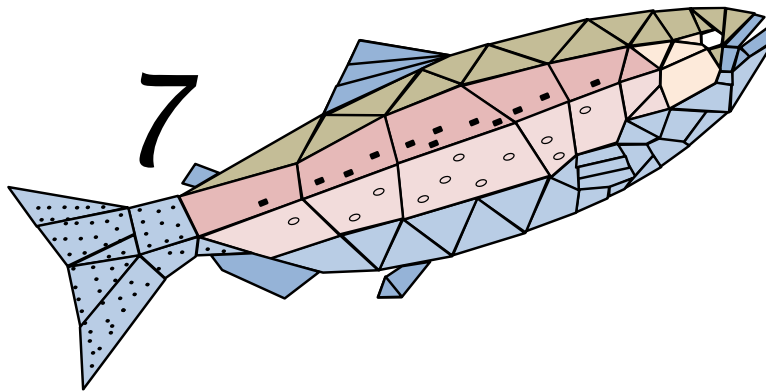# InSALMO 7 Model Description

7

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Contents

I.   Introduction

A.   Background

InSALMO is a family of individual-based models (IBMs) of the freshwater life stages of salmon, designed as river management tools. Their primary purpose is as an instream flow and temperature assessment tool, for predicting how alternative flow and temperature regimes (e.g., resulting from alternative reservoir management rules) affect spawning, incubation, juvenile rearing, and smolt production of a river salmon population. The models have also proven useful for other management and research issues such as designing and evaluating habitat restoration projects. InSALMO is not intended to be a full population model but instead a model of how river management affects freshwater life stages of salmon.

InSALMO version 1.5 was released in 2013 as a Chinook Salmon (*Oncorhynchus tshawytscha*) model, documented by Railsback and Harvey (2013) and used by Railsback et al. (2013) to evaluate the benefits of a habitat restoration project. InSALMO 1.5 was modified into inSALMO-FA, a version also representing facultative anadromy in species such as Steelhead Trout (*O. mykiss*). Railsback et al. (2014) explored the differences between inSALMO-FA and individual-level theory for facultative anadromy.

Each version of inSALMO has been closely based on a version of inSTREAM, a family of resident trout IBMs. InSALMO 1.5 and inSALMO-FA were based on version 4 of inSTREAM, documented by Railsback et al. (2009). The latest version of inSTREAM, designated inSTREAM 7 (Railsback et al., in prep.), is a major update with many changes from previous versions, including:

- Representation of the daily light cycle via four time steps per day, representing dawn, day, dusk, and night;
- Explicit representation of how light intensity varies over space and time (with date, time of day, water depth, and turbidity), and how both food intake and predation risk depend on light;
- Implementation in the NetLogo platform for agent-based modeling (Wilensky 1999), which makes the software much easier to maintain, modify, and use; and
- Updates to many model processes and parameter values based on new literature.

This document describes a new version of inSALMO that is directly based on inSTREAM 7. This version is designated inSALMO 7. (There were no versions 2-6 of inSALMO.) Specifically, this report documents inSALMO version 7.1, which represents obligate anadromous species such as Chinook Salmon.

B.   Report purpose and overview

Sect. 0 of this report describes the inSALMO 7 model: its assumptions, algorithms, and parameters. It does so by describing the changes made to inSTREAM 7 to turn it from an IBM of resident trout into a model of freshwater life stages of salmon. Sect. II.J provides standard values of parameters that are new to inSALMO, and Chinook Salmon values for parameters common to both models. These parameter values should be reviewed carefully for any application of

inSALMO. Sect. IV then describes the few ways that inSALMO's software differs from inSTREAM's.

Railsback et al. (in prep.) provide a complete user manual for inSTREAM 7, including a model description, a software user guide, and a guide to applying the model to new sites. Almost all the information in that manual applies as well to inSALMO 7. Therefore, this report describes inSALMO 7 simply by documenting how it differs from inSTREAM 7. The description follows the organization of the inSTREAM User Manual (Railsback et al. in prep.), which follows the ODD model description format of Grimm et al. (2020).

Here, we refer to the inSTREAM User Manual as the IUM and to specific sections of it as, for example, "IUM 3.1" for the manual's section 3.1. The IUM and the inSTREAM and inSALMO software refer to all simulated fish as "trout". In this document, we refer to resident species and individuals as trout, and anadromous species and individuals as salmon; we use the term "fish" in reference to both trout and salmon. Fish parameter and variable names, however, start with "trout", in keeping with the inSTREAM convention.

As in the IUM, this document provides footnotes that link the description of a model process to the place in the model software where it is implemented.

C.   Acknowledgements

D. Change log

Date	Change	Version information
February 18, 2021	Fork inSALMO 7 from inSTREAM version 7.1	
March 10, 2021	Release inSALMO 7.1	First version of inSALMO 7, representing multiple races of Chinook Salmon and resident trout.
March 15, 2021	Minor change to report Sect. IV.C.	
May 6, 2021	Updated for version 7.2: Revise Sect. II.E.1 on habitat selection radius.	Version 7.2, corresponding to v. 7.2 of inSTREAM. All changes from inSTREAM 7.1 to 7.2 are incorporated: logistic habitat selection radius, elimination of high velocity mortality, fitness set to 0.0 for cells where swimming speed exceeds maximum sustainable.

II. Model Description

A. Model purposes

The purposes of inSALMO are closely related to those of inSTREAM (IUM 3.1), but there is an important difference: inSALMO does not represent the full salmon life cycle and therefore is not useful for predicting river management effects on long-term population dynamics. Instead, inSALMO is intended to predict and explain river management effects on the salmon reproductive cycle, from adult holding and spawning through redd incubation, juvenile rearing, and outmigration. (InSALMO can still represent resident trout, so it could also be used to study how salmon affect trout population dynamics.)

This version of inSALMO represents salmon species that are completely anadromous; it does not represent species such as steelhead or sea trout with individuals that may or may not migrate to the ocean. Even more specifically, inSALMO 7.1 is based on the Chinook Salmon life history and, without modification, may not well represent species or populations in which most juveniles spend their first winter in freshwater. The standard parameter values provided in Sect. III were developed for Central Valley, California, populations of fall-run Chinook.

