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Development of a Numerical Fish Surrogate for Improved Selection of Fish Passage Design and Operation Alternatives for Lower Granite Dam: Phase I

John M. Nestler, R. Andrew Goodwin, and Raymond S. Chapman

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Environmental Laboratory

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Preface

Reasonable and Prudent Alternatives (RPA) 11 of the Biological Opinion for the restoration of Columbia River salmon stocks directs the U.S. Corps of Engineers to investigate the application of surface collection technology at lower Snake and Columbia River projects. Identifying optimum design or operations of Columbia River basin dams for passage of juvenile salmon requires collection and integration of both hydraulic and biological information. This report describes a quantitative method for combining biological and hydraulic information into a coupled Eulerian-Lagrangian framework ideally suited to this task. The method will be completed in FY00 and will include a decision support system that can be used to identify optimum design or operations for surface collection.

This report was prepared by the Environmental Laboratory (EL), U.S. Army Engineer Research and Development Center (ERDC), Vicksburg, MS, and Ray Chapman and Associates, Vicksburg, MS. This report was written by Dr. John M. Nestler and Mr. R. Andrew Goodwin, EL, contract student from Cornell University, Ithica, NY, and Dr. Raymond S. Chapman under the general supervision of Dr. Mark S. Dortch, Chief, Water Quality and Contaminant Modeling Branch (WQCMB), EL; Dr. Richard E. Price, Chief, Ecosystem Processes and Effects Division (EPED), EL; and Dr. John Keeley, Director, EL. In-house technical review was performed by Ms. L. Toni Schneider, WQCMB, Dr. Dennis Brandon, Contaminants Assessment and Monitoring Branch, EPED, and Mr. Robert L. Johnson, Battelle's Pacific Northwest National Laboratory. This study was funded by the U.S. Army Engineer District, Walla Walla.

Patents are pending on the methods used to simulate aquatic animal movement to aid in the design and operation of fish passage systems and on CEL Hybrid Ecological models as an improved method for simulating population dynamics in an ecosystem context.

At the time of publication of this report, Director of ERDC was Dr. James R. Houston, COL James S. Weller, EN, was Commander.

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1 Introduction

Background

Historically, studies to support decision-making for salmon restoration in the Columbia River Basin have focused on comparison of treatments. Investigators felt that variability in meteorology, flow, operations, and other factors that normally change during the passage season would be captured in the experimental design of the study if monitoring was sufficiently comprehensive. Unfortunately, process-based information associated with the treatments, such as variations in flow fields resulting from changes in operation or structural modifications, could not be rigorously controlled or described. Consequently, findings from treatment studies were difficult to extrapolate to other sites within the basin since the projects differ substantially in design and operation. Additionally, findings were of questionable value when applied to years other than when they were originally made because of variations in the processes associated with the treatments. Passage successes of a particular design or operation in one year would not guarantee success in future years because of new operations or designs that cause associated processes to fall outside the range originally encountered. Clearly, process-based information (such as relatively complete descriptions of flow fields and the response of salmon to them) must supplement treatment studies (Coutant 1999). Without process information, it is doubtful that optimum design or operations for juvenile salmon passage can be selected. The need for process information is particularly telling for a program such as surface collection whose success depends upon the creation of attracting flow fields because the hydraulic features that will attract juvenile salmon are still largely unknown.

Recently, tools have become available and accepted within the region to provide detailed measurements or predictions of both the physical environment and biological responses. For example, tools are available to directly measure the hydraulic variation (Acoustic Doppler Current Profilers – ADCP and Acoustic Doppler Velocimetry – ADVM) associated with different bypass design and operation alternatives or to predict them using detailed numerical hydraulic models (Computational Fluid Dynamics – CFD). Within the limits of scale effects, flow field data can be obtained from physical hydraulic model studies using video imaging of graffiti tracers or laser Doppler velocimetry. In the biological realm, new tools such as multi-beam (Johnson et al. 1999) and split-beam hydroacoustics (Gerolotto, F., M. Soria, and P. Fréon 1999) and acoustic tag tracking can provide detailed descriptions of the 3-dimensional distribution of juvenile salmon or other aquatic species of interest within the basin. Unfortunately, the detailed information provided by the new generation of measurement tools and predictive models has not been integrated with the technology for describing the detailed 3-dimensional position of individuals of aquatic species. Consequently, the full potential of these new technologies has not been employed to support decision-making within the basin. Therefore, decision-making is hindered, and undue reliance is based on a time-consuming, expensive, and potentially salmon damaging "build and test" paradigm. Improved decision-making would result if the information provided by these new tools could be combined into a comprehensive, unified framework that makes integrated information available to decision-makers.

