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APPLICATION OF THE OUT-MIGRANT SURVIVAL SIMULATOR (OMSS) USING THE SWARM MODELING ENVIRONMENT TO STUDY SMOLT-PREDATOR INTERACTIONS

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PROJECT GOALS

The first goal of this modeling exercise was to model the rate of smolt migration and survival of different life history types of chinook salmon through a reservoir in the Snake River. The second goal was to use the model to help understand how physical and behavioral processes control the fish migration and survival. An applied goal is to predict the effects of Snake River Reservoir drawdown on the survival of migrating chinook smolts.

We are interested to know whether fundamental behavioral attributes of predators and prey can be used to explain population level survival as observed in the field. When the key element have been identified, we will apply the principles to an unknown and unstudied river condition (drawdown) in order to anticipate predator prey relationships.

BACKGROUND

Chinook salmon smolts migrate through the Snake and Columbia River hydrosystem in the spring and summer. The spring migrants emerged from the gravel in tributaries the year before they begin their seaward migration. When they migrate, they move with the water flow and stay mostly in the middle of the river. The summer migrants begin their seaward migration in the year they emerge from the gravel in the spring. They are smaller than the spring migrants and in their passage through the Snake River reservoirs they stay near-shore and move slower than the water velocity. By the time the summer migrants reach the estuary, they are larger and move with the water much like the spring migrants. Recent studies (NMFS 1999) indicate the survival of the spring migrants is largely independent of water flow, while for the summer migrants their survival in the upper tributaries is correlated with water flow, temperature and turbidity.

These different patterns of habitat use and response to flow between the two life history types suggests that the response of the fish to reservoir drawdown to a natural river condition is likely to be complex. More importantly, it is not straightforward to project how fish will respond to drawdown.

Because of this complexity, we developed an individual based model to investigate this system. We believe that an IBM is essentially the only approach that can link the large scale observations of travel time, survival, and river flow to the small scale observations of fish habitat choice, fish size, and the local water velocity.

METHODS

We designated this model the Out-Migrant Survival Simulator Model (OMSS). The model algorithms and coding evolved in stages. In the first stage the basic model algorithms were developed at Columbia Basins Research (CBR) with the assistance of Lang Railsback and Associates under contract with CBR. Lang Railsback and Associates coded the model in the Swarm software is a GNU Publicly Licensed Library, originally developed at the Santa Fe Institute (www.swarm.org). In the second stage of development the model was modified by CBR, incorporating new features and enhancing performance.

The model defines in detail the flow and bathymetry of the Little Goose Reservoir in the Snake River and moves individual salmon smolts and their predators about the reservoir. The smolts enter at the top of the reservoir and exit the bottom. The predators are resident in the reservoir. The movement of the smolts and the predators follow separate rules, which are dependent on either the local water depth or the local water velocity. Fish may have a habitat preference and alter their swimming behaviors to congregate in their preferred habitat. When a predator encounters a smolt it may consume the smolt depending on the predator's stomach content. That is, a satiated predator will not consume prey it encounters.

The model is written in the Swarm objected oriented software and the algorithm control is illustrated in Figure 1. Each box in this diagram represents a class, which has its own header (.h) and methods (.m) source code files. (A few minor classes are not shown in this diagram.). The main class starts execution of the model. It can be run with a graphical user interface or in a batch mode, which significantly improves performance. The SalmonModelSwarm controls the simulation. The model contains a habitat class (FlowField) that defines the depth and velocity field in the reservoir. Classes are defined for the Migrant (smolt) and Predator. The Fish class controls the interaction of the Migrant and Predator. Further details of the code structure can be obtained by contacting the authors.
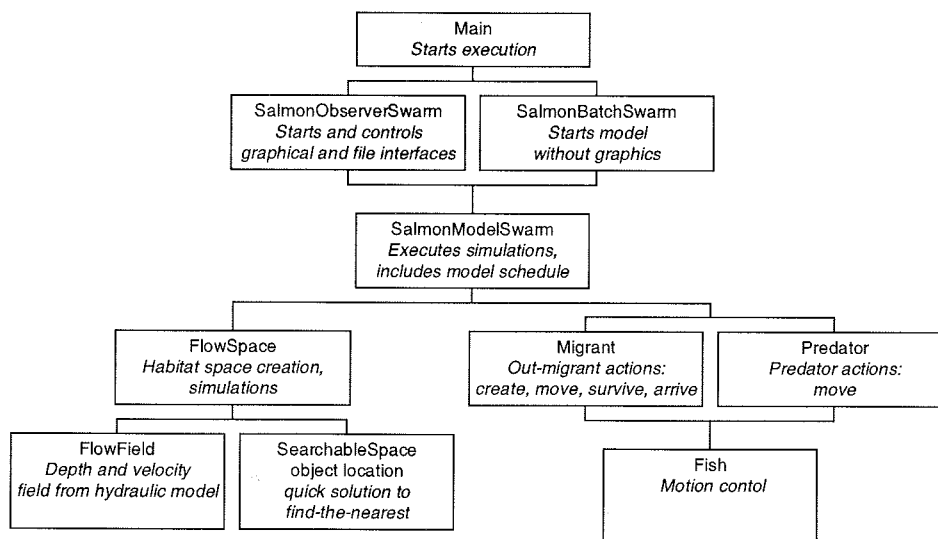