B. Anadromous and resident species

Unlike inSTREAM, inSALMO must distinguish among species that are anadromous vs. resident, and between anadromous individuals that are vs. are not adults (because anadromous adults are assumed not to feed and cannot outmigrate; sects. 0 and II.I). In any application, inSALMO can represent one or more anadromous species and one or more resident trout species. The anadromous "species" can actually be separate races of salmon, such as fall- and spring-run Chinook.

Anadromous species are identified via a new fish parameter ***trout-is-anadromous?***, which has a value of true for anadromous species and false for resident trout. (Fish parameters have one value per species.)

Adult anadromous individuals are identified via a new fish state variable *trout-life-history-type*. That variable has a value of "anad-adult" only for simulated salmon spawners created via the adult arrival action described in Sect. II.C. For simulated juvenile salmon, *trout-life-history-type* has a value of "anad-juvenile". For all trout, its value is "resident"[1].

C. Adult arrival

Adult arrival is the model process that represents arrival of anadromous adults from the ocean to the simulated stream reaches. (InSALMO represents stream habitat as one or more "reaches" that may or may not be contiguous.) InSALMO 7 uses almost exactly the same methods as inSALMO 1.5; these include reading the number and characteristics of arriving adults for each year, species, and reach from an input file, then creating the adults and adding each to the model on the simulated date of its arrival. Arriving adults simply appear in their designated reach; there is no simulation of upstream migration.

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[1] The variable *trout-life-history-type* is set in the procedures `add-adults`, `build-initial-populations`, and `redd-emergence`.

Adult arrival includes a new part of model initialization (IUM 7) and a new action in the model's schedule (IUM 5). Initialization of inSALMO 7 includes identifying the characteristics of each adult, including when it arrives in the model; and the new schedule action actually creates the adults at the time they arrive.

1. Adult initialization

Initialization of inSALMO 7 includes a new submodel called adult initialization, which sets the characteristics of each adult from the input provided in adult arrival input file[2]. (The format of this file is provided in Sect. IV.A.) The input file includes one row for each combination of species, reach, and year. It specifies:

- The number of adult spawners of the species to be created and placed in the reach that year (which becomes the variable *num-spawners*);
- The fraction of those adults that are female (*frac-female*);
- The dates (year, month, and day) that adult arrive starts and ends (*arrival-start-date* and *arrival-end-date*) and peaks (*arrival-peak-date*); and
- The parameters of a triangular distribution from which lengths are drawn (*length-min*, *length-mode*, and *length-min*).

The year variable that each line starts with is not actually used by inSALMO; it is included only as an aid to the user in building and understanding the arrival input file. Typically it refers to the brood year: the water year in which the spawners' offspring will emerge.

The adult initialization submodel performs the following steps for each data row of the adult arrival input file.

First, irrelevant rows are identified and excluded. Rows are excluded if the reach name does not correspond to a reach in the simulation (therefore, the input file can include data for reaches not used in all simulations), or if the species is not among those being simulated. Rows are also excluded if they refer to dates not in the current simulation: if *arrival-start-date* is after the last date simulated or if *arrival-end-date* precedes the first date simulated.

Next, the characteristics of each adult that could be initialized are determined and recorded on a list. This "arrival list" can be thought of as an array with one row per adult and columns containing the information to initialize the adult on its arrival date. (In the software it is a list of lists, with each item on the arrival list being a list of variable values for one salmon.) The arrival list is created by going through the unexcluded rows of the adult arrival input file and adding one item to the arrival list for each fish specified in the input file.

For each row of the input file, the numbers of female and male adults are first calculated. The number of females (*num-females*) is equal to *num-spawners* × *frac-female*, rounded to an integer; *num-males* is set to *num-spawners* – *num-females*. Then, *num-females* rows are added to the arrival list. The characteristics of the adult represented by each row are set using these methods:

- The reach it will arrive in is set to the reach in the input data row.

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[2] This submodel is coded in the procedure `build-adult-arrival-list`.

- The adult's species is set to the value in the input data row.
- Sex is set to female.
- Age is set to 4, an arbitrary value that has no effect.
- The date of arrival is drawn from a random triangular distribution with minimum equal to *arrival-start-date*, mode of *arrival-peak-date*, and maximum of *arrival-end-date*. Dates drawn from the distribution are rounded to an integer. (This arrival period can span the end of a year.)
- Length is drawn from a random triangular distribution defined by *length-min*, *length-mode*, and *length-min*.

Next, *num-males* rows are added to the arrival list, and the same steps used to set each individual's characteristics except that sex is set to male.

At this point, the arrival list contains one entry for each adult specified by relevant rows of the adult arrival input file. This list is then sorted by date of arrival, from earliest to latest. Any arrival dates before the first simulated date are removed from the list; such dates could occur if a simulation starts during the period of adult arrivals.

2. Adult arrival

A new item on the model schedule (IUM 5) creates and initializes simulated adults on the date their arrival is scheduled[3]. This action is executed by the model (the "observer" object) after the habitat update actions and before the trout update, activity and habitat selection, survival, and growth actions. This scheduling causes anadromous adults to select habitat and activity, be subject to mortality, and possibly spawn on the same day they arrive from the ocean. Like spawning, adult arrival is executed only once per day, on the first time step in daytime.

Arrival is executed by the observer examining the sorted arrival list. For each entry on that list that has an arrival date equal to the current simulate date (if there are any), a new adult is created and then that entry removed from the arrival list. Each new individual is initialized by:

- Setting its species, sex, and length to the values specified in its entry in the arrival list;
- Setting its value of *trout-life-history-type* to "anad-adult"; and
- Initializing other state variables (for weight, spawning status, memories, location, and activity) as they are for trout (IUM 7.3). That process includes placing the new fish in a cell selected randomly (weighted by cell area) from among the reach's non-dry cells. The subsequent habitat and activity selection action allows the newly arrived adult to select a good location before being subject to mortality.