In addition, the gears and technologies available to collect biological data often function at different scales or are based on different assumptions. Differences across gears and technologies sometimes produce conclusions in conflict with one another. For example, the relatively long tracks provided by acoustic tags provide a somewhat different perspective of fish behavior than shorter traces from multi-beam hydroacoustics. Generally, acoustic tags track fish across distances of a hundred meters or more whereas the multi-beam acoustic system samples immediately in front of the surface collector openings. The mean and range of hydraulic variables associated with the area sampled by the acoustic tags will probably be different than the mean and range of hydraulic variables associated with acoustic tag tracks. Consequently, the flow-behavior relationships obtained from acoustic tags will differ from relationships obtained from multi-beam acoustics. Integrating conflicting biological data sets with hydraulic data sets may provide an approach for reconciling conflicting findings by encouraging researchers to carefully consider their data at several different scales. Similarly, results from hydraulic model studies may also provide conflicting information because of scale effects or assumptions inherent in different approaches for simulating different operational or design alternatives. For example, the velocity component of the flow field is hypothesized to be the primary stimulus to which juvenile salmon respond. However, it is likely that relatively small instabilities in the flow field or the presence of unknown or uncontrolled secondary fields, such as magnetic fields or acoustical fields may limit the success of surface collection technology. Integration between and among biological, hydraulic, and secondary (e.g., magnetic, electrical, acoustic data sets) is needed to fully utilize the information potential of each and to reconcile perceived conflicts between different data sets. Use of integrated information based on reconciled data placed into a predictive or summary context helps insure that optimum design or operations for salmon restoration will be selected.

Goals

The goal of this Phase I report is to develop, describe, and apply an approach for integrating biological, operational, and hydraulic information to support selection of optimum hydraulic designs and project operation for Surface Bypass at Lower Granite Dam. We present the approach in a preliminary, proof-of-concept context in anticipation that the ideas and concepts will provide the foundation for future process-oriented research. We also provide preliminary results from the analysis to show the form of the output and how the output is used to develop a decision-support framework. However, final results cannot be presented until final hydraulic calibration is performed and stationing uncertainties in the multi-beam data are reconciled. We anticipate that the tools and procedures developed for Lower Granite will find application at other sites within the basin. We anticipate that the statistical and analytical tools described in this report will be improved as more experience is gained.

Objectives

This study has the following objectives:

a. Evaluate relevant biological data and associated hydraulic data sets collected in 1998 at Lower Granite Dam.

b. In consultation with the providers of data, adjust the geo-referencing, scaling, and coordinate system of each relevant biological data set and associated hydraulic data set(s) so that biological data sets can be overlain on hydraulic data using a common coordinate system.

c. Develop and apply an analytical or statistical process that can be used to explore and describe the relationship between biological response variables and hydraulic variables (flow-behavior relationship).

d. Develop a process for confirming the flow-behavior relationships developed in "c." by checking them in a mathematical framework (Numerical Fish Surrogate – NFS) and modifying them to account for inappropriate statistical assumptions.

e. Couple flow-response relationships to a fluid dynamics framework so that different design-operation alternatives can be evaluated in a predictive framework to explore fish passage design and operational alternatives. The NFS will be able to use either statistically derived fish traffic rules or hypotheses about fish movement (e.g., fish avoid water velocities greater than 4.0 ms^{-1}).

f. Develop a decision-support shell for assessing and selecting different fish passage design or operational alternatives. The decision-support shell will ensure that all relevant biological and hydraulic data are utilized for decision-making.

2 Data Preprocessing

Integrating information to produce a database that can be used to explain and predict fish behavior in hydraulic fields requires: 1) field data collected by biologists, 2) measured or predicted hydraulic information using sound engineering practice, and 3) "as built" archived project plans. Unfortunately, these disparate data sources may differ in scale, resolution, and georeferencing system so that they cannot be easily merged into a unified data base to explain or predict juvenile salmon behavior. Achieving the listed objectives for this study required preprocessing and manipulating

a. multi-beam hydroacoustics data,

b. CFD output data, and

c. project structural data.

After preprocessing and manipulation, these three different data sets were combined into a single data set in which the different types of data can be overlain on each other. Data preprocessing and manipulation are presented in detail here so that they can be used as a general guide for future data collection in the basin.

Multi-beam Hydroacoustics Data

Multi-beam hydroacoustics data were provided by Mr. Robert Johnson of Battelle Pacific Northwest National Laboratories (PNNL) for 9-10 and 22-23 May 1998. Examples of data provided by PNNL are shown in Table 1. Spatial descriptions of the data are based on US State Plane 1983, Washington South 4602, NAD 1983 (Conus). The origin for the hydroacoustics data set is located on the forebay deck between the powerhouse and spillway at 734,904.970 m (2,412,937.985 ft) East and 151,886.911 m (498,695.358 ft) North (Figures 1 and 2). Based on this origin, multi-beam determined individual fish locations (pings) were placed in a three dimensional coordinate system with the X-dimension running parallel to the face of the powerhouse, the Z-dimension running perpendicular to the long axis of the powerhouse and the Y-dimension representing depth referenced to the existing water surface elevation. Normally, the water surface elevation was about 223.42 m NGVD (733 ft) and did not change more than about 0.15 m (0.5 ft) during the course of the study. Two

