2	500	100	100	500	0.95	1
B	Stream B	Off Channel Habitat	m^2	2,000	375	500	2,000	1	1
C	Location C	Riparian Planting 10m wide	km	5	1	1	5	0.9	1

Figure 6. Example of the Location Implementation worksheet for CEMPRA socio-economic modelling.

1.3.3 Location Size Attributes Worksheet

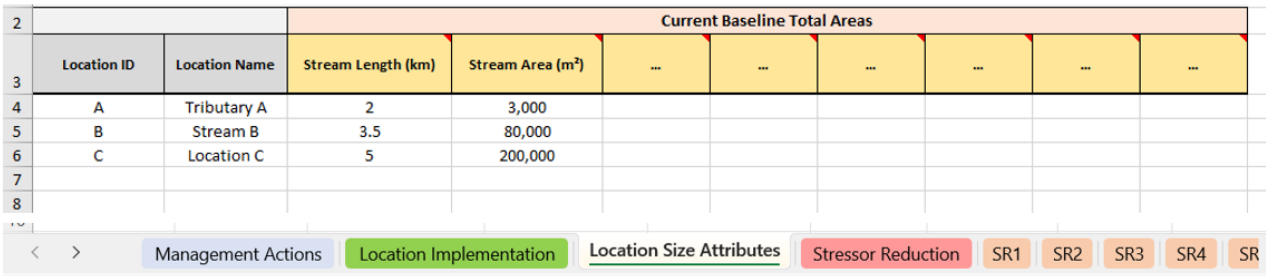
The Joe Model focuses on the relative status and condition among locations or spatial polygons, but it does not explicitly consider habitat area or the size of each polygon or spatial unit (e.g., location, HUC, or reach). Defining the absolute quantity (or extent) of a restoration action relative to the size of the location or spatial unit becomes essential when evaluating the relative impact and cost of the intervention. This worksheet allows users to specify location-specific size and area attributes (for both the restoration intervention and the location/polygon where it takes place) so that the socio-economic module can calculate stressor reduction potential.

The yellow highlighted attribute area columns represent the current (baseline) area/extent of habitat features that are targeted for restoration such as stream length, stream area, current off-channel habitat, total spawning habitat, total pool habitat, etc. Columns for three of the most common habitat features including total stream length (which could be increased by barrier removal), total stream area, and off-channel habitat are included by default, but users can define their own custom column names to replace the "..." placeholder values in adjacent columns; each column the user defines should be associated with at least one specific restoration action type included in the Management Actions worksheet, and also match the associated habitat measurement units. The defined area/extent attributes are then used as the current baseline condition to convert location-specific restoration actions (defined in the Location Implementation worksheet) into a standardized restoration effort per area associated with each intervention (e.g., # of BDAs per kilometre of stream; total length of riparian planting relative to the total stream length, total off-channel habitat created relative to the current quantity of off-channel habitat etc.). Location-specific stressor reductions are then calculated by linking area-standardized restoration effort to stressor levels using stressor-reduction functions, as described in section 1.3.4 below.

Table 1. Example pairings of spatial units for popular management action types, corresponding spatial units for management actions, spatial units to represent the size of each location/polygon, and the corresponding restoration effort per area metric for linking habitat restoration to stressor reduction.

Management Action Name	Management Action Spatial Measurement Unit	Location Total Area or Length Unit (suggested values)	Restoration Effort per Unit Area
Riparian Planting	km planted	km of stream within the location or polygon	km planted per km of stream
Off Channel Habitat	m^2 of off-channel habitat created	Total Current Off-Channel Habitat m^2	Ratio of *new:current* off-channel habitat
BDA	Number of BDAs (#)	km of stream within the location or polygon	# of BDAs / km of stream (density)
LWD	Number of LWD (#)	km of stream within the location or polygon	# of LWD / km of stream (density)

- **Location ID**: The unique location ID field (or HUC ID field) associated with the stressor magnitude input workbook and locations GIS polygon layer.
- **Location Name**: This is optional, but specifying relevant labels (e.g., Rock Creek) is recommended to for convenience in keeping track of restoration sites. However, all data lookups use the Location ID field above rather than the location name.
- **Yellow Highlighted Columns**: Change or modify the name of the yellow highlighted columns to define the current area, length, or other metric of baseline extent of habitat associated with the target restoration actions; these are user-defined and will vary depending on the habitat types targeted for restoration (e.g., total length of stream if removing barriers; or spawning, rearing, etc. habitat if restoration is life-stage-specific). Ensure that column names in columns C:J exactly match the values used in column D (location baseline size scaling column) in the "Stressor Reduction" worksheet. Use columns C and D as examples.
    - Stream length (km): Sometimes stream length might be a valuable unit to use to represent the size of each location (e.g., riparian planting is represented as length of stream planted relative to total stream length)
    - Stream area (m^2): Common unit for in-stream restoration projects (e.g., off-channel habitat and side channel creation could be expressed relative to total stream area at a location)



		Current Baseline Total Areas							
Location ID	Location Name	Stream Length (km)	Stream Area (m²)	...	...	...	...	...	...
A	Tributary A	2	3,000						
B	Stream B	3.5	80,000						
C	Location C	5	200,000						

Figure 7. Location Size Attributes worksheet for stressor reduction calculations

1.3.4 Stressor Reduction Worksheet

The stressor reduction workbook (see Figure 7 below) defines the relationship between each management action type and the predicted reduction in stressor level. This can be thought of as defining novel "stressor-response" functions where the management intervention is the "stressor" (x-axis), and the stressor becomes the response (y-axis). Each row in the stressor reduction workbook must have a unique identifier in the "Stress Reduction Curve ID" column (e.g., SR1, SR2, SR3… etc.) that is associated with a specific stressor being affected by a management intervention. These identifiers should exactly match the names of the associated "SR#" Excel worksheets that define each Stressor Reduction function in more detail (see section 1.3.7 below). Note that each management action may affect more than one stressor, resulting in multiple rows (and therefore SR# worksheets) for a given intervention.

Restoration effort per unit area is the x-axis on all stressor reduction functions, and it links the management action to stressor reductions (y-axis). Restoration effort per unit area (or length) scales the absolute quantity of restoration effort to a standardized unit of area (or length). For example, the total number of pieces of LWD placed at a location will commonly be divided by the total stream length at the location to convert # of LWD placements into # LWD placements per km of stream. Expressing restoration action in terms of "densities" (i.e., effort per area or length) is essential to standardize stressor reduction functions across restoration scenarios.

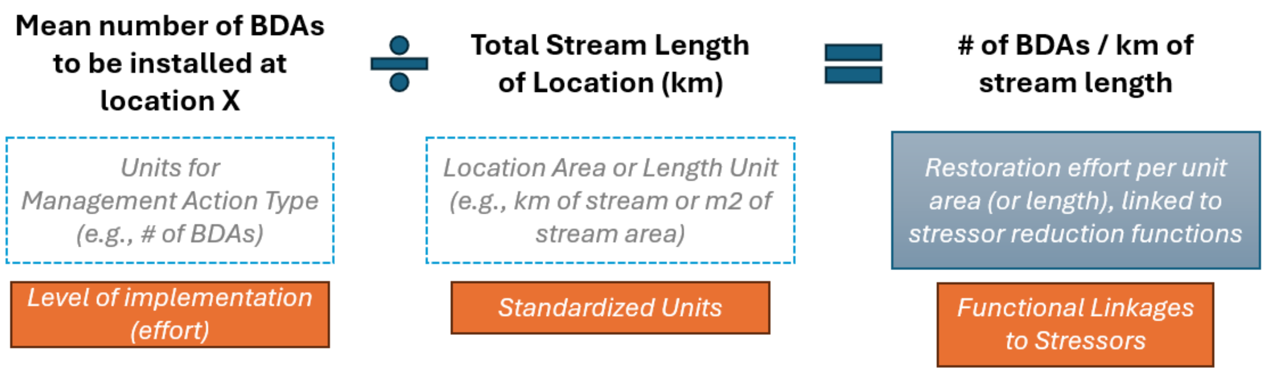


Figure 8. Derived restoration effort per unit area (or length) metric to link scale of restoration action at each location to stressor reduction functions.

