Appendices. Supplementary data


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Appendix A. Description of the SEIBM-1D SNS submodels

The following sections describe submodels of a spatially explicit (1-dimensional) individual-based model for shovelnose sturgeon (Scaphirhynchus platorynchus) (SEIBM-1DSNS). Parameter values used for the model are provided in Appendix B. The model consists of one prey submodel and six sturgeon submodels with a total of 72 parameters as described below.

Drift invertebrate production. Drift prey biomass \( B_{\text{prey},t,i} \) in grid cell \( i \) on day \( t \) is calculated as

\[
B_{\text{prey},t,i} = B_{\text{prey},t-1,i} + \text{Prod}_{\text{prey},t,i} + M_{\text{prey},t,i} - C_{\text{pred},t,i} \tag{A1}
\]

where \( \text{Prod}_{\text{prey},t,i} \) is daily production (g • m\(^{-2} \) • d\(^{-1} \)), \( M_{\text{prey},t,i} \) is net migration (g • d\(^{-1} \)) from neighboring cells, and \( C_{\text{pred},t,i} \) is consumption by sturgeon (g • d\(^{-1} \)). \( \text{Prod}_{\text{prey},t,i} \) is calculated daily using a logistic growth function (Rashleigh and Grossman, 2005) as

\[
\text{Prod}_{\text{prey}} = GR_{\text{prey}} \times (1 + Var_{\text{preyprod}} \sin \left( \frac{2\pi \text{DOY}}{365} \right) \times (1 - \frac{Bio_{\text{prey}}}{q_{\text{prod}} \times B_{\text{max,prod}}})) \times Bio_{\text{prey}} \tag{A1a}
\]

where \( GR_{\text{prey}} \) is the growth rate (d\(^{-1} \)), \( Var_{\text{preyprod}} \) is a term that accounts for variation in \( \text{Prod}_{\text{prey}} \), \( q_{\text{prod}} \) is an indicator of discharge-dependent habitat quality (which ranges from 0-1), \( Bio_{\text{prey}} \) is prey biomass in a grid cell (g • m\(^{-2} \)), and \( B_{\text{max,prod}} \) is the maximum biomass (g • m\(^{-2} \)) (Appendix B). \( q_{\text{prod}} \) is a flow-dependent non-linear function calculated as

\[
q_{\text{prod}} = 1.01e^{-0.5(V_{\text{mean}} - 0.603)/0.249}^2,
\]

where \( V_{\text{mean}} \) is mean water velocity (m • s\(^{-1} \)); \( V_{\text{mean}} \) is calculated as \( V_{\text{mean}} = Disc \times (\text{Width} \times \text{Depth}) \), where \( Disc, \text{Width,} \) and \( \text{Depth} \) are river discharge, width, and depth (Appendix C). \( M_{\text{prey},t} \) is calculated as

\[
M_{\text{prey},t} = m_{\text{prod}} \times (B_{\text{prey},t,i} - B_{\text{prey},t-1,i}) \tag{A1b}
\]

where \( m_{\text{prod}} \) is net migration rate (d\(^{-1} \)) (Appendix B, Rashleigh and Grossman, 2005). Prey biomass in each grid cell is then distributed into five body length classes (1-3, 3-5, 5-7,7-9, and 9-11 mm). Relative density of each size class is calculated assuming the Poisson distribution with mean of 0.41 mm (= ~1 μg).

Embryonic and larval development. Embryonic development is evaluated by a cumulative fractional temperature-dependent function derived from data reported by Wang et al. (1985). Daily development of eggs \( (D_{\text{egg}}) \) is calculated as

\[
D_{\text{egg}} = 1/(\alpha_{\text{egg}}e^{-\beta_{\text{egg}}T_{\text{ave}}} / 24) \tag{A2}
\]

where \( \alpha_{\text{egg}} \) and \( \beta_{\text{egg}} \) are constants (Appendix B), and \( T_{\text{ave}} \) is daily mean water temperature. Hatching occurs when \( D_{\text{egg}} \geq 1 \). We assume that hatched larvae use their yolk sac for ~10 days (at 17-18 °C, Wang et al., 1985) before exogenous feeding. Post-hatch yolk-sac larval development to the first exogenous feeding \( (D_{\text{yolk sac}}) \) is calculated with a temperature-dependent function derived from data reported by Wang et al. (1985) as

\[
D_{\text{yolk sac}} = 1 / ((\alpha_{\text{yolk sac}}e^{-\beta_{\text{yolk sac}}T_{\text{ave}}} - \alpha_{\text{egg}}e^{-\beta_{\text{egg}}T_{\text{ave}}}) / 24) \tag{A3}
\]
where $\alpha_{\text{yolksac}}$ and $\beta_{\text{yolksac}}$ are constants (Appendix B). Exogenous feeding occurs when $D_{\text{yolksac}} \geq 1$, after which we track foraging, growth, movement, and mortality for each $\text{SI}_{\text{yolksac}}$.