Table 1
Example of Select Variables Describing Fish Position as Provided by Battelle Pacific Northwest National Laboratories. DN = Day or Night. FID = seven digit Fish (trace) Identification Designation. Dtime = Decimal time. Xc = lateral position along face of dam. Yc = depth. Zc = distance upstream from dam. Vx = velocity along x-axis. Vy = velocity along y-axis. Vz = velocity along z-axis. Distances are in m and velocities are in m s^{-1}

DN	FID	Dtime	Xc	Yc	Zc	Vx	Vy	Vz
D	1115462	12.013333	46.64	-19.08	17.78	0	0	0
D	1115462	12.013408	46.01	-18.99	17.75	-2.32	0.36	-0.14
D	1115462	12.013500	45.72	-19.18	17.49	-0.87	-0.60	-0.77
D	1115462	12.013608	46.88	-19.37	17.84	2.97	-0.47	0.90
D	1115462	12.013700	46.33	-20.19	17.65	-1.67	-2.49	-0.58
D	1115462	12.013775	46.55	-18.68	17.85	0.81	5.60	0.76

pole mounted prisms were placed in line with the axis of the multibeam head as it was oriented toward the middle entrance. A line drawn between the two prisms passed through the center of the multibeam heads offset by their depth. These two prisms provided an orientation of the multibeam platform on a second by second basis. This data was compared to a flux-gate compass and tilt sensor package that was attached to the multibeam pole. The prisms were used for orientation control because PNNL staff were unsure of the compass accuracy in this region of high magnetic flux. Range and bearing of each ping collected by the multi-beam acoustics system were converted to the coordinate system during processing of the data. Detailed methods of data collection and preliminary processing are described in Johnson et al. 1999.

CFD Data

CFD modeling of hydraulic conditions present when the multi-beam hydro-acoustics data were collected was performed by Dr. Larry Weber and his students at Iowa Institute of Hydraulic Research (IIHR) using the Unsteady, Unstructured Reynolds Averaged Navier Stokes (U^2RANS) model (Lai 1999; Lai and Patel 1999). The CFD model output presents the flow field as a group of contiguous cells whose boundaries are defined by grid lines. Hydraulic information as used for statistical analysis is presented at the nodes of the grid, i.e., at the intersections of the grid lines (Figure 4).

IIHR provided two steady-state model runs, identified as Run09 and Run12, for the analysis with single block output (CFD calculations and output use a single contiguous representation of the system) for each run. However, a multi-blocked representation of the system is planned for the future, and we intend to modify our programs to accommodate multi-blocking. Both Run09 and Run12 simulated flow conditions that were field tested in the spring of 1998. The 1998 test, as compared to previous testing, had the Simulated Wells Intake (SWI) added to the bottom of the original surface bypass collector structure. In addition, the Behavioral Guidance Structure (BGS) along with an additional SBC gate opening was added for testing. Run09 evaluated the maximum (MAX) area gate settings where three fish entrance gates were set to full width of 4.88 m (16 ft) and full depth of 16.76 m (55 ft). Flows at the BGS, South, and Middle entrances were estimated to equal 23.13 $m^3 s^{-1}$ (817 $ft^3 s^{-1}$), 29.76 (1051 $ft^3 s^{-1}$), and 60.37 $m^3 s^{-1}$ (2132 $ft^3 s^{-1}$) respectively, and the North entrance was closed. Run12 corresponds to the shallow entrance gate settings (Ice Harbor Configuration - IHC) where three fish entrance gates were set to full width of 4.88 m (16 ft) and to a partial depth 6.71 m (22 ft). Flows at the South, Middle, and North entrances were estimated to equal 16.14 $m^3 s^{-1}$ (570.00 $ft^3 s^{-1}$), 25.99 $m^3 s^{-1}$ (918 $ft^3 s^{-1}$), and 22.46 $m^3 s^{-1}$ (793 $ft^3 s^{-1}$), respectively. The BGS entrance, which was constantly open in the MAX area position since it could only be closed with the use of stoplogs, had an estimated flow of 48.68 $m^3 s^{-1}$ (1,719 $ft^3 s^{-1}$). Data used for statistical analysis were provided in Tabular form (Table 2). We were informed (personal communication 2 Nov 99, Mr. Lynn Reese of Walla Walla District) that the rating curve used to estimate the discharge through the SBC for CFD simulations was inaccurate and probably overestimated discharge by about 20-25%.

The grid and coordinate system used for the CFD was oriented and scaled to describe the dominant near field flow features associated with the SBC (Figure 1). In the model grid, the water surface is at 44.5 m NGVD (146 ft) corresponding to a water surface elevation of 223.42 m (733 ft). Maximum grid size was 74.92 meters (245.8 feet) in the x-direction (perpendicular to the powerhouse face), 102.6 meters (336.6 feet) in the y-direction (parallel to the powerhouse face), and 44.5 meters (146.3 feet) in the z-direction (depth). In the grid, the face of the SBC was set at x = 54.864 meters (180.0 ft). For both scenarios, powerhouse discharge through units 4,5, and 6 only (units 1-3 were not operated) was set to 561 m^3s^{-1} (19,800 f^3s^{-1}).