- **Stress Reduction Curve ID**: The stressor reduction curve ID for each row in the Stressor Reduction worksheet represents a unique relationship between a restoration action and a stressor. SR# IDs are linked to associated worksheets (Figure 8) that define each stressor reduction function (unique relationships between standardized restoration effort (x-axis) and specific stressor levels (y-axis)).
- **Management Intervention Name:** Name of management action. Ensure spelling matches name of management action in both the Location Implementation and Management Actions worksheets.
- **Measurement Unit for Management Action**: References the "Measurement Unit" from the "Management Actions" worksheet (e.g., # of LWD placements, m^2, km). Included here for convenience and reference.
- **Location Baseline Size Scaling Column**: The location baseline size scaling column references one of columns C:J representing the total baseline (pre-intervention) habitat area (or length) in the "Location Size Attributes" worksheet. The location size scaling column is used as the denominator to divide the absolute quantity of a management action implemented at a given location (e.g., number of BDAs, number of LWD placements, total off-channel habitat created, total length of stream planted, etc.) by the baseline size of that specific habitat at the location/polygon (e.g., total length of stream, total stream area, existing off-channel habitat etc.). This generates a standardized metric of restoration effort per unit area (or length), i.e., relative "density" of restoration outcomes (e.g., number of BDAs per kilometer of stream).
- **Restoration Effort per Unit Area (or Length)**: This defines the units that are used for linking the standardized restoration effort to stressor reduction functions across all locations. Restoration effort per unit area or length is calculated as the absolute quantity of a restoration action at a given location (in terms of the measurement unit for each management action) divided by the total size of the associated habitat at a location (location baseline size scaling column). The resulting metric becomes the x-axis variable in the associated stressor reduction functions described below.

- **Affected Stressor**: This column should be populated with one of the original stressor response curve ID labels from the original stressor response workbook used to run the Joe Model. Ensure that spelling matches the "Stressors" column from the "Main" worksheet of the Stressor Response input workbook. Note that specific restoration actions may be linked to one or more stressors; to define linkages between a single management intervention and multiple stressors, use additional rows to represent each unique relationship between a management action and a different stressor (e.g., riparian planting may reduce both temperature and sediment).

Stressor Reduction Worksheet: Define linkages between management actions and stressor response curves (converting management interventions into stressor reduction).

The stressor reduction workbook defines the relationships between each management action type and the linkages between management actions and stressors. Each row in the stressor reduction workbook must have a unique identifier in the "Stress Reduction Curve ID" column (e.g., SR1, SR2, SR3... etc.) that corresponds to the appropriate stressor reduction function. Subsequent Excel worksheets should be labelled to match the IDs in this column (e.g., SR1, SR2... etc.). The "SR" "#" worksheets define the functional relationships between each unique combination of stressor and restoration action, i.e. how increasing units of restoration translate into lower stressor levels (or increased habitat area, where habitat loss is considered a stressor).

All stressor reduction functions are linked to derived length or area-based metrics as densities (e.g., km of riparian planted per km of channel, LWD placements/km, BDAs/km). These metrics combine the absolute quantity of restoration and scale it by a location weighting factor to produced length or area-based metrics. For example, the total number of LWD placements at a location will commonly be divided by the total stream length at the location to convert # of LWD placements into # LWD placements per km of stream. Expressing restoration action in terms of densities makes it easier to define global stressor reduction functions across restoration scenarios.

Stressor Reduction Curve ID	Management Intervention Name	Measurement Unit for Management Action	Location Baseline Size Scaling Column	Restoration Effort per Unit Area	Affected Stressor
SR1	Riparian Planting 2m wide	km	Stream Length (km)	km planted / km stream	August Stream Temperature
SR2	Riparian Planting 2m wide	km	Stream Length (km)	km planted / km stream	Riparian Habitat Indicator
SR3	BDAs	#	Stream Length (km)	# BDAs / km stream	August Stream Temperature
SR4	BDAs	#	Stream Length (km)	# BDAs / km stream	Habitat Loss
SR5	Off Channel Habitat	m²	Off Channel Habitat (m²)	Ratio of new:current off channel habitat	Off Channel Habitat Loss
SR6	Riparian Planting 10m wide	km	Stream Length (km)	km planted / km stream	August Stream Temperature
SR7	Riparian Planting 10m wide	km	Stream Length (km)	km planted / km stream	Riparian Habitat Indicator

Management Actions | Location Implementation | Location Size Attributes | Stressor Reduction | SR1 | SR2 | SR3 | SR4 | SR

Figure 9. Example of the Stressor Reduction worksheet linking restoration actions to stressors.

1.3.5 Stressor Reduction Function Worksheet

The final data input requirement for the socio-economic component of this CEMPRA tool is the stressor reduction (SR) function worksheets. The stressor reduction worksheets characterize each unique relationship between a restoration action type and an affected stressor. Each SR worksheet must be described as a row in the linked 'Stressor Reduction' overview worksheet and referenced in the associated 'Stressor Reduction Curve ID' column (e.g., SR1, SR2…, etc.).

Each stressor reduction worksheet specifies how increasing levels of a restoration action will change stressor levels at a given location. When the Joe Model is run within the CEMPRA tool, the stressor magnitude values will be adjusted based on the effects specified by the Stressor Reduction functions to produce a modified response after restoration actions are applied. Restoration actions modify each location/polygon's stressor levels (the x-axis component of the stressor response functions). For example, if a given restoration action has the potential to modify stream temperature (a stressor variable) by -2 ˚C, the original stressor level (from the stressor magnitude workbook) will be set to a new value (e.g., 17˚C - 2˚C = 15˚C).