FIGURE 1. Model flow diagram.

Ecological Modeling

Using the OMSS we modeled the travel time and survival of the spring and summer migrants through Little Goose Reservoir under full pool conditions and under a natural river condition, in which the reservoir is drawn down to the natural river level. In order to do this, we found model parameters that fit the smolt travel time and survival through the reservoir under the full pool conditions. We then changed the physical environment to represent a natural river with shallower depths and higher velocities and determined the smolt travel time and survival through the river reach.

We used the known travel time and survival of spring (yearling) and summer (sub-yearling) migrating juvenile chinook salmon that pass through the Little Goose Reservoir. Simple movement rules and habitat preferences were defined as mid-river and near-shore corresponding with observed behaviors of yearling and sub-yearling chinook salmon. We also defined a

generic migrant with no habitat preference but otherwise constrained by the same movement rules.

The travel time t was defined as the average time it takes the smolt to travel through the river reach or reservoir. Our estimates of t were based on the following assumptions, which produce a discrete simulation similar to the analytical travel time model of Zabel and Anderson (1997).

• We assume movement of migrants is an advective-diffusive process, where the movement velocity of each migrant at each time step has a component in the downstream direction and a component in a random direction.

• The magnitude and direction of the downstream (advective) component is proportional to the water velocity, as determined from two-dimensional (depth-averaged) hydraulic simulations.

• The random (diffusive) velocity component is constant over time and among migrants in a simulation. The direction of this component is randomly selected and changes at a frequency determined by the model user.

OMSS was first used to estimate t for a steady flow scenario (two-dimensional velocity field through a river reach were obtained from the output of MASS2 (Richmond 1999)), over a range of values for the random velocity. This was done by simulating the downstream travel of a number of migrants, with separate simulations for each value of random velocity. There were several numerical considerations for estimating t from OMSS output.

• The travel time t was simulated with no mortality, to prevent t from being biased by the lower survival probability of migrants that travel longer paths.

• The value of t should be nearly independent of the magnitude of the random component of migrant movement; however, higher values of random velocity could reduce travel times because more migrants reach the end sooner.

• To represent the process of dam passage at the lower end of Little Goose Reservoir once

migrants reached the downstream end of the river reach, they were removed from the simulation.

• The value of random velocity also affects travel times by changing likelihood that migrants spend time in slower water along channel margins.

The hydraulic model MASS2 (Richmond, 1999) simulated habitat at points (which we call nodes) spaced approximately 15-30 m apart; these points were not on a rectangular grid. We assumed the water velocity and depth at a fish's location was that at the nearest node. The distance between nodes and the time step size of the movement simulations were important controls on the accuracy and execution speed of the migrant model.

For these reasons, the model was used to estimate how t varies with random velocity and the downstream velocity before it was used to estimate survival rates.

With our simple method for moving migrants, smaller spatial resolution (more nodes spaced more closely together) and shorter time steps reduced the errors that resulted from discretization. To make these errors acceptable, the time step size was chosen so that the distance a migrant travels each time step was usually less than the distance between nodes. The ratio of distance moved per time step to cell size could be reduced by using short time steps or by aggregating nodes. Using shorter time steps and unaggregated nodes described the velocity field more accurately but increased execution time. The number of nodes by itself had little effect on execution time with our algorithm; so aggregating them had little benefit and reduced the information on velocity variation.

Selection Of Appropriate Space And Time Discretization Depends On Several Factors

With steady flow simulations and the habitat modeling method used in our software, the habitat spatial resolution (node spacing) had little effect on computer execution times. However, execution times depended directly on the time step size. Execution times for our software were most dependent on the time step size and the number of migrants and predators simulated.