Table 2
Example of Select Variables Describing CFD Output Data. Positions are in m, velocities are in $m\ s^{-1}$, accelerations are in $m\ s^{-2}$, energies are in $m^2\ s^{-2}$, and energy dissipations are in $m^3\ s^{-2}$

Position			Velocity			Acceleration			Turbulent	
X	Y	Z	U	V	W	A_X	A_Y	A_Z	Intensity	Dissipation
0.00E+00	0.00E+00	9.14E+00	1.66E-01	3.90E-01	-2.26E-02	0.00E+00	0.00E+00	0.00E+00	1.41E-03	6.36E-05
3.54E+00	0.00E+00	8.44E+00	1.25E-01	2.92E-01	-1.69E-02	0.00E+00	0.00E+00	0.00E+00	1.42E-03	9.29E-05
6.82E+00	0.00E+00	7.78E+00	1.25E-01	2.92E-01	-1.69E-02	0.00E+00	0.00E+00	0.00E+00	1.42E-03	9.07E-05
9.85E+00	0.00E+00	7.17E+00	1.00E-01	3.11E-01	-3.13E-02	0.00E+00	0.00E+00	0.00E+00	1.42E-03	9.00E-05
1.26E+01	0.00E+00	6.61E+00	7.59E-02	3.29E-01	-4.56E-02	0.00E+00	0.00E+00	0.00E+00	1.43E-03	8.96E-05
1.52E+01	0.00E+00	6.10E+00	7.59E-02	3.29E-01	-4.56E-02	0.00E+00	0.00E+00	0.00E+00	1.43E-03	8.79E-05
1.76E+01	0.00E+00	5.62E+00	7.59E-02	3.29E-01	-4.56E-02	0.00E+00	0.00E+00	0.00E+00	1.43E-03	8.62E-05
1.98E+01	0.00E+00	5.17E+00	7.59E-02	3.29E-01	-4.56E-02	0.00E+00	0.00E+00	0.00E+00	1.43E-03	8.48E-05
2.19E+01	0.00E+00	4.76E+00	7.59E-02	3.29E-01	-4.56E-02	0.00E+00	0.00E+00	0.00E+00	1.43E-03	8.35E-05

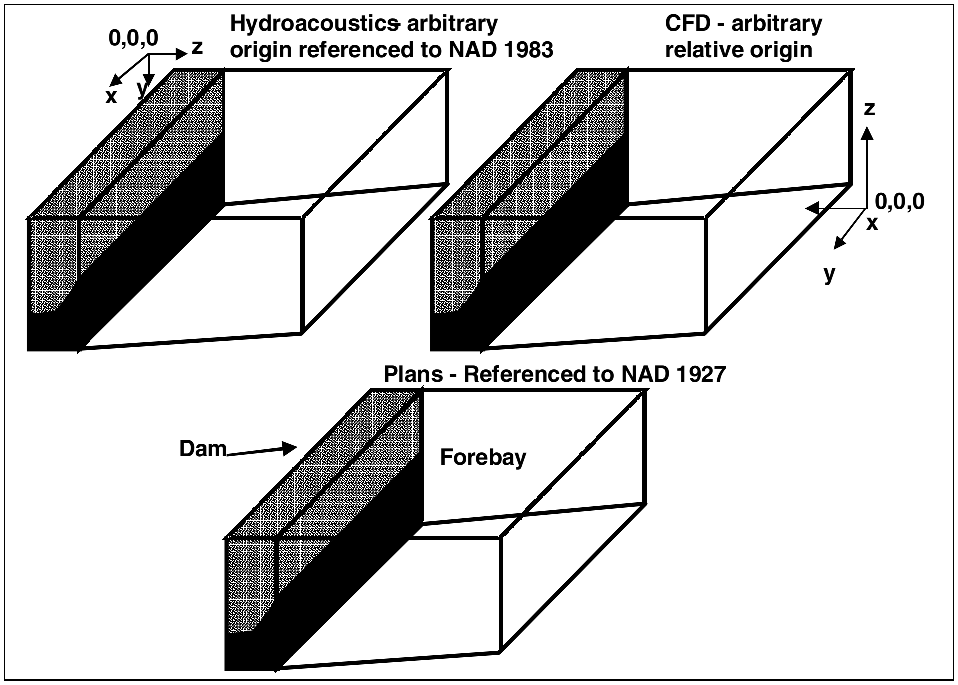

Figure 1. Schematic comparison of different geo-referencing used for CFD simulations, hydroacoustics data set, and dam design plans

Project Plan Data

Project construction plans were provided by Walla Walla District to Mr. Glenn Davis of the U.S. Army Engineer Research and Development Center (ERDC) Coastal and Hydraulics Laboratory, who in turn provided them to the authors of this study. Spatial descriptions of the dam were based on US State Plane 1927 for Washington State (Conus). Note that project plans and multi-beam hydroacoustics data do not use the same geo-referencing system. Location of features in the forebay common to the CFD output, hydroacoustics data set, and project plans required conversion between the different geospatial reference frames. Future integration activities should insure that all data sets have a common georeference and are based on a common coordinate system and origin.