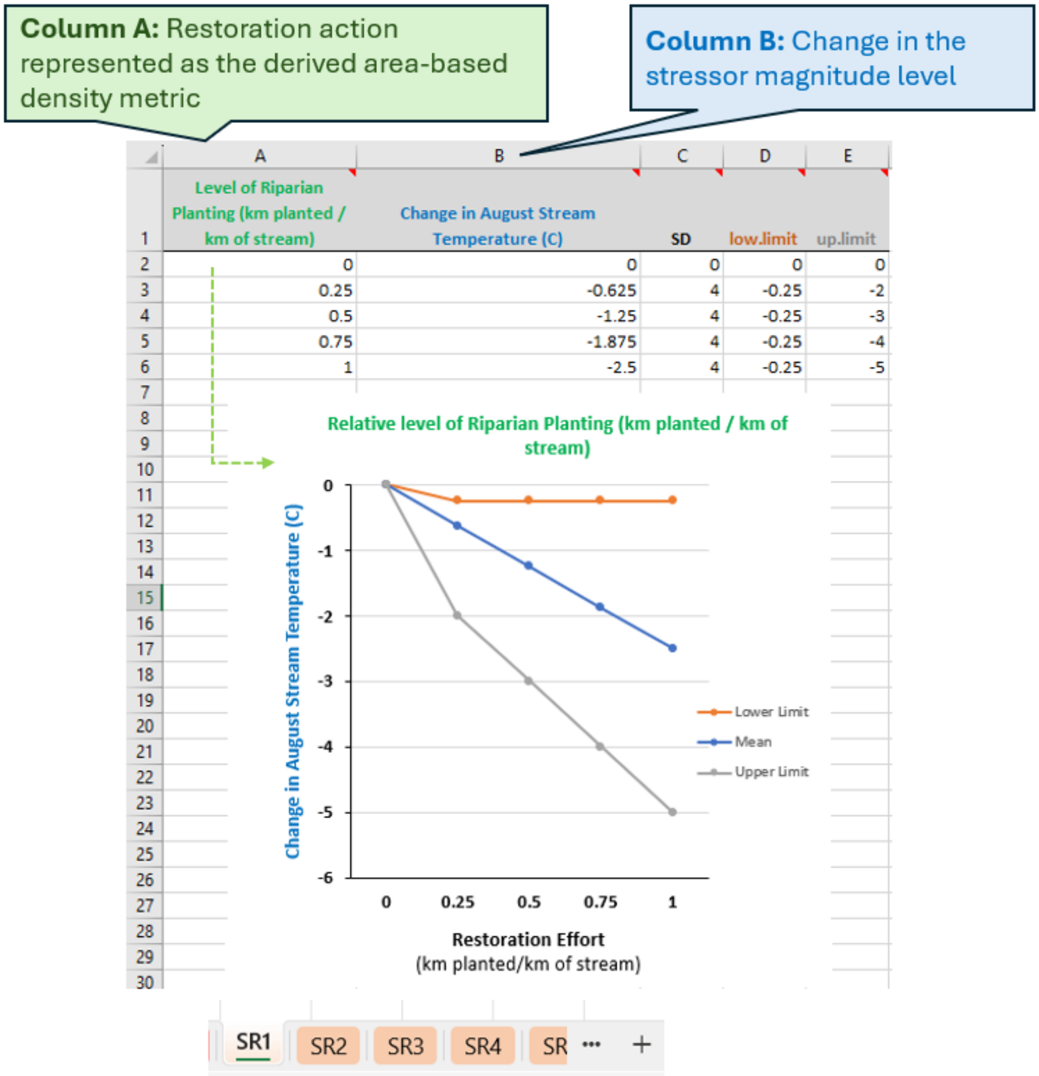


Figure 10. Sample stressor reduction workbook for riparian planting (the restoration action) and stream temperatures (the stressor that is reduced by riparian planting).

Figure 10 provides an example stressor reduction Excel worksheet for riparian planting (the restoration action) and stream temperature (the affected stressor). The values on the y-axis show how stream temperatures will change with increasing levels of restoration action (values on the x-axis). The values on the y-axis are negative because stream temperatures will decrease (i.e., stressor reduction) with increasing levels of riparian planting.

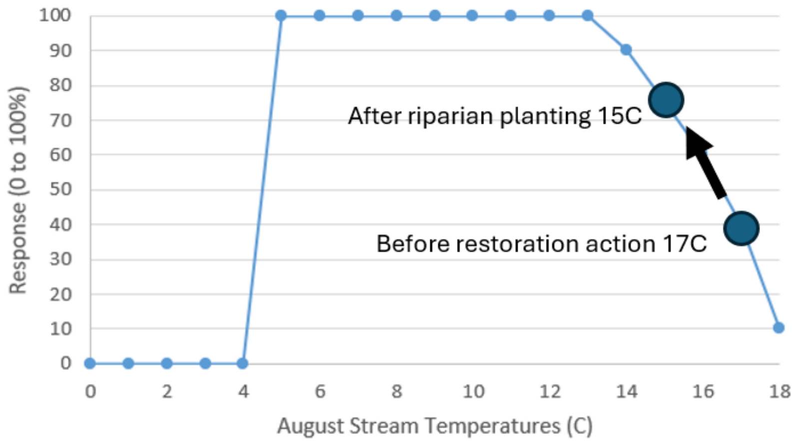


Figure 11. Hypothetical change in stressor levels for stream temperatures before and after riparian planting.

Figure 11 illustrates how we would expect stream temperatures to change for a given location when a hypothetical riparian planting program is initiated to plant approximately 750 meters of stream bank for every kilometre of stream length in a designated polygon (location).

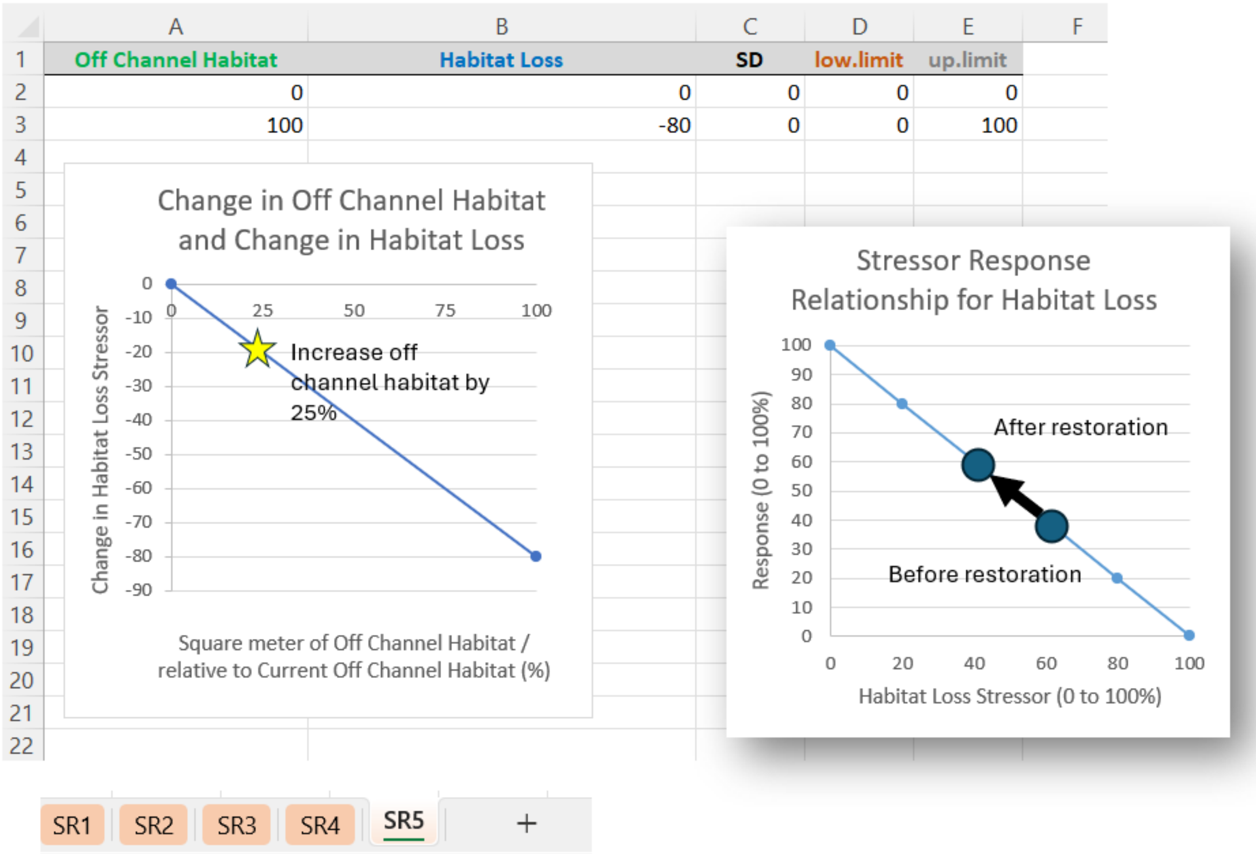


Figure 12. Example relationship between off-channel habitat creation (a restoration action) and reduction in habitat loss (a stressor).