**Foraging.** Foraging is simulated with the functional response model by Beddington (1975) and DeAngelis et al. (1975), which is a function of encounter rate, handling time, prey selectivity, and prey and predator densities. This model incorporates both predator and prey density-dependent effects to reflect flow-dependent resource competition. Daily consumption rate of prey size class $i$ ($C_i$, g $\cdot$ d$^{-1}$) is calculated as

$$C_i = \frac{W_{\text{prey}, i} \times N_{\text{prey}, i}}{1 + \sum (E_{\text{prey}, i} \times Q_{\text{prey}, i} \times HT_{\text{prey}, i}) + \sum (E_{\text{intra}} \times D_{\text{intra}})}$$  \hspace{1cm} (A4)

where $W_{\text{prey}, i}$ is body mass (mg, wet) of the $i$th prey size class, $N_{\text{prey}, i}$ is the realized number of the $i$th prey size class consumed (number $\cdot$ s$^{-1}$), $E_{\text{prey}, i}$ and $E_{\text{intra}}$ are the realized encounter rates for the $i$th prey size class and other sturgeon individuals (number $\cdot$ s$^{-1}$, respectively), $Q_{\text{prey}, i}$ is the probability of attacking the $i$th prey size class, which is used to calculate $N_{\text{prey}, i}$, $HT_{\text{prey}, i}$ is handling time (s) of the $i$th prey size class, and $D_{\text{prey}, i}$ and $D_{\text{intra}}$ are the density of $i$th prey size class and sturgeon (g $\cdot$ m$^{-2}$) in a given cell, respectively.

To account for direct flow-dependence in foraging by shovelnose sturgeon (Modde and Schmulbach, 1977; Seibert et al., 2011), we use the drift foraging model by Guensch et al. (2001) to calculate the realized encounter rate ($E_{\text{prey}, i}$ and $E_{\text{intra}}$); drift-feeding sturgeon are assumed to encounter and capture prey within an area defined by fish swimming speed and water velocity. $E_{\text{prey}, i}$ and $E_{\text{intra}}$ are calculated by a randomly drawn number from a Poisson distribution with potential encounter rate ($ER_{\text{prey}, i \text{ or intra}}$, number $\cdot$ s$^{-1}$) as the number of trials, calculated as

$$ER_{\text{prey, i or intra}} = V_{\text{max}} \times MCA_{\text{prey, i or intra}} \times D_{\text{prey, i or intra}}$$  \hspace{1cm} (A4a)

where $V_{\text{max}}$ is the maximum sustainable swimming speed of sturgeon (m $\cdot$ s$^{-1}$), and $MCA_{\text{prey, i or intra}}$ is the maximal capture (or competition for $MCA_{\text{intra}}$) area (m$^2$). $V_{\text{max}}$ is calculated by empirically derived functions of temperature and fish length; $V_{\text{max}}$ increases with increasing temperature and fish length. $MCA_i$ is calculated as

$$MCA_i = \frac{\Delta \Theta}{2} \times MCD_i^2$$  \hspace{1cm} (A4b)

where $\Delta \Theta$ is an incremental angle perpendicular to the flow vector ($MCA$ is divided into 10 equal segments, Guensch et al., 2001), and $MCD_i$ is the maximal capture (or competition) distance (m). $MCD_i$ is a function of fish swimming speed and water velocity and is calculated as

$$MCD_i = \frac{RD_i \times (V_{\text{max}}^2 - V_{\text{mean}}^2)}{V_{\text{bottom}}^2 + V_{\text{max}}^2 - V_{\text{mean}}^2}$$  \hspace{1cm} (A4c)

where $RD_i$ is the reactive distance to the $i$th prey size class (m) and $V_{\text{bottom}}$ is bottom water velocity (m $\cdot$ s$^{-1}$). $V_{\text{bottom}}$ is calculated using a function of $V_{\text{mean}}$ empirically derived for the LPR using data reported by Peters and Parham (2008); $V_{\text{bottom}} = 0.1176 + 0.4031V_{\text{mean}}$. When water velocity is greater than their swimming speed, sturgeon stop foraging. $RD_i$ is calculated by an empirically derived function of prey and sturgeon lengths as
\[ RD_i = \alpha_{RD}(L_{prey}/10) \times (1 - e^{-\beta_{RD}L_{fish}}) \]  

(A4d)

where \( \alpha_{RD} \) and \( \beta_{RD} \) are constants (Appendix B), \( L_{prey} \) is prey length (mm) and \( L_{fish} \) is sturgeon length (mm). In the Foraging submodel, exact body length of drift prey is randomly assigned using a uniform distribution (between minimum and maximum of each size class) each day. The attack probability \( (Q_{preyi}) \) is then calculated as a function of selectivity and prey density as

\[ Q_{preyi} = \frac{C_{\alpha_i} \times D_{preyi}}{\sum C_{\alpha_i} \times D_{preyi}} \]  

(A4e)

where \( C_{\alpha_i} \) is prey selectivity based on Chesson’s alpha for the prey size class \( i \). \( D_{preyi} \) is calculated by dividing total biomass by individual mass (i.e., \( D_{preyi} = B_{preyi} / W_{preyi} \), where \( W_{preyi} \) is the body mass of the \( i \)th prey size class (g wet), calculated using an empirically derived function as \( W_{preyi} = 0.0018L_{prey}^{2.62} / 0.145 / 1000 \) (Benke et al., 1999). \( C_{\alpha_i} \) is calculated by a prey size-dependent function as

\[ C_{\alpha_i} = \alpha_{Ca} \times \beta_{Ca}(L_{prey} / L_{fish}) \]  

(A4f)

where \( \alpha_{Ca} \) and \( \beta_{Ca} \) are constant (Rose et al. 1997). Handling time \( (HT_{prey}, \text{s}) \) for drift-feeding sturgeon is assumed to be 1.0.