Data Overlay

All georeferencing systems were converted to that of the CFD grid using the following steps. The axes of the hydroacoustics data sets were renamed to that employed by the CFD model grid: X-stationing in the hydroacoustics data set was renamed to Y-stationing, Y-stationing in the hydroacoustics data sets was renamed to Z-stationing, and Z-stationing in the hydroacoustics data sets was renamed to X-stationing. Although the axes for the CFD output data set and multi-beam hydroacoustic data sets were parallel, they did not share the same origin. Each of the hydroacoustics axes was offset so that the origin of the hydroacoustic data set was identical to that of the CFD grid. The offsets were determined by referencing both the hydroacoustics and CFD grid to the openings of the surface collector (features that could be made to be common to both data sets). The locations of the openings to the surface collector were not part of the hydroacoustics data sets provided by PNNL and had to be determined by referencing the hydroacoustics data set to project plans. To get the locations of the openings of the surface collector, the Washington state plane NAD 1983 georeferencing system used for the hydroacoustics data was converted to the Washington state plane NAD 1927 used for the project design plans using Corpscon for Windows Version 5.11.03, a conversion program downloaded from the U.S. Army Engineer Research and Development Center, Topographical Engineering Center website.

The origin of the hydroacoustics data sets was located on the project plans using AutoCadd and then the locations of the openings to the surface collector were located. The opening locations from the project plans in NAD 1927 state plan system were then converted back to the NAD 1983 system. Comparison of the locations of the openings between the two data sets provided the offsets to modify the hydroacoustics system to the CFD grid (Figure 2). The following offsets were employed to transform the hydroacoustics georeferencing

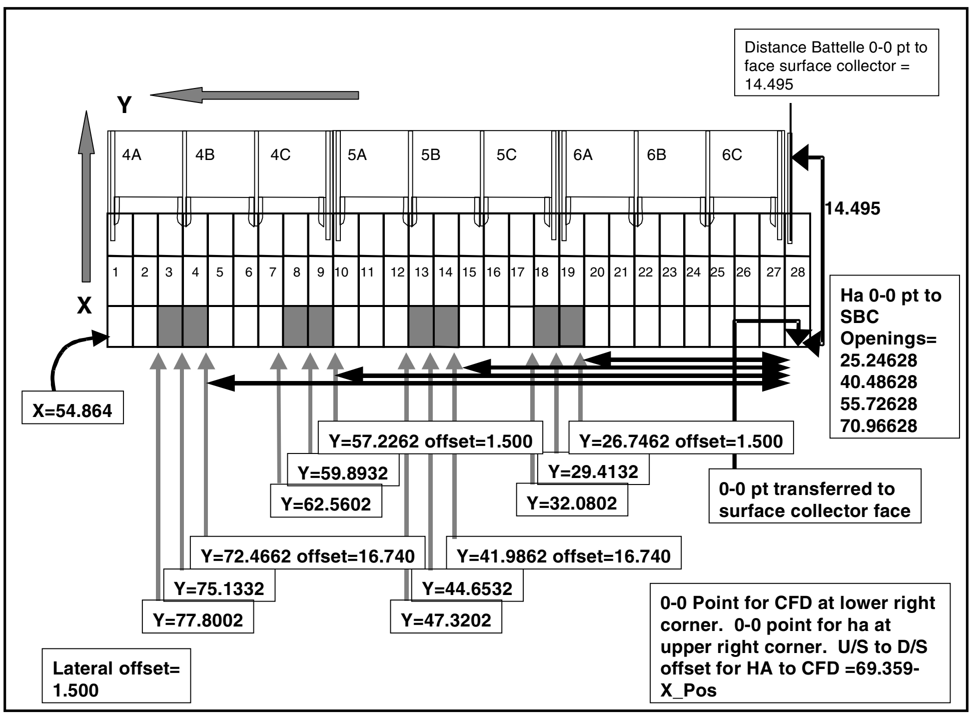

Figure 2. Plan view of Lower Granite Dam surface collector schematic (all distances in meters from the 0,0 point). Using the project design plans as an intermediate step, openings to the surface collector were used as common reference points for the two data sets. Hydro-acoustics data (HA) set spatial referencing system (black lines) was adjusted to match the CFD grid (gray lines).

framework to that used by the CFD: position in X was subtracted from 69.814 m (229.05 ft), 1.5 m (4.92 ft) was added to position in Y, and 44.5 m (146 ft) was added to the Z-position. Lack of a common spatial referencing system added considerable difficulty to the analysis as well as adding additional and time-consuming quality assurance and quality control steps.