D. Initialization of juvenile salmon

Juvenile salmon can be initialized at the start of a simulation. This capability (which previous versions of inSALMO lacked) allows simulations to skip adult arrival, spawning, and egg incubation and focus only on how river management affects juvenile rearing and downstream

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[3] This action is coded in the procedure `add-adults`. This procedure must be scheduled before `update-trout` because the newly arrived adult salmon must be updated before executing any of their other actions.

migration. Simulations of more than one year would depend on adult arrival and spawning to create juveniles after the first year.

Juvenile salmon can be initialized at the start of a simulation simply by including them in the initial population input file that defines the initial trout population (IUM 13.4). Initialization of juvenile salmon is the same as for resident trout (IUM 7.3) with one exception. When individuals of a resident species are initialized, their value of *trout-life-history-type* is set to "resident", whereas individuals of anadromous species have *trout-life-history-type* initialized to "anad-juve"[4].

Juvenile salmon created at the start of a simulation are initially placed in a randomly chosen cell in their reach. This method does not necessarily expose such individuals to the habitat conditions that newly emerged fry are exposed to when they emerge from redds, which are typically placed in relatively high water velocities. For that reason, initializing juvenile salmon at the size of new emerged fry may or may not be a good way to represent the first few days after emergence, when (in many real populations) many fry migrate downstream before they can find productive feeding habitat. The period of high fry outmigration can be avoided, if desired, by initializing juvenile salmon with lengths that allow them a good chance of finding productive habitat (IUM 9.13.1).

E. Habitat and activity selection by adults except spawned females

In inSTREAM and inSALMO 7, all simulated fish select habitat (which cell to occupy) and activity (whether to feed vs. conceal themselves) each time step. InSALMO assumes that the methods used to make this decision vary among life stages. For anadromous adults, habitat and activity selection differs from inSTREAM's methods (IUM 9.13) in the three ways described below. However, female adults that have already spawned instead use methods described in Sect. II.G.1.

1. Limited habitat selection radius and restriction to reach

Starting with version 7.2, inSALMO and inSTREAM both model the radius over which fish select habitat as a logistic function of length that approaches a maximum radius (IUM 9.13.1). The same method and parameters apply to juveniles and adults. The parameters for this function are ***trout-move-radius-max*** (cm), the maximum radius; ***trout-move-radius-L1*** (cm), the fish length at which the radius is 10% of the maximum; and ***trout-move-radius-L9*** (cm), the length at which the radius is 90% of maximum. The values of these parameters should differ between trout and salmon species so that adults of all species have reasonable habitat selection radii. For salmon, values of 20000, 7, and 20 cm for ***trout-move-radius-max***, ***trout-move-radius-L1***, and ***trout-move-radius-L9*** produce habitat selection radius values of 5.6 m for a juvenile at 3 cm length, 11 m at 5 cm, 47 m at 10 cm, and 125 m at 15 cm; and values close to 200 m for all adults.

InSALMO also restricts anadromous (but not resident) adults from selecting habitat in different reaches[5]. This restriction (which is easily removed) allows users to control how many adults

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[4] This assignment of life history type is done automatically in the procedure `build-initial-populations`.

[5] The restriction from moving among reaches is coded in the procedure `select-activity-and-habitat`, where comments say how to remove it.

spawn in each reach, which is often important for reproducing observed conditions. (In fact, input on the number of spawners per reach is often developed from field counts of redds.)

2. No feeding

InSALMO assumes adult salmon do not feed: food intake for all habitat and activity options is zero. Adults therefore select behavior to maximize their expected probability of surviving predation and starvation when starvation probability depends only on their rate of energy use (IUM 9.13.2). As a consequence, they seek habitat with low predation risk, low swimming speed, and (if there are options) low temperature.

This assumption and the one in the following subsection are implemented by defining a new activity (in addition to search feeding, drift feeding, and concealment) used only by anadromous adults. This "hold" activity is identical to the drift-feeding activity except that food intake is zero[6]. Consequently, holding fish:

- Consider swimming costs in selecting habitat,
- Can use velocity shelter and exclude other fish from velocity shelter,
- Do not deplete food, and
- Cannot use hiding places.

3. No concealment

InSTREAM 7 assumes that predation risk is affected by the availability of hiding places, discrete locations where one individual can conceal itself (IUM 9.19.6). Including adult salmon complicates this assumption because large adult salmon cannot occupy many places that provide typical concealment cover for resident trout. To represent concealment by salmon we would need to provide separate input on hiding places large enough for them.

To avoid the need for additional input, inSALMO 7 simply assumes that adult salmon do not use hiding places. We know that this assumption is not always true, but it seems reasonable considering that concealment cover large enough for adult salmon is typically rare, especially in the relatively large alluvial rivers where we expect inSALMO to be used most. Without the ability to use concealment cover, model salmon should select habitat where depth and proximity to escape cover reduce predation risk.

F. Spawning readiness

The spawning readiness submodel (IUM 9.28) determines whether a female fish spawns on a particular day, considering characteristics of the female and its habitat. InSALMO modifies this submodel for anadromous species. For anadromous individuals (female and male), the criteria for minimum age, length, and condition are not applied; instead, spawners must have *trout-life-history-type* equal to "anad-adult". This change implements the assumption that all arriving adult salmon are able to spawn.

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[6] The hold activity is implemented in procedures `select-activity-and-habitat`, `fitness-for`, `growth-rate-for`, `survive`, `non-starve-survival-for`, and `use-cell-and-activity`.

G. Spawning

1. Redd guarding

Female salmon spawners, unlike trout, are assumed to guard their redds from the time of spawning until their death. (Spawner mortality is discussed in Sect. II.K.) Redd guarding behavior is represented by a new potential value of the fish state variable *trout-activity*. This variable is set to "guarding" for fish that (a) are anadromous (***trout-is-anadromous?*** for the species is true), (b) are female, and (c) have spawned. All fish meeting these criteria have *trout-activity* set to "guard" upon spawning, and this variable never changes value until the fish dies[7]. (On the model's graphical interface, the color of adults is darkened when they spawn, to indicate guarding, although guarding females are typically hidden behind their redd.)