The daily foraging rate is limited by a temperature-dependent maximum daily consumption rate \( (C_{max}, \text{g} \cdot \text{d}^{-1}) \) and is calculated as

\[ C_{max} = \alpha_{cmax}W_{fish}^{\beta_{cmax}} \times fT_{cmax} \]  

(A5)

where \( \alpha_{cmax} \) and \( \beta_{cmax} \) are constants (Appendix B), \( W_{fish} \) is total mass of sturgeon (g wet), and \( fT_{cmax} \) is a temperature-dependent function, calculated as

\[ fT_{cmax} = (\alpha_{Tc} - \beta_{Tc}T_{ave})^{\gamma_{Tc}} \times e^{(\delta_{Tc}T_{ave} - \epsilon_{Tc})} \]  

(A5a)

where \( \alpha_{Tc}, \beta_{Tc}, \gamma_{Tc}, \delta_{Tc}, \) and \( \epsilon_{Tc} \) are constants (Appendix B).

Growth. Growth is simulated by the bioenergetics model (Hanson et al., 1997) modified to incorporate energy allocation to storage and gonad tissues (Bevelhimer, 2002; Sibly et al., 2013); The standard bioenergetics model assumes that energy available for growth is a function of energy consumed less energy lost due to metabolism as

\[ G = C - R - F - U - SDA \]  

(A6)

where \( G \) is growth, \( C \) is consumption, \( R \) is respiration, \( F \) is egestion, \( U \) is excretion, and \( SDA \) is specific dynamic action. All units are in \( \text{g} \cdot \text{g}^{-1} \cdot \text{day}^{-1} \). \( C \) is derived from the Foraging submodel. \( R \) is calculated as

\[ R = \alpha_R W_{fish}^{\beta R} \times fT_R \times ACT \times OF \]  

(A6a)
where $\alpha_R$ and $\beta_R$ are constants, $fT_R$ is a temperature-dependent function, $ACT$ is an activity multiplier, and $OF$ is an oxycalorific factor (Appendix B). $fT_R$ is calculated as

$$fT_R = e^{\alpha_{TR}T_{av}}$$

(A6b)

where $\alpha_{TR}$ is a constant (Appendix B).

$F$ is calculated as

$$F = \alpha_F C$$

(A6c)

where $\alpha_F$ is a constant (Appendix B). $U$ is calculated as

$$U = \alpha_U (C - F)$$

(A6d)

where $\alpha_U$ is a constant (Appendix B). $SDA$ is calculated as

$$SDA = \alpha_{SDA} (C - F)$$

(A6e)

where $\alpha_{SDA}$ is a constant (Appendix B).

In this model, we assume that once assimilated, energy is allocated to storage (reversible, $W_{str}$) and structural (irreversible, $W_{strc}$) tissues (Gurney et al., 2003; Höök et al., 2008). To calculate growth, grams of prey consumed from the Foraging submodel are first converted to joules ($ED_{prey}$, Appendix B). For post-settlement larvae and juveniles, when $W_{str}$ is less than optimal storage mass ($W_{stropt}$), surplus net energy is allocated to storage tissue first until $W_{stropt}$ is reached. $W_{stropt}$ is calculated as

$$W_{stropt} = W_{fish} \times \rho_{opt}$$

(A7)

where $\rho_{opt}$ is the proportion of optimal storage mass relative to total mass. $\rho_{opt}$ is calculated using a length-dependent function as

$$\rho_{opt} = \alpha_\rho \ln(L_{fish}) + \beta_\rho, \text{ when } \rho_{opt} > 0.2$$

$$\rho_{opt} = 0.2, \text{ otherwise}$$

(A7a)

where $\alpha_\rho$ and $\beta_\rho$ are constants (Appendix B, Höök et al., 2008). When $W_{str}$ is greater than $W_{stropt}$, the surplus energy is allocated to both storage and structural mass such that $\rho_{opt}$ is maintained as

$$W_{str} = \rho_{opt} \times \frac{ED_{str}}{ED_{str} + ED_{strc}}$$

(A7b)

$$W_{strc} = (1 - \rho_{opt}) \times \frac{ED_{strc}}{ED_{str} + ED_{strc}}$$

(A7c)

where $ED_{str}$ and $ED_{strc}$ are energy density of storage and structural tissues (Appendix B).