Preliminary evaluations of the multi-beam hydroacoustics data could be performed after they were placed into the same spatial framework used by the CFD. As a first step, we plotted the traces relative to their position to the SBC (Table 3). Note that only about 12 percent of the traces occurred within 10 m (30.48 ft) of the SBC (at 54.864 m or 180.0 ft). Pings were categorized by distance from the transducer into "Combined" (ping distance from 45 to 60 m or 147.6 to 196.9 ft) and "Far" (ping distance less than 45 m (147.6 ft)). In addition, a relatively small number of traces (1.0) contained one or more pings that were out of bounds (Figure 3, top subplot), i.e., their location was outside of the physical domain of the forebay as described by the CFD. We calculated the swimming speed of fish between individual pings as the distance between pings divided by elapsed time. We evaluated the data by first deleting all traces which contained at least one inter-ping swimming velocity greater than 2.5 m s^{-1} (8.2 ft s^{-1}) (Figure 3, middle subplot) and then 2.0 m s^{-1} (6.6 ft s^{-1}) (Figure 3, bottom subplot). Note that all "out of bounds" traces were deleted when the 2.5 m s^{-1} (8.2 ft s^{-1}) criterion was selected and additional traces in the region of the plot containing the "out of bounds" traces were deleted when the 2.0 m s^{-1} (6.6 ft s^{-1}) velocity criterion were selected. Based on these findings, we performed the following data editing. Any trace in which one or more pings were "out of bounds" was deleted. Traces exhibiting one or more passive transport corrected velocities between pings greater than 2.0 m s^{-1} (6.6 ft s^{-1}) were deleted.

Table 3
Distribution of Targets by Time of Day, Range, and Orientation in X-Direction

	Range from CFD Origin (SBC at 54.864m)			
Time of Day	**60m-50m**	**50m-45m**	**45m-40m**	**Row Totals**
Day - Head-first	17	92	1,107	**1,216**
Tail-first	31	203	3,447	**3,681**
Night- Head-first	19	179	867	**1,065**
Tail-first	29	311	1,973	**2,313**
Column Totals	**96**	**785**	**7,394**	**8,275**