The spatial resolution of the velocity nodes was defined by the hydraulic model used to simulate velocities. Outputs from the hydraulic model MASS2 was provided by Marshall Richmond of Pacific Northwest Labs. It had a spatial resolution of approximately 15-30 m (50-100 ft) giving about 50000 nodes for Little Goose Reservoir. Node velocities range from 0 to 3 m/s (0 to 10 ft/s).

Discretization errors in the migrant movement simulations were more important when the random component of movement was small. In designing the model, we assumed the random components were small enough to make these errors significant. Discretization errors in travel simulations were higher at the upstream end of a river reach where the velocities are higher.

The time step size was a user-specified parameter (timeStepSize). A time step of 30 seconds made almost all migrant movement distances less than the distance between nodes. Therefore, migrants were affected by every node they encounter during movement.

River Environment

Two flow and depth fields were defined: the Little Goose Reservoir in its existing state and a more natural river that is expected to exist if the pool is drawn down. These flow fields were derived from data files provided by Marshall Richmond of Pacific Northwest Labs. The original files were modified so that inputs to OMSS consisted of an ASCII file in which there was one row per hydraulic node (point in the river where the PNL hydraulic model predicts depth and velocity or is defined as a boundary). Each point then had an East and North coordinate, a velocity in the East and North direction and a depth. A shoreline or island was represented by a loop of points defined between a START and END token that outlined a polygon. These shoreline points had 0 depth and 0 East and North velocities.

The outlines of the rivers are shown in Figure 2. East and North distances are in meters referenced to the Southwest corner of the reach.

Fish Movements

In the fish movement algorithm both predators and migrants respond to their local environment and look ahead to destination points before moving. Specific rules for keeping fish in the river and moving freely were implemented. The rules for moving fish about the river so that they select a preferred habitat are illustrated in Figure 3. The most important factors are:

• Fish have both directed and random movements described by the following parameters:

V is the velocity at a particular node

R is the maximum random velocity

a is a scalar defining directed movement in terms of V

b is a scalar defining random velocity in terms of R

q is the angle for the random movement.

• For smolts the parameter a gives a directed downstream movement. For the predators a is zero, representing the fact that predators are resident in the reach and move about freely.