Growth in length is then calculated using length-mass functions, which are modified such that length increases only when structural mass increases as
where $\alpha_{\text{grow}}$ and $\beta_{\text{grow}}$ are constants (Appendix B). When the assimilated energy is less than the energy expended through metabolism (negative net energy), mass is lost only from the storage tissue, while structural mass and length remain the same.

In SEIBM-1D$_{\text{SNS}}$, maturity status is evaluated once a year at the beginning of each simulation year. Probability of maturation ($P_{\text{mature}}$) is calculated by an empirically derived function of body length using data reported by Tripp et al. (2009) as

$$P_{\text{mature}} = \frac{1}{1 + \left(\frac{L_{\text{fish}}}{\alpha_{\text{PM}}}\right)^{-\beta_{\text{PM}}}}$$

(A9)

where $\alpha_{\text{PM}}$ and $\beta_{\text{PM}}$ are constants (Appendix B).

For reproductive adults, energy is also allocated to gonad development. We assume that mature sturgeon in the reproductive cycle gradually allocate energy to gonad tissue between spawning events. The energy allocation to gonadal development follows the formulation by Van Winkle et al. (1997). Adults initiate the annual reproductive cycle only when their physiological condition ($KS$) is above the threshold value for reproduction ($KS_{\text{rep}}$). In SEIBM-1D$_{\text{SNS}}$, we calculate $KS$ using relative storage mass (as $KS = W_{\text{stor}}/W_{\text{optstor}}$). Adults who do not meet the minimum physiological condition do not enter the annual reproductive cycle and allocate energy only to structural and storage tissues.

The amount of daily energy allocated to $E_{\text{gonad}}$ ($\gamma_{\text{gonad}}$, J • d$^{-1}$) by healthy ($KS \geq 1.0$) adults is a function of expected gonad energy content on the spawning day, the minimal spawning interval (1 year for males and 3 years for females), and the earliest expected spawning day (Appendix B). The expected gonad energy content on the spawning day is calculated by an allometric function as

$$E_{\text{gonad}} = \alpha_{g}W_{\text{struc}}^{\beta_{g}}$$

(A10)

where $\alpha_{g}$ and $\beta_{g}$ are constants (Appendix B).

While the earliest expected spawning day is assumed to occur in late March (when daylight hours $>$12 h), the realized spawning day is determined by discharge, temperature, and gonadosomatic index or GSI (see Spawning submodel). $\gamma_{\text{gonad}}$ is further adjusted when the physiological condition is below the threshold as

$$\gamma_{\text{gonad}} = \begin{cases} \gamma_{\text{gonad}}, & \text{when } KS \geq KS_{\text{norm}} \\ \gamma_{\text{gonad}} \times (1 - e^{-\delta_{g}(KS - KS_{spwn})}), & \text{when } KS < KS_{\text{norm}} \\ 0, & \text{when } KS < KS_{spwn} \end{cases}$$

(A11)

where $KS_{\text{norm}}$ is the normal physiological condition, $\delta_{g}$ is a constant, and $KS_{spwn}$ is the minimum physiological condition to remain in the reproductive cycle (Appendix B).

Spawning. Spawning is a stochastic event and occurs only when the following ecological and physiological conditions are concurrently met: (1) water temperature (Gilliland et al., 1985); (2) minimum discharge rate; and (3) the minimal GSI (Pelletier and Mahévas, 2005) (Appendix B).
These conditions determine the spawning day, as well as the number of spawning adults producing viable gametes. Fecundity \((N_{\text{egg}})\) is calculated by dividing energy content of gonad by that of an egg (i.e., \(N_{\text{egg}} = E_{\text{gonad}}/E_{\text{egg}}\), where \(E_{\text{gonad}}\) is the energy content (J) of the gonad on the spawning day, and \(E_{\text{egg}}\) is the energy content of a single egg (J \(\cdot\) egg\(^{-1}\), Appendix B). We assume that size and energy content of eggs are uniform and constant. After spawning, these individuals lose all gonad mass, and their KS and total mass are updated. Spawning adults do not re-enter the reproductive cycle until KS meets the threshold.

Movement. In the SEIBM-1D\textsubscript{SNS}, fish movement is tracked in the longitudinal direction only. The movement consists of two components; orientation (upstream and downstream) and distance (m). The movement of eggs and pre-settlement larvae is determined only by water velocity. The movement of post-settlement larvae, juveniles, and adults is determined by habitat quality based on discharge and drift prey biomass.

Shovelnose sturgeon are generally sedentary (mean daily movement rates < 350 m, Hurley et al., 1987; Peters and Parham, 2008). In the SEIBM-1D\textsubscript{SNS}, we assume that the maximum distance that fish can travel daily is limited to be within three (above or below the current grid cell) neighboring cells (or 3.0 km). We assume that during the day, fish swim within this limited area and explore these neighboring grid cells before they ‘settle’ to a new cell. Individuals that are located within the upper or lower two boundary cells (1-2 or 161-162 rkm) can move out of the model LPR system (the probability of these individuals to emigrate is set to 0.01), but the movement into tributaries of the LPR or the mainstem Missouri River is not evaluated; the fish emigrated from the LPR system are treated as being ‘lost’ from the population.