A spawned adult using the "guard" activity uses these habitat and activity selection behaviors:

- It no longer moves, but instead remains in the cell where it placed its redd.
- It does not feed or consume food.
- It uses neither hiding places nor velocity shelter and instead has swimming speed equal to the cell's velocity.

Guarding adults affect superimposition mortality of their own redd (Sect. II.J) and spawning site selection by other spawners (below).

2. Spawning cell selection

InSALMO changes the methods used by a spawning female to select the cell for its redd (IUM 9.30) in several ways[8].

Redd guarding affects spawning site selection by other females (of both resident and anadromous species) by reducing the area of available spawning gravel. The cell area that a guarding female salmon is assumed to protect from spawning by others is specified by the new parameter ***trout-spawn-defense-area*** (cm^2). Females are assumed to guard an area larger than the redd size as defined by the parameter ***redd-area***. Railsback and Harvey (2013) used literature on Chinook Salmon to select values of 56,000 cm^2 for ***redd-area*** and 200,000 cm^2 for ***trout-spawn-defense-area***. (Resident species must have values for ***trout-spawn-defense-area***, but they are not used.)

The area protected by guarding females affects spawning site selection in two ways[9]. First, inSTREAM assumes a female will not spawn in a cell with an area of available spawning gravel less than its value of ***redd-area***. For inSALMO 7, this area of available spawning gravel is defined as total gravel area (*cell-area* × *cell-frac-vel-shelter*) minus the area defended by all guarding females in the cell (the sum of ***trout-spawn-defense-area*** over all such guarders). This

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[7] The guarding activity is coded in procedures `spawn`, `select-activity-and-habitat-with-migration?`, and `growth-rate-for`.

[8] Selection of a spawning cell is in the procedure `spawn-cell`. The new procedure `available-spawning-area` calculates the area of unguarded spawning gravel.

[9] The changes in spawning cell selection are programmed in the reporter `spawn-cell`. The new reporter `available-spawning-area` computes the area of unguarded gravel in a cell.

definition makes the approximation that all the area defended by a spawner is gravel. If this definition produces a negative area of available gravel it is set to zero.

The same measure of available (unguarded) spawning gravel is also used in the method used to select the spawning cell from among the suitable cells, which uses a random draw weighted by area of available spawning gravel.

We assume that spawning salmon will search for a good redd location over a wider area than they select holding habitat from. Therefore, the maximum radius used for habitat selection (Sect. II.E.1) is not applied to selection of spawning cells. However, the restriction from moving among reaches discussed in Sect. II.E.1 does apply to selection of spawning cells by anadromous adults. (That restriction does not apply to resident spawners.)

H.   Juvenile habitat and activity selection

Habitat and activity selection by juvenile salmon merges the methods of inSALMO 1.5 and inSTREAM 7. The inSTREAM methods (IUM 9.13) are modified in two ways, both taken directly from inSALMO 1.5. The methods here apply only to simulated fish with *trout-life-history-type* equal to "anad-juve".

1.   Downstream migration as habitat selection alternative

InSALMO treats downstream migration as a habitat selection alternative[10]. On each time step, each juvenile salmon evaluates a fitness measure for each combination of habitat cell and activity (IUM 9.13.2; Sect. II.H.2, below). This fitness measure represents expected future survival of predation and starvation and growth to smolt size. The juvenile salmon also evaluate their expected fitness if they choose the alternative of migrating downstream instead of using one of the cells within their habitat selection radius. Because we cannot assume a juvenile salmon has any specific knowledge of downstream conditions, this "downstream migration fitness" is modeled simply as a logistic function that increases with juvenile size (Figure 1). The logistic function simply represents how a salmon's probability of surviving to the ocean, and its willingness to migrate downstream, increase with its length. The function is defined by two parameters, *trout-migrate-fitness-L1* and *trout-migrate-fitness-L9*, that are the salmon length (cm) at which its value is 0.1 and 0.9. Experience with earlier versions of inSALMO and exploration of example results suggests values of 4.0 and 10.0 for these parameters, but their effects on outmigrant numbers, size, and timing should be evaluated in calibration. That evaluation is usually clearer when both parameters are changed by the same amount (sliding the curve in Figure 1 left and right, instead of changing its shape). (Values of these parameters must be provided for resident trout but are ignored.)

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[10] The downstream migration decision is implemented with changes in procedures `build-logistic-functions`, `update-logistics`, and `select-activity-and-habitat-with-migration?` (which is renamed from inSTREAM's `select-activity-and-habitat`).
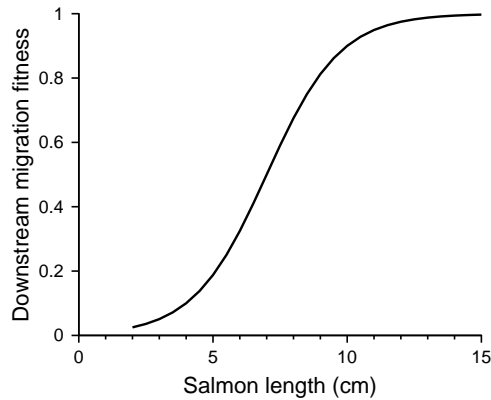
Figure 1. Downstream migration fitness function, with values of 5.0 and 10.0 cm for parameters ***trout-migrate-fitness-L1*** and ***trout-migrate-fitness-L9***.

Juvenile salmon migrate downstream (using methods described below) on any time step on which the value of the downstream migration fitness function, for their current length, exceeds the best fitness measure value for the cells within their current habitat selection radius.

Important characteristics of this model of the downstream migration decision include:

- Because of the logistic function, newly emerged fry migrate downstream only if expected fitness in their current location is very low. However, newly emerged fry often face severe competition and unproductive habitat (especially, velocities exceeding their swimming ability) that result in low expected fitness, and many do in fact migrate downstream.
- Fry able to find productive habitat tend to stay and rear until they approach smolt size.
- Because the decision of whether to migrate downstream is made every time step and considers only the current growth and survival conditions (not, for example, average growth over the past several days), short-term events such as pulses of flow, turbidity, or high temperature can cause many juveniles to migrate downstream immediately.