Figure 12 provides another helpful example illustrating the relationship between off-channel habitat creation (the restoration action) and habitat loss (the affected stressor). Suppose we assume that a given restoration program increased the off-channel habitat by ~25% at a location that had previously lost ~60% of its historic off-channel habitat area. In that case, we might expect the restoration project to modify the habitat loss stressor by -25%, setting the new stressor level (habitat loss) to ~35% (60% - 25%). However, we may wish to be cautiously optimistic about the potential for newly created off-channel habitat (installed via instream work) to replace natural off-channel habitat on a 1:1 basis—the example in Figure 12 attempts to illustrate this by limiting the absolute change in stressor level to 100% of the maximum (pre-development or reference) condition.

It is essential to be resourceful when developing restoration action and stressor reduction relationships. It is unlikely that well-defined relationships will be available from the reference literature with universal applicability. Instead, we expect that most relationships will be based on one or two data points and expert opinion. Where possible, try to represent uncertainty in the relationships by setting the SD column and the lower and upper limit columns for stochastic simulations.

Just as with stressor-response functions developed for the main Joe Model in CEMPRA, stressor reduction functions are user-defined, and their underlying rationale, supporting data (if any), and relevant references should be documented with care. Creating a stressor reduction function forces the user to explicitly define how effective they think a restoration intervention will be in reducing stress and, therefore, increasing habitat capacity for the target species; arguably, this is an essential step for evaluating the effort, utility, anticipated outcome, and relative ranking of competing options during restoration/recovery planning. Creating stressor reduction functions forces planners to be explicit about expectations, uncertainty, and data needs to improve confidence in predictions and provides a transparent framework for adaptively refining predicted effects as more information becomes available.

Stressor Reduction (SR) worksheet columns:

- **Column A: Level of Restoration Action:** Values in column A specify the standardized level of the restoration action at a given location (e.g., km planted/km of stream). Column A should consist of numeric values with units matching the restoration effort per unit area metric. This column should also contain a header.
- **Column B: Change in Stressor Magnitude Levels:** Values in column B should specify how the stressor magnitude levels will change for a given level of restoration action. Values in column B directly modify current (baseline) stressor magnitude values by addition. Therefore, if the mechanism involves a decrease in the absolute values of a stressor, these values should be negative. If the restoration action increases stressor magnitude levels, these values should be positive. This column should also contain a header.
- **Column C: SD for Change in Stressor Magnitude Levels:** In many cases, there will be uncertainty associated with the effectiveness of a restoration action. This uncertainty can be represented with stochastic simulations. Set the SD values here to randomly draw a value from a normal distribution with a mean (Column B) and SD (column C). This column should also contain the header "SD".
- **Column D: Lower Limit for Change in Stressor Magnitude Levels:** This column sets a lower limit for stochastic simulations when randomly sampling a change in stressor magnitude levels with stochastic simulations.
- **Column E: Upper Limit for Change in Stressor Magnitude Levels:** This column sets an upper limit for stochastic simulations when randomly sampling a change in stressor magnitude levels with stochastic simulations.

1.4 Implementation

The socio-economic component of the CEMPRA tool is implemented in the CEMPRA Shiny App (https://essa.shinyapps.io/CEMPRAShiny/) within the Socio-Economic tab (Figure 13) and as an optional add-on when running the Joe Model. Users can upload the socio-economic input Excel workbook either using the upload data tab or directly in the Socio-Economic tab. See 1.2.

Tutorial Video
A full tutorial video of the socio-economic component is available at the following YouTube link: (https://www.youtube.com/watch?v=kkebo1rybp4).

Sample Datasets
A complete sample dataset is available for a demo run of the socio-economic component. Working from the demo dataset and adapting it to your system is recommended. Demo files can be downloaded from the links within the app (under "Experiment with Example Datasets", in the right column), or they can be downloaded from the GitHub directory. (see: https://github.com/essatech/CEMPRAShiny/tree/main/www/demo, click on each file to download individually).

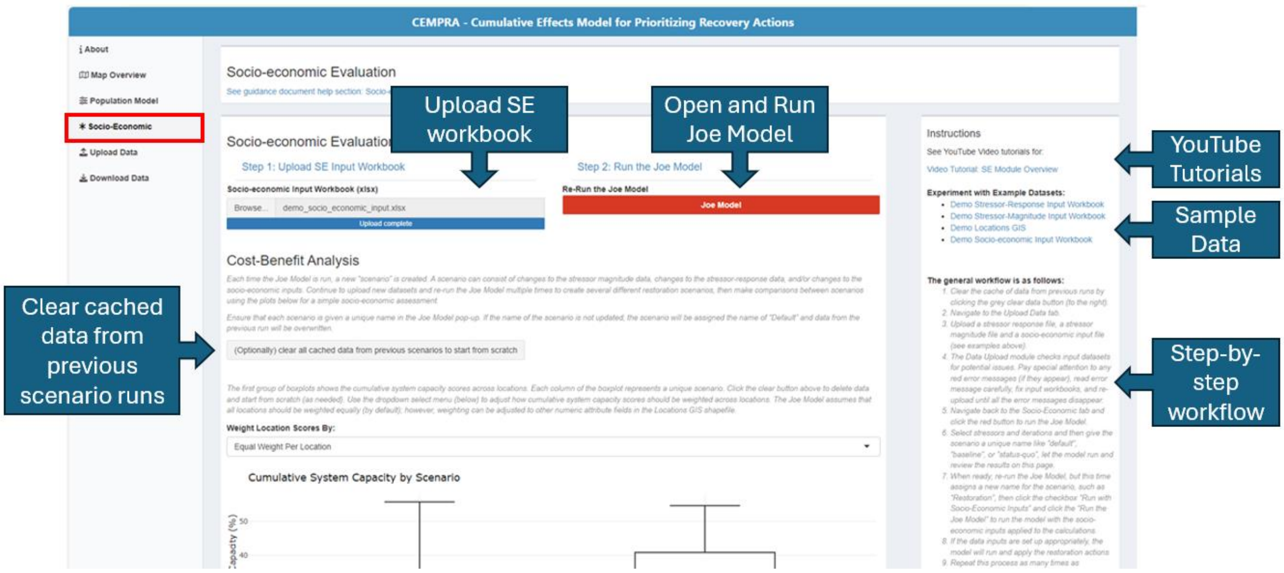


Figure 13. Socio-Economic tab of the CEMPRA Shiny App.

1.4.1 Running the Socio-Economic Module in the R-Shiny Application

The general workflow for using the socio-economic component in the CEMPRA Shiny App is as follows:

1. In the Socio-Economic tab, clear the cache of data from previous runs by clicking the grey "clear all cached data" button (to the left). If your intent is to add a new scenario for comparison (e.g., with vs. without restoration), skip this step.
2. Navigate to the Upload Data tab.
3. Upload a stressor response file, a stressor magnitude file, and a socio-economic input file (see example data sets in the right sidebar of the Socio-Economic tab).
4. The Data Upload module checks input datasets for potential issues. Pay special attention to any red error messages (if they appear), read the error message carefully, fix the input workbooks, and re-upload until all the error messages disappear.