The direction of a fish’s movement is determined by its responses to habitat quality of the current and neighboring (one above and one below) cells. The overall habitat quality of the cells is calculated as

\[
\text{ENV}_{\text{VI}} = \text{Disc}_{\text{Fi}}^{\alpha_{M}} \times \text{Connect}_{\text{Fi}}^{\beta_{M}} \times \text{Prey}_{\text{Fi}}^{\gamma_{M}} \times RU
\]

where Disc\(_{\text{Fi}}\), Connect\(_{\text{Fi}}\), and Prey\(_{\text{Fi}}\) are habitat quality indices based on habitat availability, river connectivity, and drift prey density (respectively) in the grid cell \(i\), \(RU\) is a random variate drawn from a uniform distribution for inherent uncertainty in a fish’s ability to assess habitat quality, \(\alpha_{M}\), \(\beta_{M}\), and \(\gamma_{M}\) are weights for each habitat index. In the SEIBM-1D\textsubscript{SNS}, the weights are equally assigned for discharge and drift prey density. Fish move (or stay in the current cell) in the direction (upstream or downstream) with highest overall habitat quality.

Normalized habitat-quality indices (which vary between 0 and 1) of the cells are determined as follows: Prey\(_{\text{Fi}}\) is based on a cumulative prey selectivity-adjusted density, which is a function of prey density, prey size, and fish size from the Foraging submodel (i.e., \(Q_{\text{prey}}\)); Disc\(_{\text{Fi}}\) and Connect\(_{\text{Fi}}\) are empirically derived from discharge-dependent habitat suitability and river connectivity models developed for the LPR population of shovelnose sturgeon (Peters and Parham, 2008) as

\[
\text{Disc}_{\text{Fi}} = (a_{\text{HSIdis}} e^{-(\text{Disc}-\log(k)^{2}1)}) - \beta_{\text{HSIdis}}(\delta_{\text{HSIdis}}))/a_{\text{HSIdis}}
\]

\[
\text{Connect}_{\text{Fi}} = \alpha_{\text{Connect}}(1 + e^{-(\text{Disc}-\beta_{\text{Connect}})^{\gamma_{\text{Connect}}}})
\]
where $\alpha_{\text{HSIdis}}$, $\beta_{\text{HSIdis}}$, $\delta_{\text{HSIdis}}$ $\alpha_{\text{Connect}}$, $\beta_{\text{Connect}}$, and $\delta_{\text{Connect}}$ are constants (Appendix B). Furthermore, we assume that sturgeon avoid cells with water velocity greater than their critical swimming speed ($V_{\text{max}}$; see Foraging submodel); $\text{Disc}_{\text{Fi}}$ of those cells is set to 0.

Once movement orientation is determined, the new realized location is calculated using fish swimming speed and water velocity as

$$\text{Lon}_t = \text{Lon}_{t-1} + (v_z + w_z) \times t_{\text{move}}$$

(A13c)

where $\text{Lon}_t$ and $\text{Lon}_{t-1}$ are spatial locations of fish at $t$ and $t-1$ (rkm), $v_z$ is sturgeon swimming speed (when sturgeon move upstream, $v_z = -v_z$), $w_z$ is water velocity (m $\cdot$ s$^{-1}$), and $t_{\text{move}}$ is time that sturgeon are active (h).

**Mortality.** In SEIBM-1D SNS, mortality is caused by high temperature (eggs and yolk-sac larvae), predation (eggs, larvae, and juveniles), starvation, and fishing (age 3+). We assume that a constant proportion ($M_{\text{thrm}}$) of eggs and yolk-sac larvae die when water temperature rises above 24 °C (Quist et al., 2004); $M_{\text{thrm}}$ is set to 0.8. For predation, starvation, and fishing mortality, realized mortality is calculated as a stochastic event. The probabilities of predation and fishing mortality ($M_{\text{pred}}$ and $M_{\text{angl}}$, respectively) are calculated as

$$M_{\text{pred or angl}} = 1 - e^{-Z_{\text{pred or angl}}}$$

(A14)

where $Z_{\text{pred}}$ is a size-dependent daily instantaneous mortality rate, calculated as

$$Z_{\text{pred}} = \alpha_{\text{Zpred}} e^{-\beta_{\text{Zpred} \cdot \text{fish}}}$$

(A14a)

where $\alpha_{\text{Zpred}}$ and $\beta_{\text{Zpred}}$ are constants (Appendix B). We assume that predation mortality declines as turbidity increases, the turbidity effect ($P_{\text{Trb}}$) is modeled using a logistic function based on data reported by Gadomski and Parsley (2005) as

$$P_{\text{Trb}} = \alpha_{\text{Trb}} \left(1 + e^{(\text{Trb} - 298.6103)/\beta_{\text{Trb}}}ight)$$

(A14b)

where $\text{Trb}$ is turbidity (NTB), and $\alpha_{\text{Trb}}$ and $\beta_{\text{Trb}}$ are parameters (Appendix B). Fishing mortality rate ($Z_{\text{angl}}$) is estimated from annual harvest rates in the LPR (Peters and Parham, 2008).