2.   Smolt size as growth term in objective

For juveniles, the fitness measure used in habitat and activity selection includes a term representing the benefits of growth. In inSTREAM, this growth term is the fraction of minimum spawning length a fish expects to obtain at its decision time horizon (UIM 9.13.2). That term would not make sense for inSALMO, in which juveniles seek to grow large enough to smolt and migrate to the ocean. Instead, inSALMO uses the new parameter ***trout-fitness-length*** in the growth term of all species, including resident trout. Juvenile salmon and resident trout seek further growth as long as their length is less than ***trout-fitness-length***[11].

For resident trout, setting ***trout-fitness-length*** equal to ***trout-spawn-min-length*** makes the fitness measure's growth term equivalent to inSTREAM's. For salmon species with juveniles that typically migrate out relatively early, setting ***trout-fitness-length*** to a value several cm higher than ***trout-migrate-fitness-L9*** (e.g., 15 cm) promotes early outmigration by reducing the

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[11] The growth term is implemented in procedure `fitness-for`.

expected fitness values for remaining in their reach (because expected future length is a smaller fraction of *trout-fitness-length*). Lower values of *trout-fitness-length* encourage juveniles to remain in the stream longer, which could be useful for modeling species with juveniles that typically migrate out later.

(Previous versions of inSALMO used as *trout-migrate-fitness-L9* as the target length in the fitness measure's growth term, but that approach does not work in inSALMO 7. The additional adaptive behaviors in inSALMO 7 let juveniles obtain higher fitness in their reach, making them unlikely to migrate downstream unless their growth target is higher than *trout-migrate-fitness-L9*.)

I.   Downstream migration and outmigration

This section describes the downstream migration submodel: what happens to anadromous juveniles that select the downstream migration option in their habitat and activity selection decision. Simulating downstream migration of juvenile salmon is especially uncertain and complex, because of hydraulic complexities and because the extent to which these fish move volitionally is variable and unknown. The approach could be highly mechanistic, using particle tracking methods and assumptions about swimming speeds and directions to simulate the downstream movement path. While particle tracking techniques are well-established, they would add considerable complexity and computational effort to inSALMO. A more approximate alternative that still considers water velocity as a driver of migration speed is to estimate a downstream movement speed from cell velocities (e.g., by assuming a migrating fish moves at the mean cell velocity of its reach) and calculate how far a fish moves in the time step, at that speed. This approximation would still require adding the information needed to calculate distances in the downstream direction, which inSALMO currently lacks. (Assigning a "river kilometer"—distance along the thalweg from some downstream point—to each cell is one way to provide distance information.)

This version of inSALMO adapts the simple outmigration approach of inSALMO 1.5: juveniles salmon choosing to move downstream simply jump to the next reach downstream. We use the same methods as inSALMO 1.5, with one major difference: inSALMO 7 simulates four time steps per day instead of one, so can allow juveniles to move as many as four reaches per day.

This method requires information on the arrangement of reaches (which reaches are downstream of which others), which is not provided explicitly in inSTREAM 7 (IUM 19.2). This information is provided in inSALMO 7 as in previous versions, by the user providing values for two reach parameters: *reach-upstream-junction* and *reach-downstream-junction*. The values of these parameters are integers selected to define the actual arrangement of reaches. A reach can identify any other reaches that are immediately downstream of it as those with a value of *reach-upstream-junction* equal to its value of *reach-downstream-junction*. This approach lets users define networks of reaches (tributaries; channels through a delta) as well as simple chains of reaches. (This junction approach is explained and illustrated more thoroughly in Sect. 3.1.2 of Railsback and Harvey 2013.)[12]

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[12] Reach junctions are implemented at the end of procedure `build-reaches`.

A simulated juvenile salmon that decides to migrate downstream executes the following steps.[13] They implement, in a simple way, the assumption that if a salmon migrates downstream it is carried into the next reach and, at some point in that reach, occupies habitat where it can control its own motion.

- Identify the reach(es) immediately downstream of its current reach. If there is no such reach, then the juvenile is considered as having migrated out of the simulated system, as explained below.
- Identify potential destination cells in the downstream reach(es) as those meeting two criteria: depth greater than zero and velocity less than the juvenile's maximum sustainable swimming speed. If no cell meets both criteria, then those meeting the depth criteria are identified.
- Randomly select and move to one of the potential destination cells. The cells have equal probability of being selected.
- Re-execute the habitat and activity selection submodel, but without the option of again migrating downstream. This causes the juvenile to move to the best nearby cell and use the best activity (among drift and search feeding and hiding) in its new reach. The growth rate and risk experienced with this cell and activity determine the fish's growth for the time step and are used as memory for future decisions (IUM 9.12).

Juveniles that decide to migrate out of the most-downstream reach are treated as "outmigrants" that have migrated out of the entire simulated system. They are simply removed from the model after their characteristics are recorded for output (Sect. **Error! Reference source not found.**).

J. Superimposition redd mortality and redd guarding

InSALMO implements the assumption that female spawners protect their redds from other females spawning over them (Sect. II.F). This effect of redd guarding is modeled simply by assuming that a redd cannot experience superimposition mortality (IUM 9.37) while the female that produced it is still alive[14].

K. Spawner mortality

Adult salmon typically die shortly after spawning. InSALMO represents this mortality via the low condition survival submodel. In both inSTREAM and inSALMO, fish—both males and females—are assumed to lose a large fraction of their weight when they spawn (IUM 9.29). This fraction is specified by the parameter ***trout-spawn-wt-loss-fraction***, which typically has a value of 0.4 for salmon (versus 0.2 for resident trout). As a consequence of this weight loss, salmon typically die of low condition (IUM 9.18) within a few days of spawning.