5. Navigate back to the Socio-Economic tab and click the red button to run the Joe Model.
6. Select stressors and number of iterations and then give the scenario a unique name like "default", “baseline”, or “status-quo”, let the model run and review the results on the Socio-Economic page.
7. When ready, re-run the Joe Model, but this time assign a new name for the scenario, such as “Restoration”, then click the checkbox “Run with Socio-Economic Inputs” and click the “Run the Joe Model” button to run the model with the socio-economic inputs applied to the calculations.
8. If the data inputs are set up appropriately, the model will run and apply the restoration actions.
9. Repeat this process as many times as necessary to create multiple restoration scenarios for comparison. When generating scenarios for comparison, do not click the grey “clear all cached data” button.
10. Be creative and try uploading different stressor magnitude files to simulate the effects of restoration with future climate change, etc. It is also possible that there may be multiple restoration action workbooks to represent different restoration portfolios.
11. Review the diagnostic plots to help inform restoration planning.
12. Use the Restoration Projects: Location Implementation tabs to explore the outcomes of a specific project (see blue buttons on the table at the bottom of the Socio-Economic tab).
13. Export and save results as needed via screenshot or the data download module in the Download Data tab.

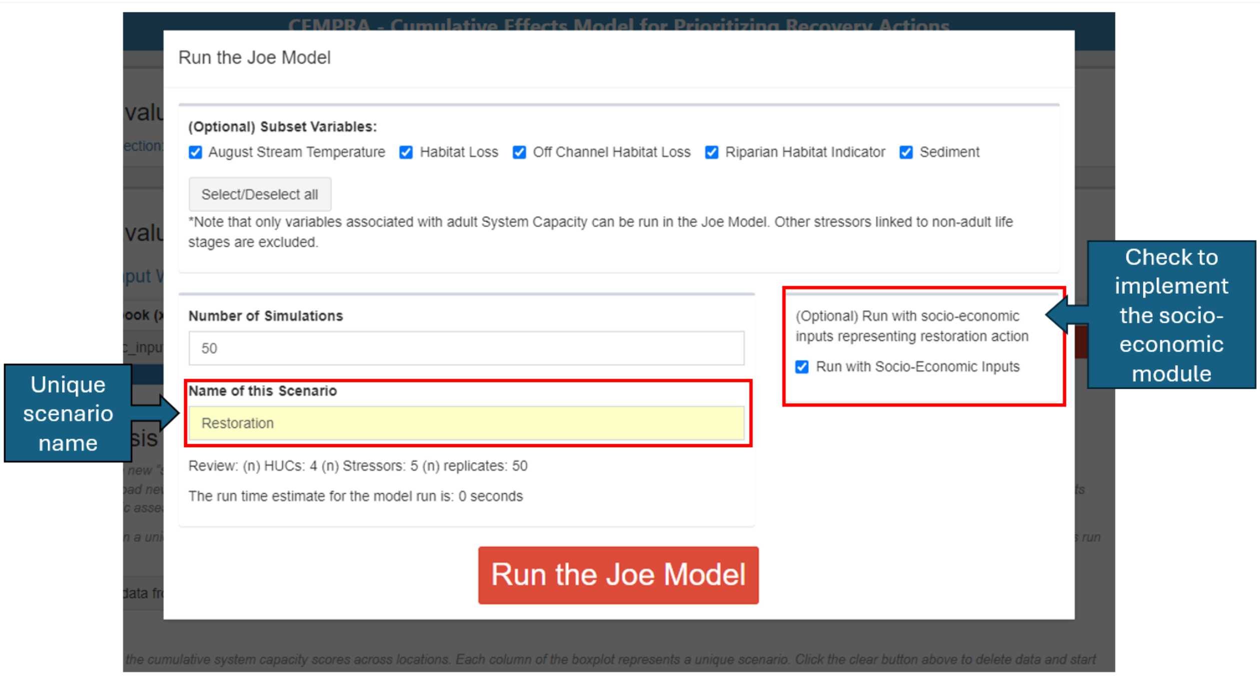


Figure 14. Running the Joe Model with the socio-economic module turned on.

Scenario Overview Plot #1: Cumulative System Capacity by Scenario

The first group of boxplots shows the cumulative system capacity scores across locations. Each column of the boxplot represents a unique scenario. Click the clear button above to delete data *and start from scratch (as needed). Use the dropdown select menu (below) to adjust how cumulative system capacity scores should be weighted across locations. The Joe Model assumes that all locations should be weighted equally (by default); however, weighting can be adjusted to other numeric attribute fields in the Locations GIS shapefile.*

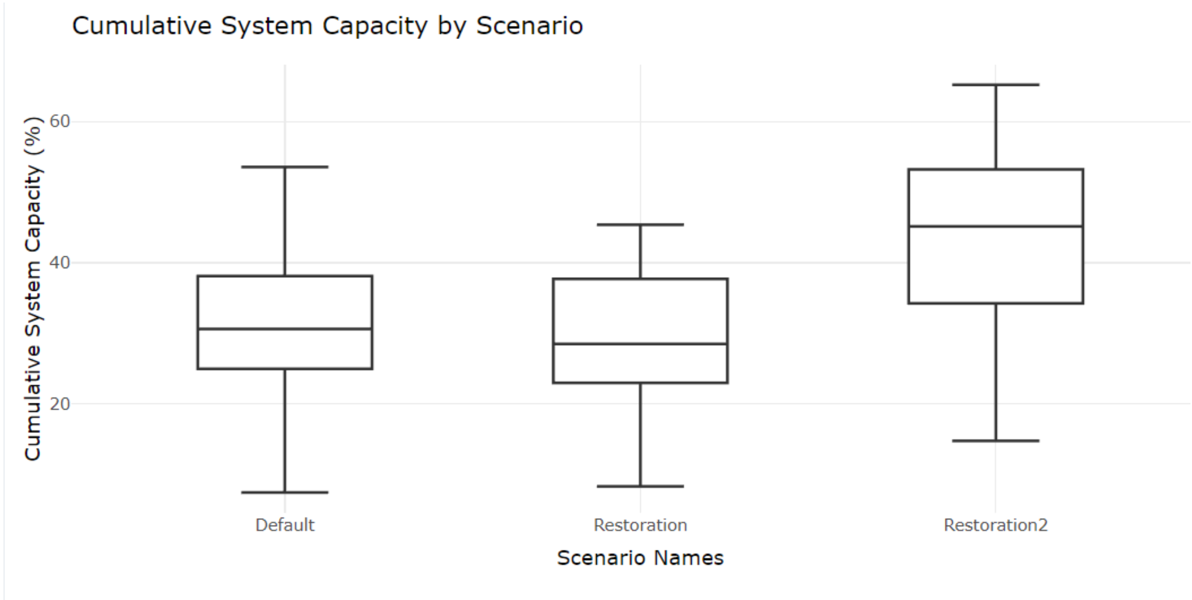


Figure 15. Impact of restoration actions on cumulative system capacity (%) compared to the default scenario where no restoration is applied. Boxplots represent the distribution of batch runs for each scenario.

Scenario Overview Plot #2: Cost Summary by Scenario

The next group of boxplots shows the total cost estimate to implement each scenario. The cost estimate is presented as a distribution of values in a boxplot to represent uncertainty and stochasticity. Each data point represents derived cost estimates from an individual batch replicate model run.