The probability of starvation mortality ($M_{\text{starv}}$) is storage weight-dependent and calculated as

$$M_{\text{starv}} = \alpha_{S} + \beta_{S} \rho_{\text{opt}}$$

(A15)

where $\alpha_{S}$ and $\beta_{S}$ are constants (Appendix B).

Realized mortality of eggs and larvae is calculated by drawing a random number from the binomial distribution with $M_{\text{pred}}$ or $M_{\text{starv}}$ as the probability and the number of individuals represented by each SI$_{\text{yoy}}$ as the number of trials. For age 1+ sturgeon, each individual dies when a random number drawn from a uniform distribution is below either $M_{\text{starv}}$ or $M_{\text{angl}}$.

Starvation mortality is evaluated only when a proportion of storage mass relative to total mass drops below the threshold ($\rho_{\text{opt}}$, Appendix B).

**References**


Hanson, P.C., Johnson, T.B., Schindler, D.E., Kitchell, J.F., 1997. Fish bioenergetics 3.0. University of Wisconsin Sea Grant Institute, Madison, WI.


Appendix B. Sources and values of the sturgeon model parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
<th>Description</th>
<th>Equation</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{fish\infty}$</td>
<td>770.78, 811.52</td>
<td>mm</td>
<td>Asymptotic average length (male and female, respectively)</td>
<td>1</td>
<td>Tripp et al. 2009</td>
</tr>
<tr>
<td>$K_L$</td>
<td>0.14, 0.11</td>
<td>year$^{-1}$</td>
<td>Brody growth rate coefficient (male and female, respectively)</td>
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<td>$i_0$</td>
<td>-1.13, -1.99</td>
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<td>von Bertalanffy parameter (male and female, respectively)</td>
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<td>Tripp et al. 2009</td>
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<tr>
<td><strong>Initialization</strong></td>
<td></td>
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<td>$\alpha_{egg}$</td>
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<td>Coefficient of the fractional development of an embryo</td>
<td>A2</td>
<td>Wang et al. 1985</td>
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<tr>
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<td>Exponent of the fractional development of an embryo</td>
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<td><strong>Embryonic development</strong></td>
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<td>$\alpha_{yolksac}$</td>
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<td>Coefficient of the fractional development of a yolk-sac larva</td>
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<td>Wang et al. 1985</td>
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<td>Exponent of the fractional development of a yolk-sac larva</td>
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<td>Wang et al. 1985</td>
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<td><strong>Larval development</strong></td>
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<td>Bevelhimer 2002</td>
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<td>Bevelhimer 2002</td>
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<td>Slope of the maximum daily consumption function</td>
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<td>Bevelhimer 2002</td>
</tr>
<tr>
<td>$\beta_{cmax}$</td>
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<td>unitless</td>
<td>Coefficients in the temperature function</td>
<td>A5a</td>
<td>Bevelhimer 2002</td>
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<td>$\gamma_{ACT}$</td>
<td>1.57, 0.19625, 3.925</td>
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<td>Oxycalorific conversion factor</td>
<td>A6a</td>
<td>Hanson et al. 1997</td>
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<tr>
<td>$\alpha_{TR}$</td>
<td>0.0693</td>
<td>unitless</td>
<td>Exponent of the temperature function</td>
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<tr>
<td>$\alpha_{F}$</td>
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<td>Proportion of consumed energy allocated to egestion</td>
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<td>Bevelhimer 2002</td>
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<tr>
<td>$\alpha_{U}$</td>
<td>0.05</td>
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<td>Proportion of consumed energy allocated to excretion</td>
<td>A6d</td>
<td>Bevelhimer 2002</td>
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<td>$\alpha_{SDA}$</td>
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<td>Proportion of consumed energy allocated to specific dynamic action</td>
<td>A6e</td>
<td>Bevelhimer 2002</td>
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<td>$\alpha_{grow}$</td>
<td>0.12768</td>
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<td>Slope of the optimal $\rho$ function</td>
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<td>Estimated from Shuman et al. 2007 data</td>
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<td>$ED_{str}$</td>
<td>8457</td>
<td>J$\cdot$g$^{-1}$</td>
<td>Energy density of storage tissue</td>
<td>A7b, A7c</td>
<td>Wang et al. 1987</td>
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<td>$ED_{strc}$</td>
<td>4396</td>
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<td>Energy density of structural tissue</td>
<td>A7b, A7c</td>
<td>USDA 2001</td>
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<td>0.000000366,</td>
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<td>Coefficient of the structural mass-length function (YOY and YAO, respectively)</td>
<td>A8</td>
<td>Estimated from Shuman et al. 2007 data</td>
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<td>Parameter</td>
<td>Value</td>
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<td>$\beta_{\text{grow}}$</td>
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<td>$\alpha_{\text{p mature}}$</td>
<td>0.9236, 1.0711</td>
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<td>Coefficient of the allometric maturation function (male and female, respectively)</td>
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<td>$\beta_{\text{p mature}}$</td>
<td>570.6, 674.7</td>
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<td>$\gamma_{\text{p mature}}$</td>
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<td>Intercept of the allometric maturation function (male and female, respectively)</td>
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<td>$\alpha_g$</td>
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<td>Intercept of the allometric gonad function (female and male, respectively)</td>
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<tr>
<td>$\beta_g$</td>
<td>1.05, 1.29</td>
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<td>Slope of the allometric gonad function (female and male, respectively)</td>
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<td>$\delta_g$</td>
<td>18.5</td>
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<td>Exponent of the gonad energy allocation function</td>
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<tr>
<td>$K_{\text{sp n}}$</td>
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<td>Minimum physiological condition to enter in the reproductive cycle</td>
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<tr>
<td>$K_{\text{sp n}}$</td>
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<td>$E_{\text{egg}}$</td>
<td>45.72</td>
<td>$J \cdot \text{egg}^{-1}$</td>
<td>Energy density of an individual egg</td>
<td>USDA 2001</td>
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<tr>
<td>$\alpha_{\text{HS d i s}}$, $\beta_{\text{HS d i s}}$</td>
<td>65.252, 111.03, 63.3, 100.083, 123.107</td>
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<td>Parameters of the discharge-habitat suitability relationship</td>
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<td>$\delta_{\text{HS d i s}}$</td>
<td>38.099</td>
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<td>Parameters in the discharge-connectivity relationship</td>
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<td>$\alpha_{\text{connect}}$, $\delta_{\text{connect}}$</td>
<td>2.5</td>
<td>hrs $\cdot d^{-1}$</td>
<td>Time that shovelnose sturgeon are active</td>
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<td>$P_{\text{mig}}$</td>
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<td>Probability of immigration from the system</td>
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<td>$Z_{\text{egg}}$</td>
<td>0.99</td>
<td>year$^{-1}$</td>
<td>Instantaneous rate of predation mortality (eggs)</td>
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<tr>
<td>$Z_{\text{yolk sac}}$</td>
<td>0.438</td>
<td>year$^{-1}$</td>
<td>Instantaneous rate of predation mortality (yolk-sac larvae)</td>
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<tr>
<td>$Z_{\text{angl}}$</td>
<td>0.43</td>
<td>year$^{-1}$</td>
<td>Instantaneous rate of angling mortality</td>
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<td>$\alpha_{\text{Z pred}}$</td>
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<td>Coefficient of the size-dependent predation mortality function (feeding larvae and YAO)</td>
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<td>$\beta_{\text{Z pred}}$</td>
<td>0.676, 0.08</td>
<td></td>
<td>Exponent of the size-dependent predation mortality function (feeding larvae and YAO)</td>
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<tr>
<td>$\alpha_{\text{Tr b}}$, $\beta_{\text{Tr b}}$, $\delta_{\text{Tr b}}$</td>
<td>1.2102, 298.61, 178.88</td>
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<td>Parameters in the turbidity function</td>
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<tr>
<td>$\alpha_{S}$</td>
<td>1</td>
<td></td>
<td>Intercept of the starvation mortality function</td>
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<tr>
<td>$\beta_{S}$</td>
<td>0.4</td>
<td></td>
<td>Coefficient of the starvation mortality function</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Spawning**