Fish move more slowly in preferred habitats and move quickly out of undesirable habitats as defined by the local velocity and depth. This habitat selection is defined by altering the parameter b depending on the magnitude of the habitat variable. The scaling value is defined by the local habitat and five parameters that mark the bends in the curve.
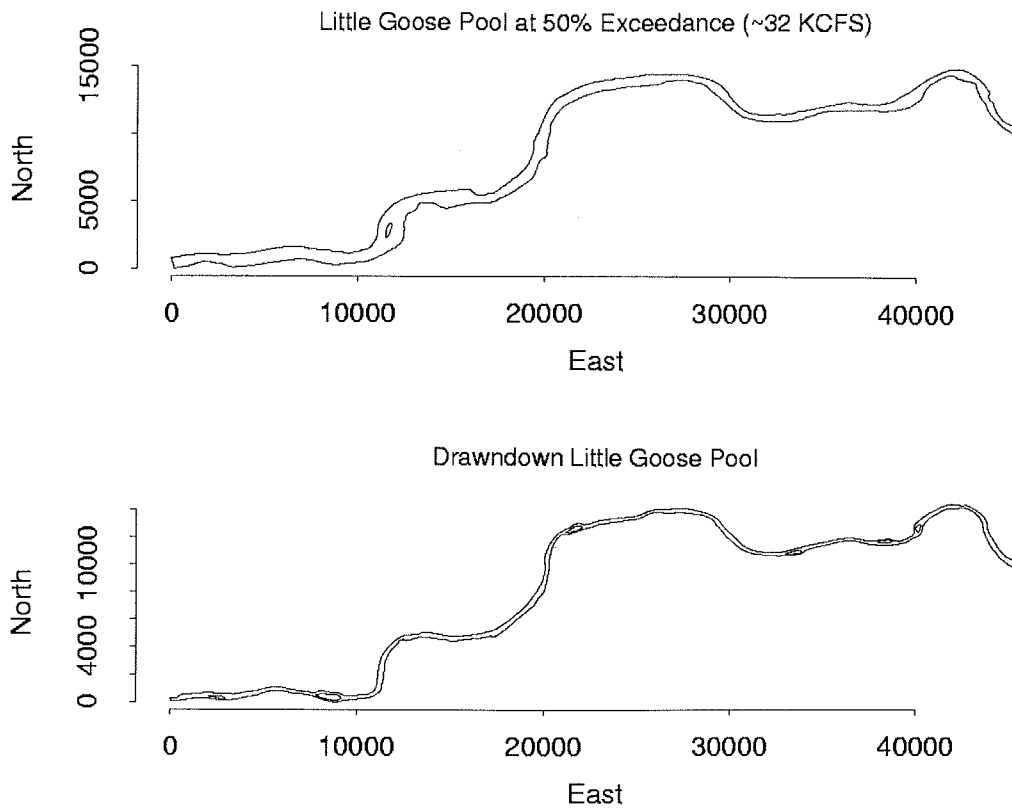
FIGURE 2. Full pool (calibration) and drawndown (simulation) rivers between Little Goose Dam and Lower Granite Dam on the Snake River Washington. Distances in meters.
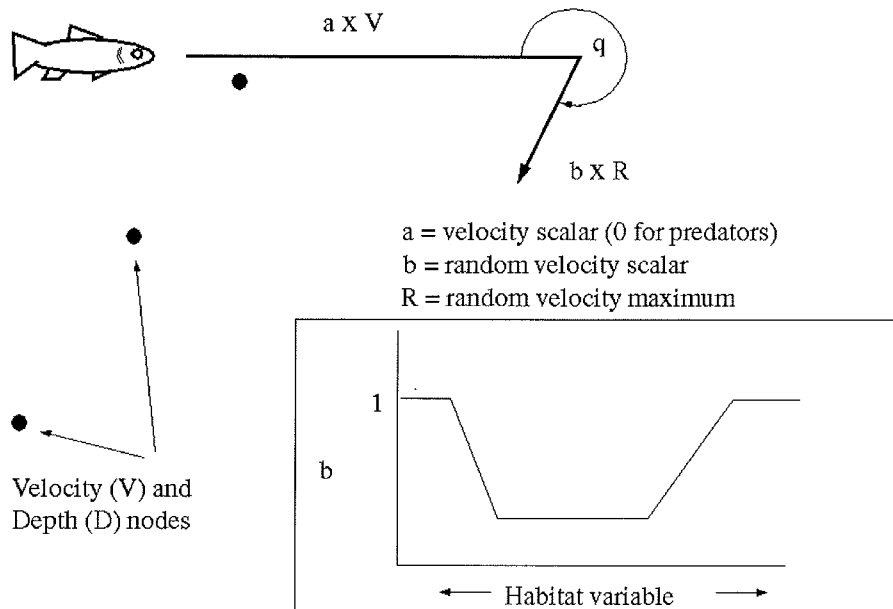
FIGURE 3. Illustration of how the movement parameters result in fish movement. The fish directed velocity is scaled by the water velocity V with the scalar a. The fish random velocity is scaled by b and the direction is determined by the random angle q. Depth and velocity from the nodes define the habitat variable, which then defines the value of b.

In stage one of the model development the response of fish travel times to the model parameters was unusual and counter intuitive. We discovered a flaw in the algorithm that detects fish location near the shoreline. In effect, since each movement was incremental over a specific time step a fish could swim up on to the bank where the river velocity was zero. At that point they still retained a random velocity (equivalent to flopping around?) but their directed velocity became zero

and so the migrating time became large (eventually the fish might flop back into the river and continue its migration). Since fish should generally remain in the water, we improved the boundary algorithm. Our boundary–encounter rule first reduced the distance the fish moved to let them continue in their intended direction. If this failed their random movement angle was altered (Figure 4).
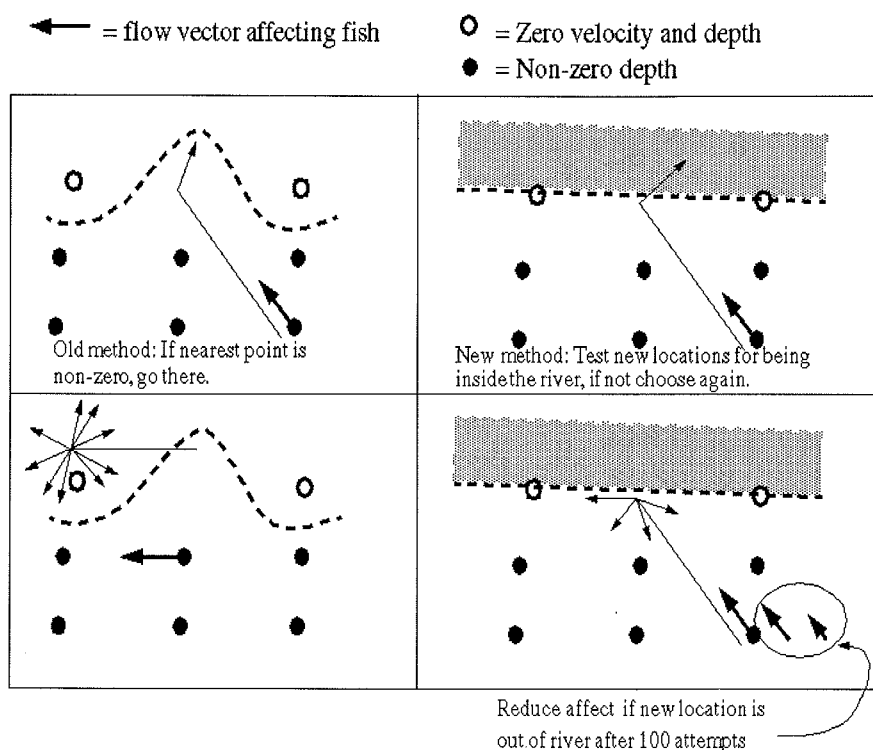
FIGURE 4. Illustration of boundary effects on fish movement. The old algorithm put fish on the shore. The new algorithm checks for landings and shortens the movement distance or alters the random angle.