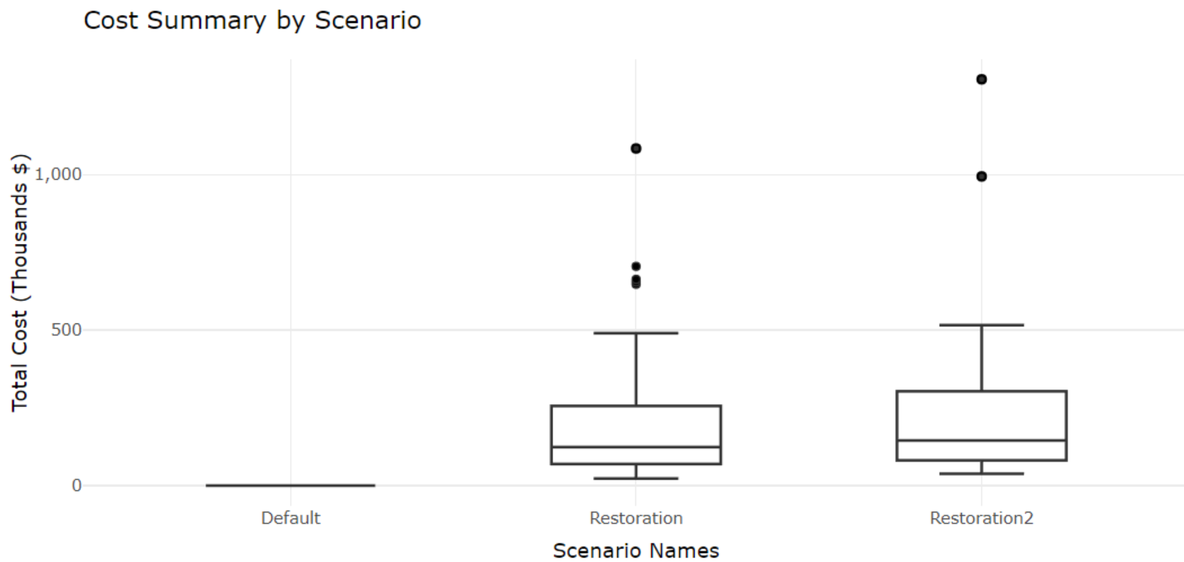


Figure 16. Cost in thousands of dollars for the applied restoration scenarios.

Scenario Overview Plot #3: Simple Cost-Benefit

The following plot shows a simplified cost-benefit analysis with the total cost on the x-axis and the cumulative system capacity score on the y-axis. Each data point represents an individual batch replicate model run. It can be helpful to run a default baseline status quo scenario first and then click and drag in the plot area to zoom in for all subsequent scenarios – this allows us to see the relative change over a pre-defined baseline status quo baseline.

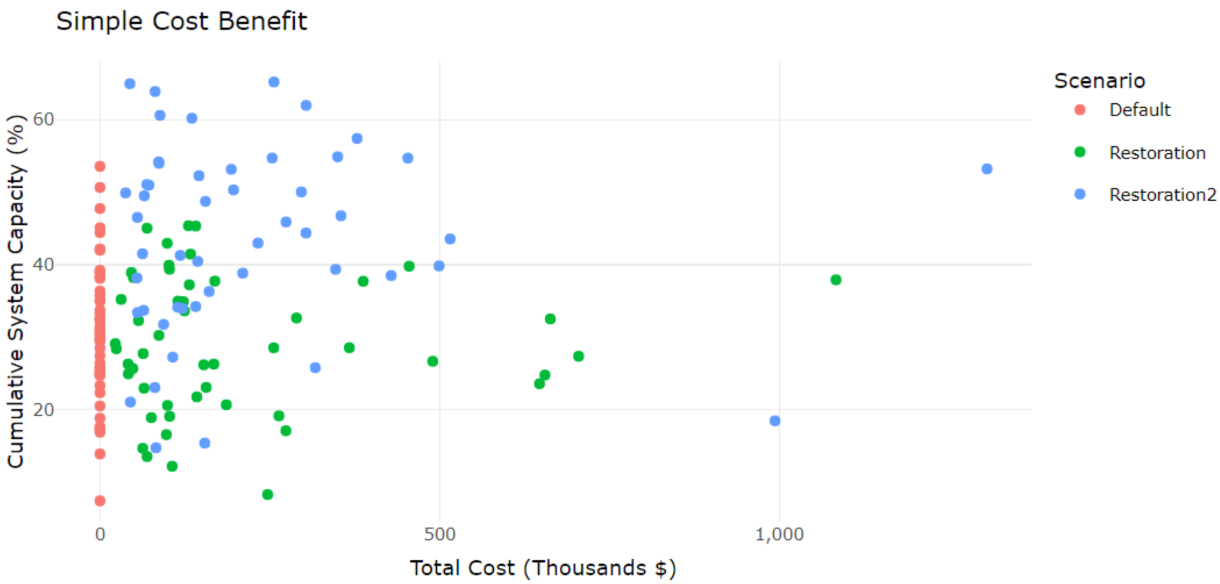


Figure 17. Cost of each scenario run compared to the resultant cumulative system capacity (%). Individual runs are shown to visualize stochasticity.

Diagnostic Plots

The next set of plots shows each stressor's average system capacity score across each scenario. Only the mean value is shown (across locations) for convenience rather than the full distribution of each stressor. However, reviewing the plot below is useful for understanding the most critical and least critical stressors across scenarios.

In this example, we can see that the cumulative system capacity score for `August Stream Temperature` improved in the restoration scenarios relative to the default model run. The `Sediment` stressor was excluded from the model run `Restoration2`.