- $E_{\text{egg}}$: Energy density of an individual egg

**Movement**

- $\alpha_{\text{HS d i s}}$, $\beta_{\text{HS d i s}}$, $\delta_{\text{HS d i s}}$, $\alpha_{\text{connect}}$, $\delta_{\text{connect}}$: Parameters of the discharge-habitat suitability relationship

**Mortality**

- $Z_{\text{egg}}$, $Z_{\text{yolk sac}}$, $Z_{\text{angl}}$: Instantaneous rates of predation and angling mortality
- $\alpha_{\text{Z pred}}$, $\beta_{\text{Z pred}}$: Parameters of the size-dependent predation mortality function
- $\alpha_{\text{Tr b}}$, $\beta_{\text{Tr b}}$, $\delta_{\text{Tr b}}$: Parameters of the turbidity function
- $\alpha_{S}$, $\beta_{S}$: Parameters of the starvation mortality function
References


Hanson, P. C., T. B. Johnson, D. E. Schindler, and J. F. Kitchell. 1997. Fish bioenergetics 3.0. University of Wisconsin Sea Grant Institute, Madison, WI.


Appendix C. Derivation of environmental input data.

Time-series inputs of temperature, discharge, depth, width, and turbidity derived from the LPR field survey data by the United States Geological Survey (USGS) National Water Information System (http://waterdata.usgs.gov/nwis). Discharge data are measured at five gauging stations along the river; Duncan (USGS station# 06774000), North Bend (#06796000), Leshara (#06796500), Ashland (#06801000), and Louisville (#06805500). In the model environment, discharge rates from these stations are assigned to grid cell # 1, 50, 76, 128, and 162, respectively. The discharge rates of grid cells between these stations are then estimated by linear interpolation.