In the model, predator density (number of predators per square meter) is specified by the user as an input. Initially, predators were distributed with a *constant predator density*. The number of predators was calculated by multiplying the predator density by the total area in the model and the predators were distributed randomly through the model space: each predator was assigned a random pair of X and Y coordinates on the location grid. After each predator was created, it located the nearest

hydraulic model node. If this node had a depth of zero (meaning that it fell on the river bank instead of in the river channel), then the predator was dropped from the model. This method assured that once simulations and predator movement began, the user-specified predator density was maintained at the scale of the simulated reach. This method also assured that the predator density in the simulation did not vary if flow rate and channel width were changed between simulations. Alterations to the

number of predators in the river were done by scaling the density during the drawdown modeling runs.

Predators were allowed to move with habitat preferences like the migrants but they had no advection component. The habitat preferences were controlled with five parameters and were sometimes "turned off" after a certain period of time when they were "established" in order to decrease overall run times.

To represent the effects of feeding and predator satiation, predators had stomach capacity and digestion rate. Satiation decreased the probability of successful predation when a migrant passed close to a predator. A probability of successful predation by a predator with an empty stomach was based on a capture radius, a capture probability, and a capture coefficient. This probability was multiplied by the fraction of the predator's stomach that was empty. Therefore, the predator's appetite was modeled as decreasing linearly as its stomach filled up. The predator resumed feeding as the stomach emptied according to the digestion rate.

The feeding algorithm was expressed by the following statements:

predCaptureRadius = r_0

predCaptureProb = p_0

predCaptureCoef = k

proportion of predator's stomach full = f

distance at closest approach = r

probability of capture = p

if ($r < r_0$)

    $p = p_0 * (1 - f)$

else

    $p = p_0 * \exp(-k * (r - r_0)) * (1 - f)$

In each time step, first the predators were moved and second the migrants were moved. Next, each migrant looked for predators that passed within its detection range during its move. For each such predator, the migrant calculated a distance of closest approach and a probability of being attacked. The successful

attacks were determined as a binomial process defined by the capture probability, p.

Calibration

Calibration occurred in two phases. First, efforts to improve model run speed were explored. A number of methods were used to improve speed. For example, we determined the fewest number of fish that gave results consistent with simulations using more fish. If a simulation could produce the same results with 100 fish as with 1000 fish, the migrant movement algorithms would run 10 times faster. Calibrations were also reduced by identifying model variables that worked in concert. For example, Figure 5 shows that migrant survival decreased linearly with the product of predator density and the predator capture radius. Therefore, we could reduce the number of predators in the model by making the predators twice as efficient at capturing prey. In this way we reduced the computation time for predators. Thus, we could represent a realistic number of predators in the river with fewer predators with larger capture probabilities. In practice, each simulation is unique so the linear relationship is not exact.