InSALMO's representation of post-spawning mortality requires two differences from inSTREAM, in addition to the higher value of ***trout-spawn-wt-loss-fraction***. First, inSALMO simply removes from the simulation any adults that have not spawned by the end of the spawning season. Female adults may not spawn if there are too few days of suitable spawning conditions (IUM 9.28) between their arrival and the end of the spawning season, compared to

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[13] Downstream migration is coded in the new procedure `migrate-downstream`.
[14] Protection of redds by guarding spawners is programmed in the procedure `be-superimposed-by`, using a new redd variable *redd-spawner*, which is set in the procedure `spawn`.

their probability of spawning on any such day (parameter **trout-spawn-prob**; Table 1). Some male adults cannot spawn if there are more males than females that spawn. Unspawned adults have little effect on simulations (the only resource they can consume is velocity shelter; Sect. II.E), but they are unrealistic and require additional computations. Therefore, inSALMO simply removes them at the end of the spawning season. Any individual with *trout-activity* still equal to "hold" on the day after the last day of spawning is removed as if it died, with the event recorded as "removed unspawned adult"[15].

The second difference is in the low condition survival submodel. InSTREAM 7 uses a new formulation for low condition survival, the mortality source that causes spawned adult salmon to die in inSALMO. The inSTREAM 7 method (IUM 9.18) assumes a linear relation between daily survival probability and *trout-condition* (weight as a fraction of "healthy" weight), which works well for balancing growth vs. risk avoidance under normal conditions and as trout recover weight after spawning. However, this method produces unrealistically long survival (and, therefore, redd guarding) in salmon spawners.

To address this problem, inSALMO uses a two-piece linear relation between condition and survival (Figure 2)[16]. This relation is defined by two parameters: **mort-condition-S-at-K8** and **mort-condition-S-at-K5**. When *trout-condition* is above 0.8, daily survival probability increases linearly from **mort-condition-S-at-K8** to 1.0 as *trout-condition* increases from 0.8 to 1.0. When *trout-condition* is less than 0.8, survival increases linearly from the value of **mort-condition-S-at-K5** to **mort-condition-S-at-K8** as *trout-condition* increases from 0.5 to 0.8.

Values for these parameters are provided in Table 1. They should be changed only very cautiously because they affect behavior of all fish as well as survival of spawned adults.

This two-piece relation for low condition is not implemented in the method fish use to project future expected survival as part of their habitat and activity selection behavior—that method still assumes a simple linear relation no matter how low expected future condition is (IUM 9.13.2).

---

[15] Unspawned adults are removed in the `survive` procedure.

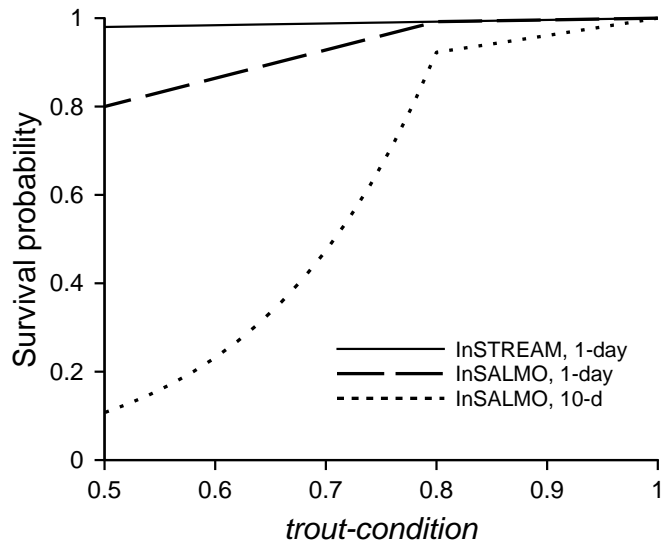[16] This change is implemented in the procedure `survival-condition-for`.

Figure 2. InSALMO's condition survival function. InSTREAM's linear relation (solid line) produces high survival at post-spawning condition, while inSALMO's two-piece relation produces lower daily survival probabilities when *trout-condition* is < 0.8. For anadromous post-spawning condition (<0.6), the probability of surviving 10 days (dotted line) is low; mean survival time at *trout-condition* of 0.6 is 5 days.

III.   Parameter Values

Table 1 identifies fish parameters that are either new to inSALMO (and therefore not discussed in the IUM) or have different standard values for salmon than for resident trout. Unless otherwise noted, standard values are adopted from inSALMO 1.5 (Railsback and Harvey 2013). Parameter values for spawning depth and velocity suitability are presented in Table 2.

Table 1. Standard parameter values for Chinook Salmon.

Parameter name	Standard value for Chinook Salmon	Notes
trout-is-anadromous?	`true`	`false` for resident species.
trout-emerge-length-min	3.5 (cm)	Values assume Chinook fry are larger than trout fry.
trout-emerge-length-mode	3.8	
trout-emerge-length-max	4.1	
trout-fitness-length	15 (cm)	Values closer to ***trout-migrate-fitness-L9*** cause juveniles to remain in the model longer and migrate out at larger size. For resident trout, the value should equal ***trout-spawn-min-length***.

15

Parameter name	Standard value for Chinook Salmon	Notes
trout-migrate-fitness-L1 *trout-migrate-fitness-L9*	4.0 (cm) 10.0	Can be adjusted in calibration to change the length of outmigrants.
trout-max-move-dist	20000 (cm)	Should represent reach size and complexity. Lower values reduce adults' ability to move among reaches.
trout-spawn-defense-area	200000 (cm^2)	Value for resident trout has no effect.
trout-spawn-fecund-mult *trout-spawn-fecund-exp*	690 0.552	These are quite different from standard trout values but documented by Railsback and Harvey (2013).
trout-spawn-start-day *trout-spawn-end-day*	Fall-run: 10/1 Fall-run: 11/30	Values will usually be specific to site and race.
trout-spawn-max-temp *trout-spawn-min-temp*	14 (°C) 5	
trout-spawn-min-age *trout-spawn-min-length* *trout-spawn-min-cond*	-9 (years) -9 (cm) -9 (unitless)	For salmon, these parameters are not used so can have any values. Negative values make it clear that the parameters are not used.
trout-spawn-prob	Fall-run: 0.2 Spring-run: 0.1	If adults can arrive near the end of the spawning date window, the value should be higher than for residents or races that hold upon arrival—otherwise, many adults will not have time to spawn. A value of 0.2 results in 50% spawning within 3 days and 80% spawning within a week; 0.1 results in 50% spawning within a week.
trout-spawn-wt-loss-fraction	0.4	Resident trout value is typically 0.2.