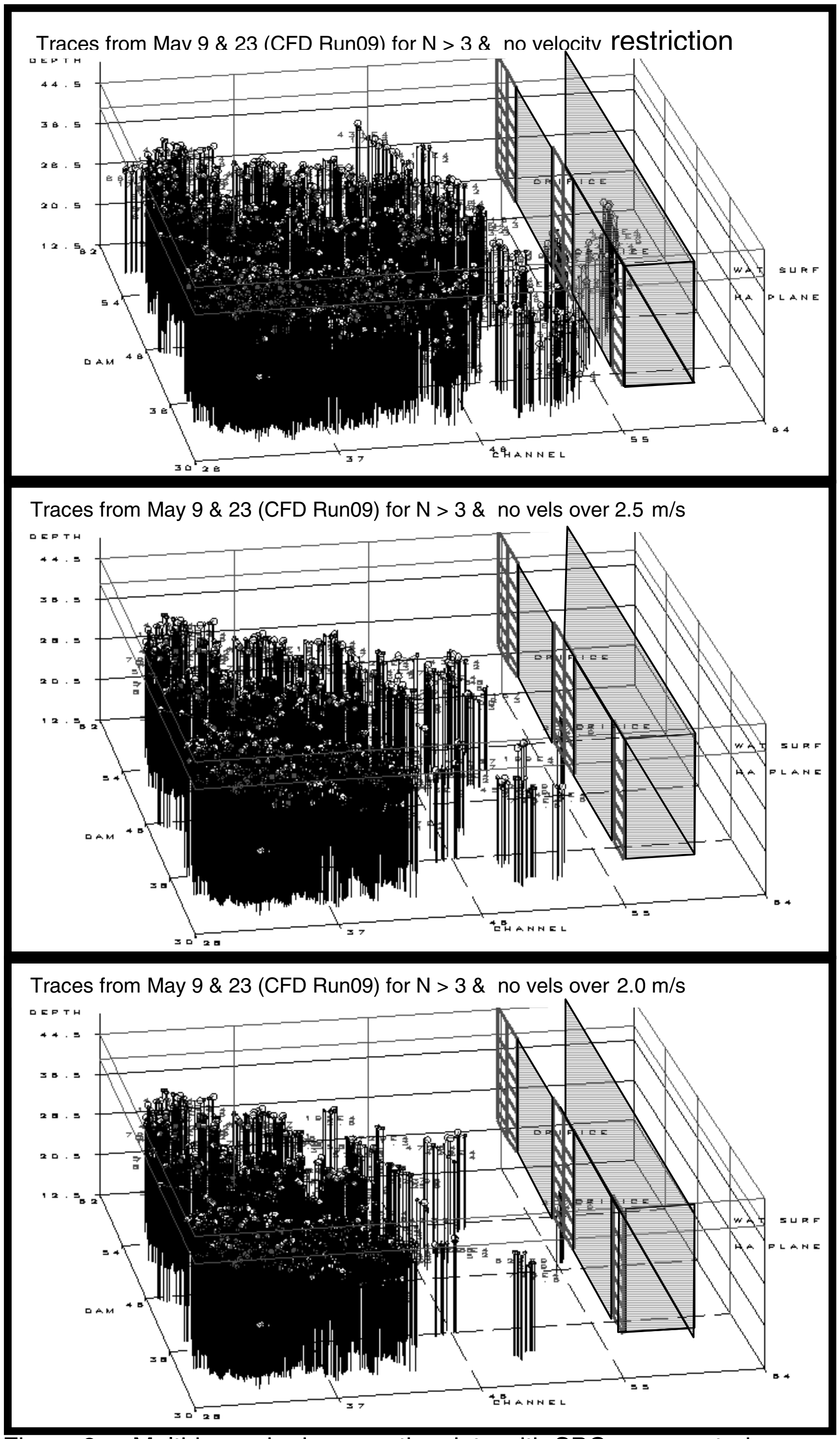

Figure 3. Multi-beam hydroacoustics data with SBC represented as shaded channel (dam to right). Subplot A contains all hydroacoustics data, Subplot B contains traces in which all targets had a calculated velocity less than 2.5 m s^{-1} (8.2 ft s^{-1}), and Subplot C contains traces in which all targets had a calculated velocity less than 2.0 m s^{-1} (6.6 ft s^{-1}). Target velocities are not corrected for passive transport.

3 Analytical and Statistical Models

Integrating hydrodynamics and fish behavior not only requires merging of these two types of data but also requires that the structure and statistical attributes of each data set be described. In this section, we first describe the detailed mathematical steps involved in integrating the two data sets. Later in the section we describe some of the statistical attributes of the two data sets and how these attributes affect the analysis. We also identify methods and strategies to avoid or mitigate many of the statistical issues of working with temporally and spatially autocorrelated data sets.

CFD output and biological position data sets can be merged once a common coordinate system is developed for them (Figure 4) and discrepancies in scale and resolution are reconciled. That is, each ping is matched with the hydraulic information at the eight corners of the cell within which it is embedded (Figure 4). Output of the CFD model run by IIHR was provided in tabular form such that each node of the grid was identified by its position in the boundary-fitted grid. The Euclidean distances between each ping and all of the nodes in the CFD output were calculated. The nearest nodes in quadrants above and below each ping were identified by minimum Euclidean distance (Figure 5). This step is normally the most difficult and time-demanding phase of data processing and normally requires one full day of run time on a 300 mHz Pentium II PC to run the programs and several days to a week to verify the output. Ideally, additional nodes representing hydraulic conditions in cells neighboring the cell within which a ping is located should also be included. Locating additional nodes allows the use of nonlinear interpolation, as is used in the NFS (described later), to characterize the hydraulic conditions at points interior of the cell. However, the search routine to identify the nearest eight points to a fish is presently too time-consuming. We are presently working on a more efficient algorithm to perform this function.

Using Hydraulic Information for Explaining Behavior

Hydraulic information can be utilized to help explain fish behavior after merging of the data sets. Hydraulic information at the nodes (or faces) of the hydraulic model can be interpolated to different positions within the cell or to

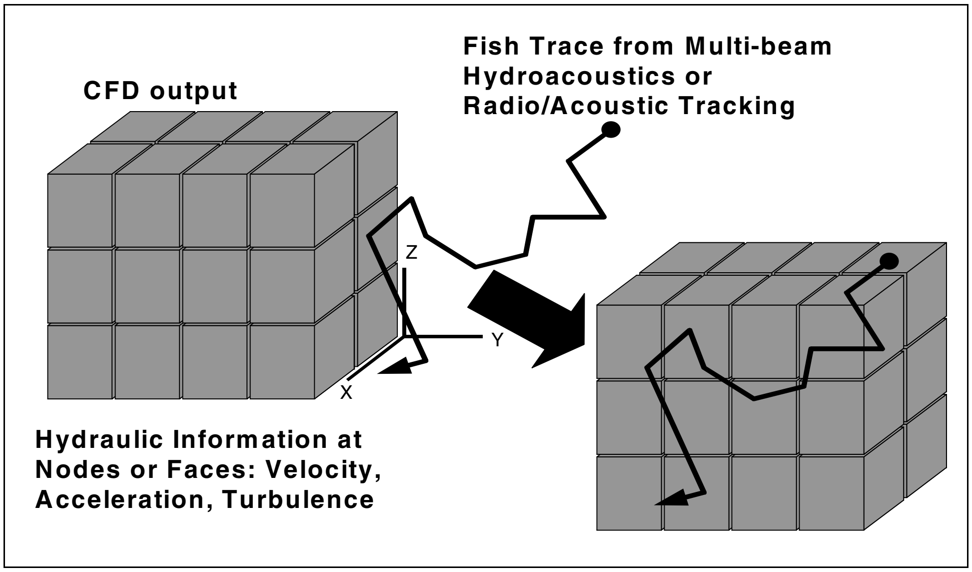

Figure 4. Conceptualization of how 3-dimensional hydroacoustics data and idealized output grid of CFD modeling are placed into a common coordinate system. Once combined, hydraulic information nearest each successive location estimate can be identified and used to develop statistical relationships between swim path selection and hydraulic conditions.