The second calibration phase involved adjusting model parameters to fit travel time and survival observations of smolts migrating through Little Goose Reservoir. This consisted of setting model parameters for all input parameters as could best be determined from literature sources and then varying the behavioral parameters (principally the migrant velocity and random movement magnitude for the migrants and the predator capture radius and capture probability for the predators) to obtain the observed travel time and survival. The variability and maximum travel times were also desirable and so habitat preference parameters were adjusted to fit these observations as well. The travel time was calibrated before the survival and then checked again after the survival calibration. In Figure 6, travel time is plotted for a range of values of the directed velocity scalar (*a* parameter) and random velocity scalar (*b* parameter). In the plots, the

target travel times for yearling and subyearling fish are shown as a solid and dotted line respectively. In Figure 7, migrant survival is plotted as a function of the predator capture radius and the capture probability. In the mid-river and near-shore plots, three lines appear for each life-history type indicating the range of survivals and the median survival rate. The Generic plot shows only the median survivals for the yearling and subyearling chinook as horizontal lines. The median travel time of the different life history groups required the a parameter set to 4 and the b parameter set greater than 1.

Mid-river

Near-shore

Generic
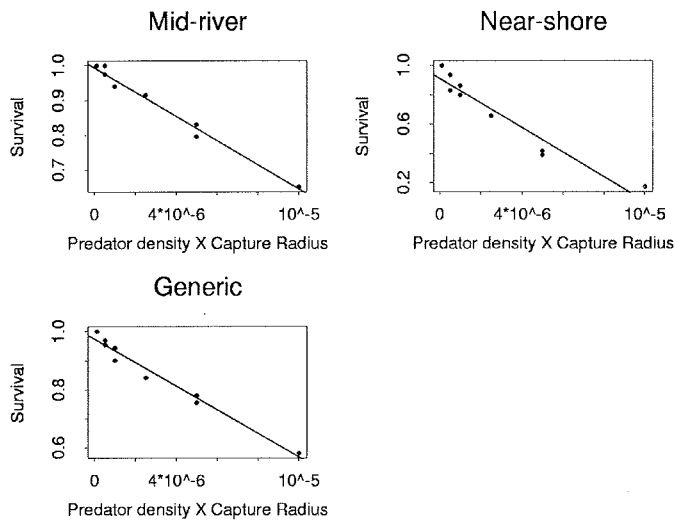
FIGURE 5. Example of parameter alteration in order to reduce run times. This demonstrates the linear effect on survival of altering the predator capture radius and predator density together to create a predation constant.
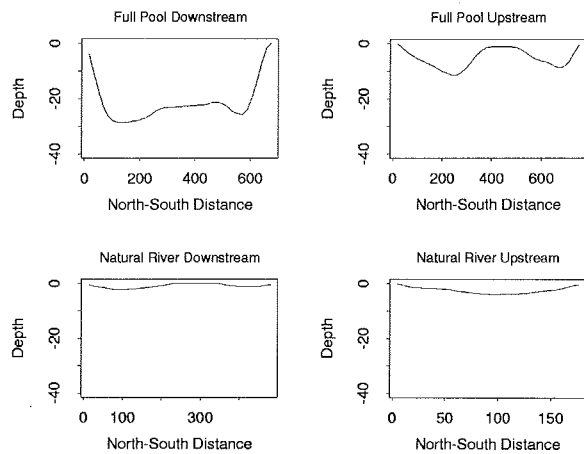