Parameter name	Standard value for Chinook Salmon	Notes
trout-superind-max-rep *trout-superind-max-length*	40 10 (cm)	Salmon simulations typically have many more and larger juveniles than trout simulations, so higher values of these parameters may be necessary to make run times acceptable.
trout-weight-A *trout-weight-B*	0.00411 3.49	Representing juveniles well is more important than representing adults.
mort-condition-S-at-K8 *mort-condition-S-at-K5*	0.992 0.8	These values should also be used for trout. They produce the same survival as inSTREAM's standard parameter value, when condition is >0.8.
mort-fish-pred-P9	-5 (predators per cm^2)	This large negative value eliminates the effect of trout density on risk of fish predation (IUM 9.20.5). The standard value for trout in the absence of other predatory fish (~5.0E-7) causes fish predation to be unrealistically low in salmon-only simulations. This negative value assumes there are always predatory fish present.
mort-high-temp-T1 *mort-high-temp-T9*	28.0 (°C) 24.0	
mort-redd-hi-temp-T1 *mort-redd-hi-temp-T9*	23.0 (°C) 17.5	
mort-redd-lo-temp-T1 *mort-redd-lo-temp-T9*	1.7 (°C) 4.0	
mort-redd-scour-depth	20 (cm)	

Parameter name	Standard value for Chinook Salmon	Notes
redd-devel-A	0.00190	These values cause inSTREAM's redd development method to exactly match the Chinook equation and parameter values of inSALMO 1.5.
redd-devel-B	0.000500	
redd-devel-C	0.0000360	
redd-area	56000 (cm^2)	

Standard values for the "suitability criteria" adult salmon use in selecting spawning habitat are also unchanged from inSALMO 1.5 (Table 2).

Table 2. Depth and velocity spawning suitability parameter values for Chinook Salmon.

Cell depth (cm)	Depth suitability	Cell velocity (cm/s)	Velocity suitability
0	0.0	0.0	0.0
12	0.0	2.3	0.0
27	0.95	3	0.06
33.5	1.0	54	1.0
204	0.0	61	1.0
		192	0.0

IV.   Software Changes

Sections 10-17 of the IUM provide guidance on using the inSTREAM software, and apply equally to inSALMO. Here we describe the few software differences between the models, which all concern input and output files. IUM 17 provides trouble-shooting help for input files.

A.   Adult arrival file

The adult arrival file is the only input file unique to inSALMO. It provides the information needed to create adult salmon (Sect. II.C). It is a text file in CSV format, designed to be maintained in spreadsheet software (general information on input files is at IUM 13.1). The name of the file must be provided by the user in this line of the parameter file:

```
set adult-arrival-file "Example-Project/ExampleB-AdultArrivals.csv"
```

The file can start with an arbitrary number of comment lines that start with a semicolon and are ignored by the model (blank lines at the top of the file are also ignored). It then must contain one line (row) for each combination of year, species, and reach. Each such line must have 11 values (or columns), comma-separated. Text values are *not* in quotes. All date values must be in M/d/yyyy format (e.g., `9/30/2015`). The values, which are explained above in Sect. II.C.1, are:

- The year (which is ignored by the model and can be user-defined);
- The salmon species name, exactly as defined in the parameter file;
- The name of the reach where the adults will arrive, exactly as in the parameter file;
- The number of adults arriving;
- The fraction of adults that are female;
- The date on which arrival starts;
- The date on which arrival peaks, which must be between the start and end dates;
- The date on which arrival ends;
- The minimum length of adults (cm);
- The mode (most likely) adult length; and
- The maximum adult length.

Figure 3 provides an example of this file. In the example, the year in column 1 is the brood year—the water year in which the spawners' offspring will emerge, which is one greater than the calendar year in which the adults arrive.

	A	B	C	D	E	F	G	H	I	J	K
1	; Adult arrival input for InSALMO-7										
2	; Test input for Example Project B										
3	; Year	Species	Reach	Number	Fraction female	Arrival start	Arrival peak	Arrival end	Length min	Length mode	Length max
4	2001	Chinook-Fall	Upstream	59	0.46	10/1/2000	10/31/2000	11/15/2000	50	65	85
5	2002	Chinook-Fall	Upstream	53	0.74	10/1/2001	10/31/2001	11/15/2001	50	65	85
6	2003	Chinook-Fall	Upstream	103	0.04	10/1/2002	10/31/2002	11/15/2002	50	65	85
7	2004	Chinook-Fall	Upstream	99	0.33	10/1/2003	10/31/2003	11/15/2003	50	65	85
8	2005	Chinook-Fall	Upstream	135	0.85	10/1/2004	10/31/2004	11/15/2004	50	65	85
9	2001	Chinook-Spring	Upstream	100	0.96	4/1/2000	6/1/2000	9/1/2000	40	60	70
10	2002	Chinook-Spring	Upstream	139	0.07	4/1/2001	6/1/2001	9/1/2001	40	60	70
11	2003	Chinook-Spring	Upstream	97	0.73	4/1/2002	6/1/2002	9/1/2002	40	60	70
12	2004	Chinook-Spring	Upstream	53	0.75	4/1/2003	6/1/2003	9/1/2003	40	60	70
13	2005	Chinook-Spring	Upstream	93	0.09	4/1/2004	6/1/2004	9/1/2004	40	60	70
14	2001	Chinook-Fall	Middle	109	0.6	10/1/2000	10/31/2000	11/15/2000	50	65	85
15	2002	Chinook-Fall	Middle	94	0.47	10/1/2001	10/31/2001	11/15/2001	50	65	85
16	2003	Chinook-Fall	Middle	142	0.57	10/1/2002	10/31/2002	11/15/2002	50	65	85
17	2004	Chinook-Fall	Middle	86	0.66	10/1/2003	10/31/2003	11/15/2003	50	65	85
18	2005	Chinook-Fall	Middle	145	0.58	10/1/2004	10/31/2004	11/15/2004	50	65	85
19	2001	Chinook-Spring	Middle	58	0.06	4/1/2000	6/1/2000	9/1/2000	40	60	70
20	2002	Chinook-Spring	Middle	87	0.68	4/1/2001	6/1/2001	9/1/2001	40	60	70
21	2003	Chinook-Spring	Middle	75	0.47	4/1/2002	6/1/2002	9/1/2002	40	60	70
22	2004	Chinook-Spring	Middle	55	0.22	4/1/2003	6/1/2003	9/1/2003	40	60	70
23	2005	Chinook-Spring	Middle	131	0.61	4/1/2004	6/1/2004	9/1/2004	40	60	70