Because of limited data availability (e.g., no measurement during winters), we used a wave function to estimate daily and depth average temperature ($T_{ave}$) as

$$T_{ave} = \alpha_T - \beta_T \cos(0.0172t_{DOY}) - \gamma_T \sin(0.0172t_{DOY})$$  \hspace{1cm} (C1)

where $\alpha_T$, $\beta_T$, and $\gamma_T$ are parameters that vary among simulation years (Appendix D).

Depth, width, and turbidity of each grid cell were estimated by empirically derived nonlinear functions of daily discharge rate for each simulation year as

$$\text{Width} = \gamma_{\text{wid}} + \alpha_{\text{wid}}(1 - \beta_{\text{wid}} \cdot \text{disc})$$  \hspace{1cm} (C2)

$$\text{Depth} = \gamma_{\text{dep}} + \alpha_{\text{dep}}(1 - e^{-\beta_{\text{dep}} \cdot \text{disc}})$$  \hspace{1cm} (C3)

$$\text{Turb} = \gamma_{\text{turb}} + \alpha_{\text{turb}}(1 - e^{-\beta_{\text{turb}} \cdot \text{disc}})$$  \hspace{1cm} (C4)

where $\alpha_{\text{wid}}$, $\beta_{\text{wid}}$, $\gamma_{\text{wid}}$, $\alpha_{\text{dep}}$, $\beta_{\text{dep}}$, $\gamma_{\text{dep}}$, $\alpha_{\text{turb}}$, $\beta_{\text{turb}}$, and $\gamma_{\text{turb}}$ are parameters that vary among simulation years (Appendix D), and disc is daily discharge rate.

Photoperiod is calculated using a function of longitude and day of year (Forsythe et al. 1995) as

$$DL = 24 - 2[(12/\pi) \arccos(\tan(\pi Lat/180) \times \tan(\delta_{DL}))]$$  \hspace{1cm} (C5)

$$\delta_{DL} = (23.45/180)\pi \cos[(2\pi / 365) \times (173 - DOY)]$$

where $Lat$ is latitude and $DOY$ is day of year.

References

Appendix D. Sources and values of the environment model parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
<th>Description</th>
<th>Equation</th>
<th>Source</th>
</tr>
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<tr>
<td>Temperature</td>
<td></td>
<td></td>
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<td></td>
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<td>α</td>
<td>varies among years (1995-2011)</td>
<td>unitless</td>
<td>Parameter in the mean daily water temperature function</td>
<td>C1</td>
<td>Estimated from field data</td>
</tr>
<tr>
<td>β</td>
<td>varies among years (1995-2011)</td>
<td>unitless</td>
<td>Parameter in the mean daily water temperature function</td>
<td>C1</td>
<td>Estimated from field data</td>
</tr>
<tr>
<td>γ</td>
<td>varies among years (1995-2011)</td>
<td>unitless</td>
<td>Parameter in the mean daily water temperature function</td>
<td>C1</td>
<td>Estimated from field data</td>
</tr>
<tr>
<td>River width</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>αwid</td>
<td>252.31, 244.49, 328.60, 229.24, 194.70</td>
<td>unitless</td>
<td>Parameter in the discharge-river width relationship (1, 50, 78, 128, and 162, respectively)</td>
<td>C2</td>
<td>Estimated from field data</td>
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<td>βwid</td>
<td>0.9041, 0.9923, 0.9943, 0.9933, 0.9992</td>
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<td>Parameter in the discharge-river width relationship (1, 50, 78, 128, and 162, respectively)</td>
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<td>γwid</td>
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<td>C2</td>
<td>Estimated from field data</td>
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<tr>
<td>River depth</td>
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<td>αdep</td>
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<td>Parameter in the discharge-river depth relationship (1, 50, 78, 128, and 162, respectively)</td>
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<td>Estimated from field data</td>
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<td>βdep</td>
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<td>Parameter in the discharge-river depth relationship (1, 50, 78, 128, and 162, respectively)</td>
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<td>Estimated from field data</td>
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<td>γdep</td>
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<td>Parameter in the discharge-river depth relationship (1, 50, 78, 128, and 162, respectively)</td>
<td>C3</td>
<td>Estimated from field data</td>
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<td>Turbidity</td>
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<tr>
<td>αturb</td>
<td>-68.8031, 12.3288</td>
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<td>Mean and SD of parameter in the discharge-turbidity relationship</td>
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<td>βturb</td>
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<td>Photoperiod</td>
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<td>Latitude of the Lower Platte River</td>
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<td>Drift prey production</td>
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<td>Bpreyinit</td>
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<td>g • m²</td>
<td>Initial drift prey biomass</td>
<td>A1a</td>
<td>Whiles and Goldowitz 2005</td>
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<td>GRprey</td>
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<td>g • d⁻¹</td>
<td>Growth rate of drift prey</td>
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<td>Rashleigh and Grossman 2005</td>
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<td>g • m²</td>
<td>Maximum drift prey biomass</td>
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<td>Net migration rate</td>
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References