Mid-river

Near-shore

Generic
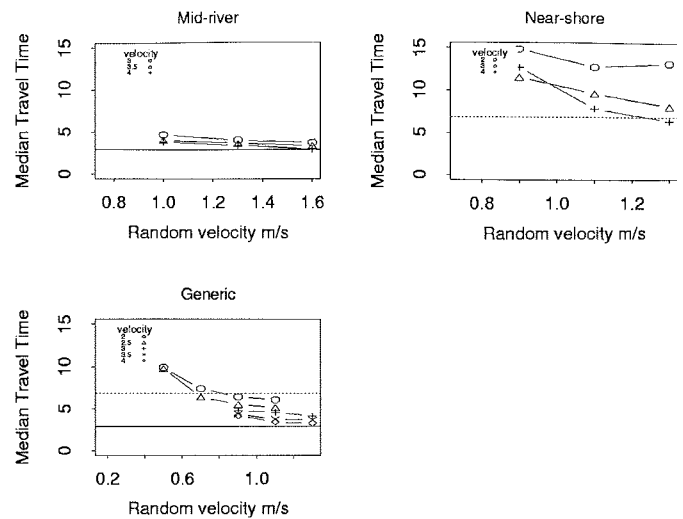
FIGURE 6. Calibration of travel time with downstream velocity scalar a and the random velocity component b for three simulated stocks. The horizontal lines in the graphs represent data on yearling (solid line) and sub-yearling (dotted line) chinook. All plots show the median value of travel time and the upper plots also show the ranges of these values.
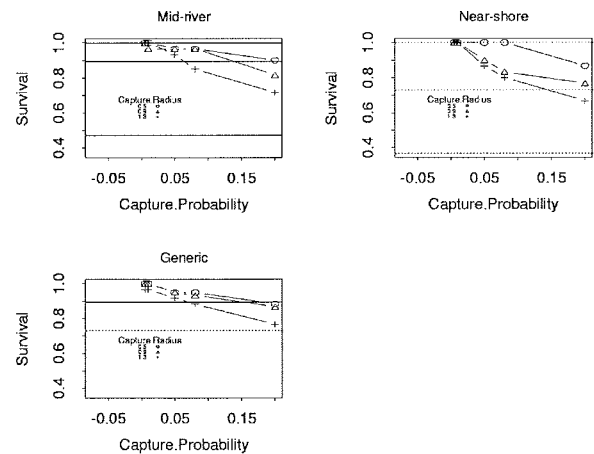
FIGURE 7. Calibration of survival with capture radius and capture probability for three simulated fish stocks. The horizontal lines in each graph represent data on yearling (solid line) and sub-yearling (dotted line) chinook. All plots show the median value of survival and the upper plots also show the ranges of these values. Modeling survival in a natural river condition
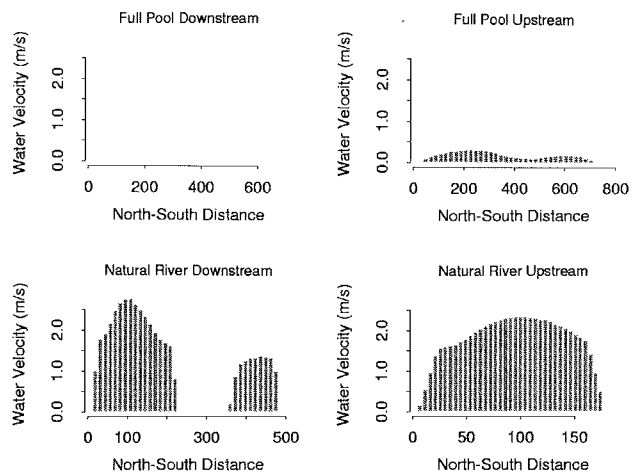
The essential difference between the full pool model runs used to calibrate the movement parameters and natural river model runs was that a different flow field data file was used. In

Figures 8 and 9, differences in the depth and velocities between the full pool and natural river conditions are illustrated for upstream and downstream transects.

FIGURE 8. Selected transects (in m) at two points along the river (an upstream and downstream location). The depth profile for the natural river indicate an island through the transect. This is also visible in the depth profile for the full pool condition.

FIGURE 9. Selected velocity transects at two points along the river (an upstream and downstream location). The water is moving so slowly in the reservoir at the downstream location that it does not appear on the graph. The two humps in the velocity profile for the natural river indicate an island through the transect.

In addition to the changes in the flow and depth fields between full pool and natural river conditions, we explored scenarios based on how predator densities could change in relation to changes in their preferred habitat with a natural river condition. The preferred habitats of the migrants and the predators were defined by either depth or velocity. Yearlings preferred deep water or higher velocities while the Sub-yearlings preferred shallow water or lower velocities. Preferred predators habitats were defined as nearshore in slower water. Changes in preferred habitats were defined in terms of decreases in the area or the volume when changing from a full pool reservoir to a natural river. For the Generic migrants, which had no preferred habitat, changes were defined in terms of the total reservoir area or volume. Including a scenario with no change in predator density, a total of 7 scenarios can be compared to the base full pool reservoir scenario. The predator density changes were defined by following scenarios:

1. no change from the full pool.

2. increase in proportion to the loss of total river area.

3. increase in proportion to the loss of total river volume.

4. increase in proportion to change in preferred habitat area defined by depth.

5. increase in proportion to change in preferred habitat area as measured by velocity.

6. increase in proportion to change in preferred habitat volume as measured by depth.

7. increase in proportion to change in preferred habitat volume as measured by velocity.

RESULTS

The model results are described in Table 1. The first column identifies the Scenario. The second column shows what habitat measure was related to predator density change. The third

column shows how habitats were defined. The fourth column gives the predator density increase. The remaining columns give travel times and survivals for the three migrant types. Predator

density changed by less than a factor of 13 except for scenario 7 in which the predator density increased by three orders of magnitude. In that scenario no migrants survived.

TABLE 1. Smolt travel time in days (TT) and survival (S) for full pool and natural river conditions with different responses of predator density to natural river conditions.