Figure 3. Example adult arrival input file, in spreadsheet software. It provides input for two Chinook Salmon races and two reaches.

B.   Population initialization file

The population initialization input file defines the trout or salmon population at the start of a simulation. It is unchanged from inSTREAM (IUM 13.4) but addressed here because inSALMO often is used without such initial populations (with arriving adults instead being the first fish). For simulations with no resident trout and no initial salmon juveniles, this file must still be

provided but should have no input rows (or the number of initial fish in each row can be set to zero).

C. Outmigrant output: the virtual screw trap

InSALMO's primary results are the number, size, and timing of juvenile outmigrants. If there are data for calibration and comparison to these results, they likely came from an outmigrant trap, typically a rotary screw trap. InSALMO provides a "virtual screw trap" output file that reports outmigrant results that are easily compared to such data.

(This output file differs from real outmigrant traps in an important way: it provides accurate output on every outmigrant, whereas real traps sample only a fraction of all the outmigrants. The fraction of outmigrants captured in a real trap varies with factors such as outmigrant size and river flow, and can only be estimated via "trap efficiency" analyses. These sources of uncertainty in trap data should be considered carefully when comparing them to inSALMO output.)

The most fundamental data reported from outmigrant traps are the counts and characteristics of individual outmigrants. Those data are often summarized as the number of outmigrants per day (or week) in several length classes. The length classes are often chosen to approximate the fry, parr, and smolt life stages, e.g., by referring to outmigrants < 5 cm length as fry, those 5-7 cm as parr, and those > 7 cm as smolts.

The outmigrant output file is controlled by a switch on the inSALMO interfaced labeled "outmigrant-output?"[17]. When this switch is on, the outmigrant file reports one line per outmigrant, with its: time of outmigration, species, natal reach (the reach it was spawned in), length, and length category. Like the other output files, the outmigrant output file is in CSV format and has a unique file name generated by each model run (IUM 12.1). Its name starts with `Outmigrants-`.

Users can then easily summarize this output into statistics comparable to screw trap results; Excel's "Pivot Tables" tool is especially useful for this. In Excel, inSALMO's date and time output can be reduced to a date by truncating it to an integer (Excel treats a date-time value as an integer day and time as fraction of a day); and to a week using Excel's `weeknum` function.

The length categories used in the outmigrant output file are user-defined. They can be the same categories used in real outmigrant trap data that inSALMO results are compared to, or otherwise selected to distinguish juveniles that (a) migrated out shortly after emergence without growing, (b) stayed and grew at least some, and (c) found productive habitat and stayed in the model until they approached smolt size. They are specified by a new model parameter that is set in the parameter file as a list, in a line that looks like:

```
set outmigrant-length-classes (list 5 7)
```

The ***outmigrant-length-classes*** list must contain exactly two values (for three length categories) and its values must be in ascending order. The output file then labels each outmigrant as either (a) "small"—having fork length (cm) less than or equal to the first value on the list, (b) "med"—

---

[17] The new output file affects code in `globals`, `set-globals`, `build-output-file-named`, and `update-output`. The code to count outmigrants by length category is in a new procedure `record-outmigrant`.

with length between the two list values (in this example, 5-7 cm), or (c) "large", greater than or equal to the highest value on the list.

D.   BehaviorSpace output

BehaviorSpace is NetLogo's tool for automating multi-run simulation experiments (IUM 15). InSALMO is designed so that BehaviorSpace experiments can produce the model's standard output files, but BehaviorSpace produces its own summary output file that is typically much easier to analyze than separate files. However, making the BehaviorSpace output file useful requires the software to update the variables reported in it.

The inSALMO code includes global variables used only to report summary results in BehaviorSpace experiments. Unfortunately, the number and names of these variables must be modified in the code when the number or name of species is changed.

The variables for the number and size of simulated salmon are defined and updated exactly as those for trout are, so the information at IUM 16.6 can be used to modify them. However, additional variables to report the number of outmigrants, by size category, are used by inSALMO. These variables are defined (created) in the block of BehaviorSpace output variables in the `globals` statement near the top of the code. They are updated via the `reset-outmigrant-counters` and `record-outmigrant` procedures.

The standard code we distribute contains BehaviorSpace output variables for fall- and spring-run Chinook (species "Fall-Chinook" and "Spring-Chinook"). (If either of these races is not included in a simulation then its output will be zeroes and blanks.) For each of the species, the variables report the:

- Number of adults alive (`CH-F-adult-abund` for fall Chinook and `CH-S-adult-abund` for spring-run);
- Number of juveniles alive (`CH-F-juve-abund` and `CH-S-juve-abund`);
- Mean length of juveniles (`CH-F-juve-length` and `CH-S-juve-length`); and
- Number of outmigrants by species and length category (`CH-F-outmig-small`, `CH-F-outmig-med`, `CH-F-outmig-large`, etc.).

Therefore, a BehaviorSpace experiment for an inSALMO application with one resident trout species and these two salmon species will typically use the output commands illustrated in Figure 4.

Figure 4. Typical output commands for an inSALMO BehaviorSpace experiment.

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