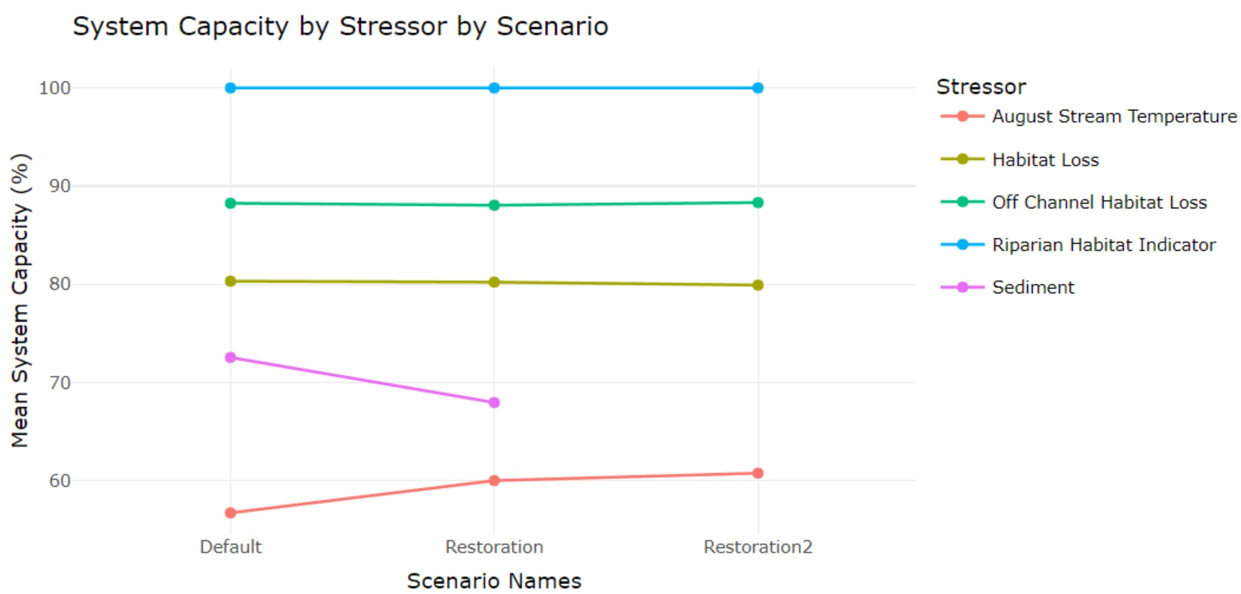
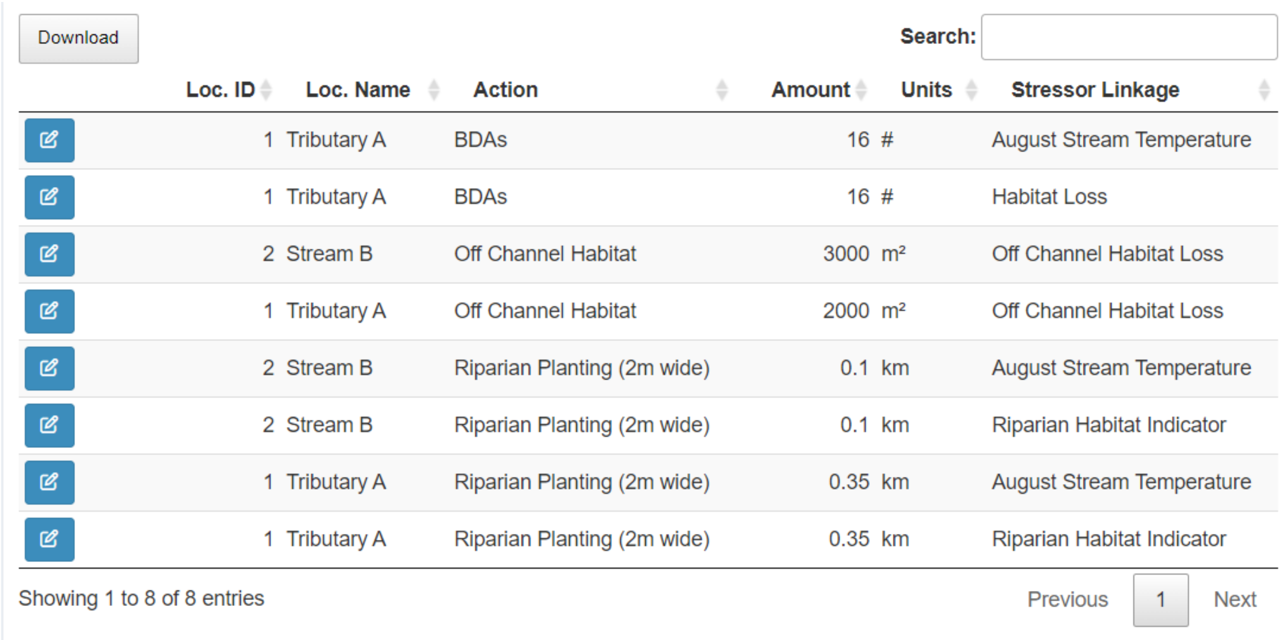


Figure 18. Mean system capacity (%) across restoration scenarios separated by stressor.

Restoration Projects: Location Implementation

The socio-economic module will output cost-benefit results for each Joe Model run. Different runs (scenarios) will be plotted together until the user clears the cache or overwrites previous runs. Breakdowns for each location are available in the Restoration Projects: Location Implementation section of the Socio-Economic tab (Figure 20). The restoration action magnitude (Implementation Amount) can also be adjusted in this section. When the user updates the Implementation Amount and then clicks the blue "Save and Update" button at the bottom of the window, they can view how the cost, density, stressor response, and overall cost-effectiveness of the restoration action change as a result in the Sample Calculations section.



Loc. ID	Loc. Name	Action	Amount	Units	Stressor Linkage
1	Tributary A	BDAs	16	#	August Stream Temperature
1	Tributary A	BDAs	16	#	Habitat Loss
2	Stream B	Off Channel Habitat	3000	m²	Off Channel Habitat Loss
1	Tributary A	Off Channel Habitat	2000	m²	Off Channel Habitat Loss
2	Stream B	Riparian Planting (2m wide)	0.1	km	August Stream Temperature
2	Stream B	Riparian Planting (2m wide)	0.1	km	Riparian Habitat Indicator
1	Tributary A	Riparian Planting (2m wide)	0.35	km	August Stream Temperature
1	Tributary A	Riparian Planting (2m wide)	0.35	km	Riparian Habitat Indicator

Figure 19. Restoration Projects: Location Implementation section. Restoration actions and their affected stressors are shown for each location.

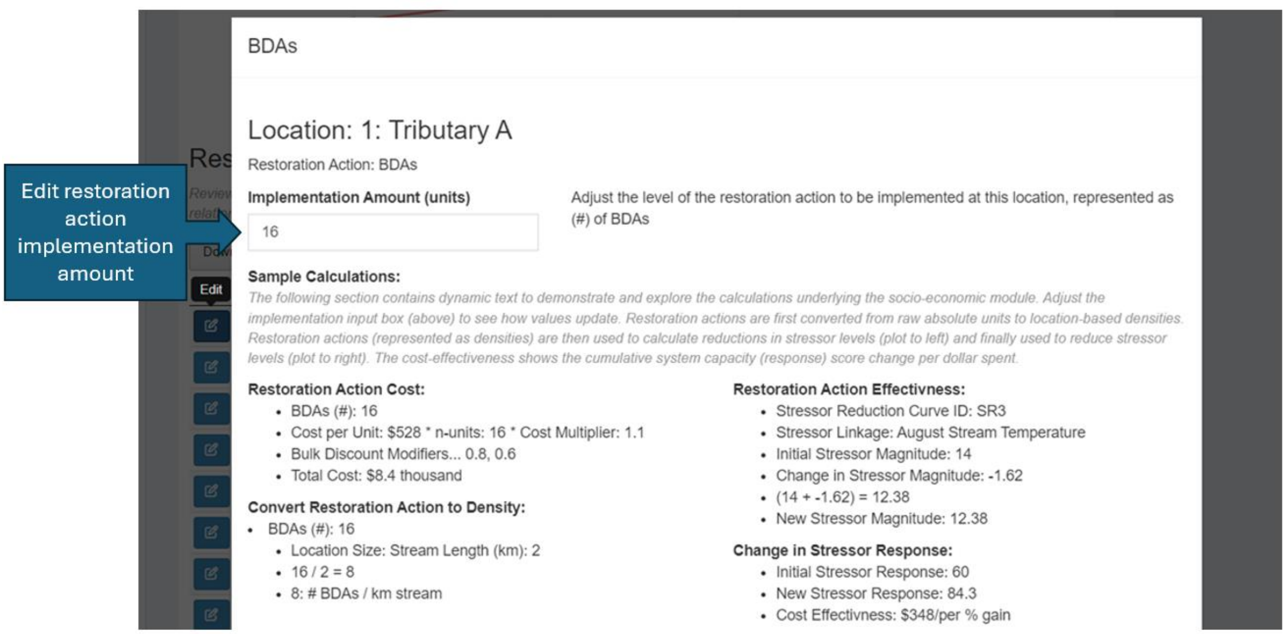


Figure 20. Example of a Location Implementation pop-up from the Restoration Projects: Location Implementation section of the Socio-Economic tab.