Scenario	Density increases by change in habitat	Preferred Habitat size defined by	Density increase factor	Generic fish (no habitat preference)		Yearlings (mid-river preference)		Sub-yearlings (near-shore preference)	
				TT	S	TT	S	TT	S
Full pool			1	3.67	0.85	3.40	0.93	7.45	0.87
1	No change		1	0.16	0.98	0.16	1	0.17	0.97
2	Area	Reservoir	2.0	0.16	0.96	0.16	0.96	0.16	0.97
3	Volume	Reservoir	13.0	0.16	0.78	0.16	0.73	0.17	0.74
4	Area	Depth	1			0.16	0.98	0.16	0.98
5	Area	Velocity	5.6			0.16	0.87	0.16	0.85
6	Volume	Depth	2.3			0.16	0.95	0.16	0.93
7	Volume	Velocity	1101			NA	0	NA	0

The modeled smolt velocities were similar to the observed smolt velocities under full pool conditions and were similar to the modeled full pool water velocities (Table 2). When the full pool migration parameters were applied to the natural river condition the modeled smolt velocities were exceptionally fast when compared to the modeled river velocities. In this comparison the yearling smolts prefer a mid-river habitat and the sub-yearlings prefer a nearshore

habitat. The table also gives the water velocities predicted from the MASS2 model for transects 0.25 and 25 km upstream of Little Goose Dam. The modeled full pool velocities for the fish were the calibrated from the observed velocities but the natural river fish velocities were based on the fish movement rules derived from the full pool scenario and flow derived from the hydraulic model natural river conditions.

TABLE 2. Observed and modeled smolt migration and water velocities (m/s) in Little Goose Reservoir under full pool and natural river conditions. Observed velocities derived from travel time of tagged fish through Little Goose Reservoir.

	Observed under full pool	Modeled full pool	Modeled natural river
Yearling smolt velocity	0.17	0.2	3.75
Sub-yearling fish velocity	0.07	0.09	3.75
Water velocity @ km 25		0.11	0.35
Water velocity @ 0.25 km		0.04	1.6

DISCUSSION

As is illustrated in Table 1, smolt survival was highly dependent on the assumptions made about the response of predator density to changes in the river configuration. Thus, the model clearly illustrates the importance of predator behavior in determining the survival of smolts under natural river conditions. If the predators congregate in the

nearshore environment where the sub-yearling migrate, then smolt survival would be expected to decrease in natural river conditions compared to full pool conditions. In terms of this result, the model provides useful information. The comparisons in Table 2 present another issue though. The model predicted exceptionally large smolt velocities under natural river conditions,

exceeding the average natural river water velocity by up to a factor of ten. The predicted natural river smolt velocity at 3.75 m/s is faster than the fish can swim. The problem results because to fit the observed travel times under full pool conditions, the directed velocity-scaling factor must be on the order of 4. This implies that fish swim four times the water velocity, which under the natural river conditions is impossible. The problem was not in fitting the model to the full pool conditions, it was in our formulation of fish movements. The algorithm has fish moving randomly at a velocity of over 1 m/s. Since this is in all directions a very fast downstream directed velocity is required to get the fish through the reservoir in the observed travel time. The directed velocity scalar of $a = 4$ in effect is the ratio of the total distance the fish travels to the distance a water particle travels. The random movements of the fish make them travel four times further than the water and so they must swim four times faster than the water. From this reasoning we conclude that the movement algorithm used for smolts was inadequate. Fish do not rapidly swim about in a random manner. In reality conditioned by their environment, they move in a bioenergetically efficient manner feeding and avoiding predators. From the knowledge gained in this exercise we have redeveloped our model, including a more behaviorally realistic algorithm that considers fish motivation and their perception of the local environment. This model will be published in the Natural Resource Modeling Journal in the near future.

Notes: MASS2 Two-Dimensional Depth-Averaged Model

MASS2 is a general purpose, unsteady two-dimensional depth-averaged hydrodynamics and transport model. Currently, MASS2 simulates time-varying distributions of the depth-averaged velocities, water temperature, and total dissolved gas. The model is coded in standard FORTRAN90 and runs on WINDOWS and UNIX computer systems.

The model is an unsteady finite-volume code that is formulated using a structured multi-block grid scheme on a curvilinear grid system. The governing equations are formulated in a conservation form using the contravariant velocity components in a curvilinear coordinate system. The coupling of the momentum and mass conservation (continuity) equations is achieved using a variation of the SIMPLE algorithm extended to shallow-water flows.

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