Key figures produced in the Restoration Projects: Location Implementation windows are the change in a stressor and stressor response with a given restoration effort, and a cost vs. benefit plot. Ideally, a restoration action should decrease the impact of a stressor in a way that maximally increases system capacity, given restoration effort.

Figure 20, Figure 21, and Figure 22 show the results of the sample calculations and mean estimates.

The first plot on the left side in Figure 21 ('Restoration Effort'), shows reductions in stressor levels for increased restoration action. The red marker shows the default status quo condition with (no action), and the green marker shows the effect of the restoration action. In this example, we see that the addition of BDAs decreases stream temperature by ~1.5°C. The "grey area" shows one standard deviation in the mean estimate for this relationship, informing the user that there is considerable uncertainty here. The second plot on the right side of Figure 21 ('Change in Stressor Response'), shows the resulting change in the stressor response relationship from the restoration action. In this example, we move from the red dot to the green dot along the stressor response curve. This occurs because the BDAs alter the stressor magnitude level, decreasing stream temperature and improving the score in the response.

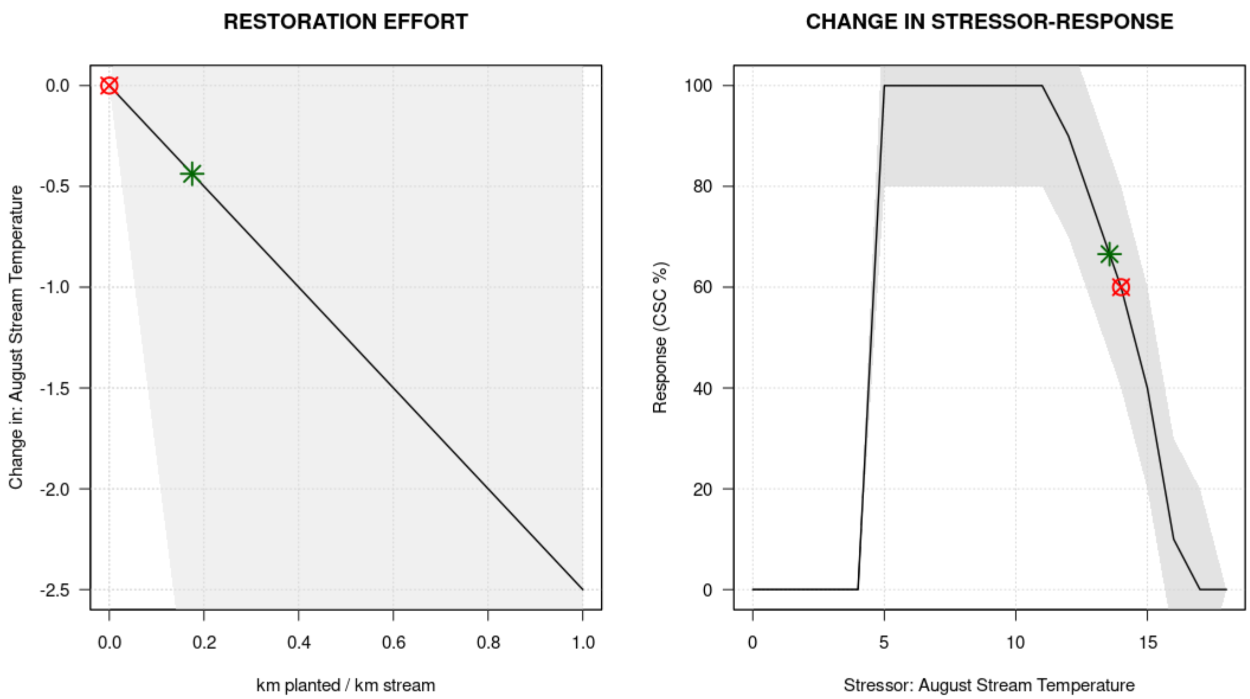


Figure 21. Reductions in stressor levels for increased restoration action (left) and the resulting change in the stressor response relationship from the restoration action. The red marker shows the default status quo condition with (no action), and the green marker shows the effect of the restoration action.

The user should also note any inflection points in the cost-benefit relationship, where gains in system capacity from a restoration action may diminish after a certain point. The user may want to adjust the magnitude of the restoration action to ensure maximum benefit given the cost.

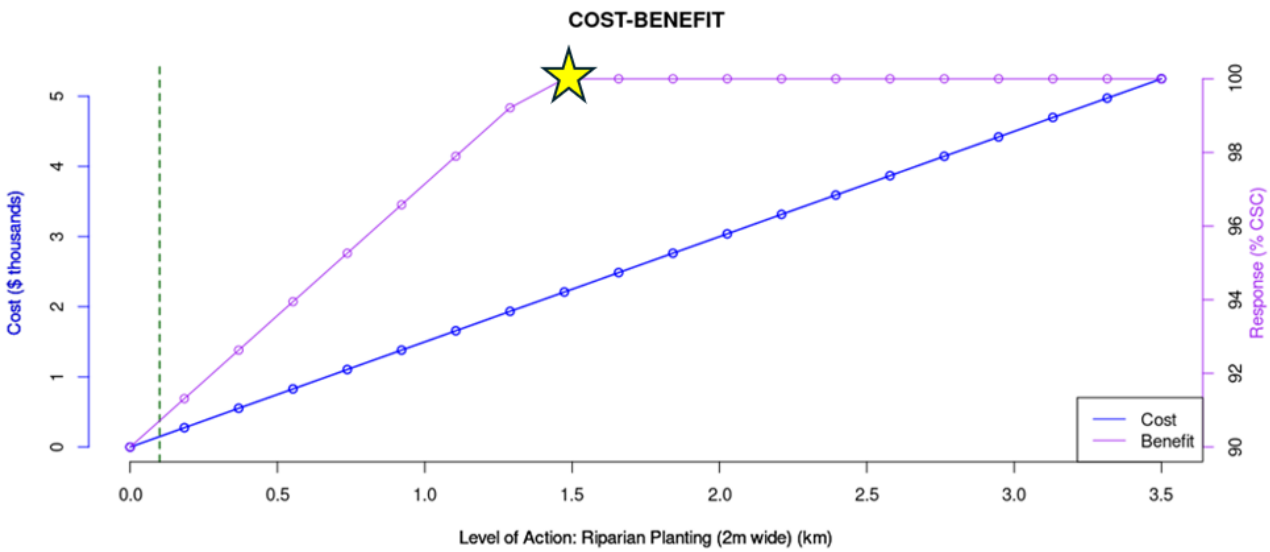


Figure 22. Example of a cost-benefit plot in the Restoration Projects: Location Implementation section. The level of restoration action at the target location is plotted on the x-axis. The total derived cost is plotted on the y-axis (blue line: right side), with the response score from the stressor-response relationship (purple line: left side). An example of an inflection point is highlighted by the yellow star.

1.4.2 R-Package Implementation

The socio-economic module can also be implemented in the R package version of the CEMPRA tool. The user can import the socio-economic workbook using the **SocioEconomicWorkbook()** function and the file name of the workbook. The user can then run the Joe Model using the **JoeModel_Run()** function; the socio-economic module can be activated in this function by providing the imported socio-economic list object for the socioeconomic_inputs argument. The **SocioEconomicRun()** function can also be used to run calculations outside of the Joe Model, this can be useful if the goal is to integrate the functionality in a custom script linked to the population model.