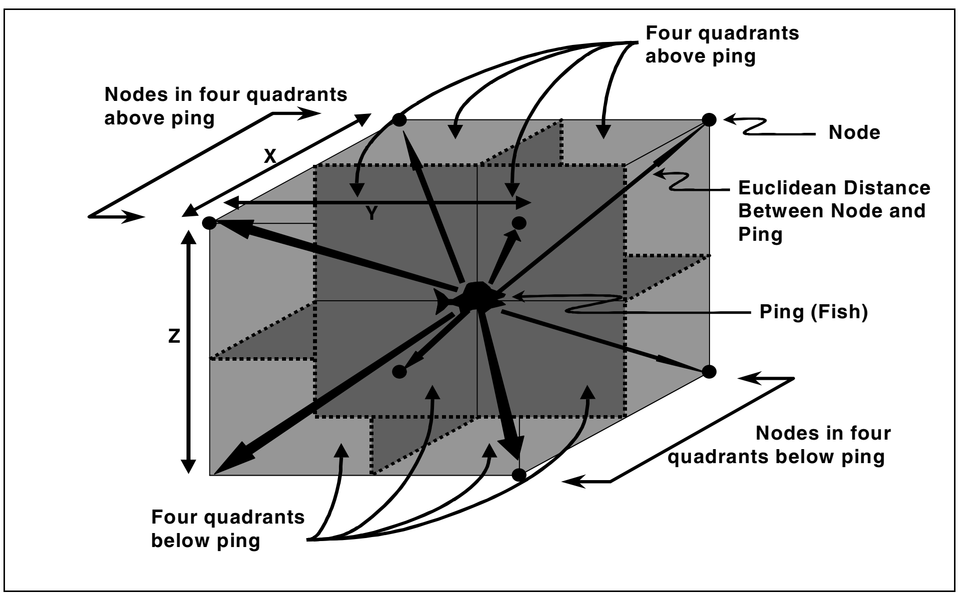

Figure 5. The Euclidean distance is calculated between each successive fish position estimate and every node in the CFD output local to the position of the fish. The hydraulic nodes defining the cell within which a fish is located can be identified by finding the nodes in each quadrant having minimum Euclidien distance.

opposing faces of the cell. Information on opposing faces of the cell can be used to calculate gradients of different hydraulic variables passing through the position of the fish or to interpolate hydraulic conditions to the location of the fish (Figure 6).

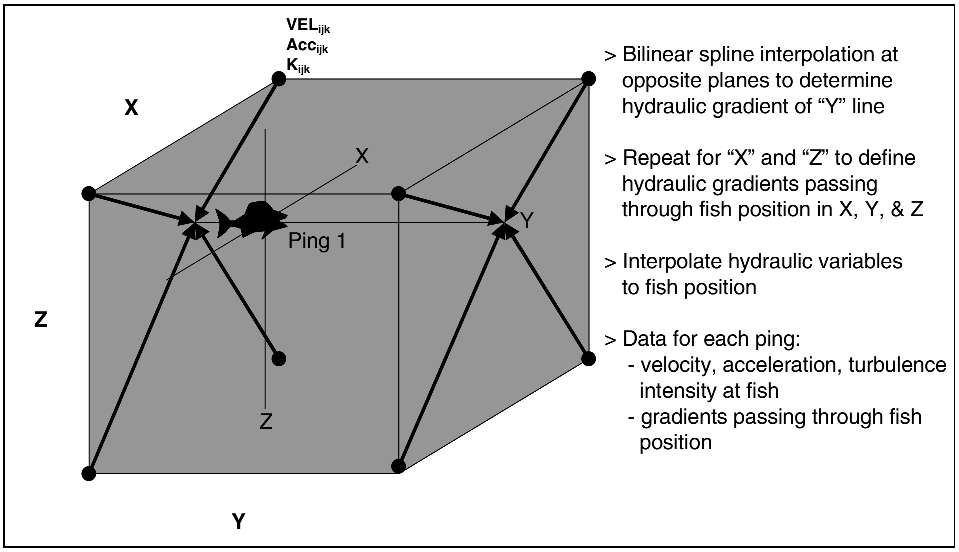

Figure 6. A bilinear spline was employed to interpolate hydraulic information at the nodes to various positions relative to the fish either to determine hydraulic gradients passing through the fish or to determine hydraulic conditions at the location of the fish.

In the analysis phase of this study, a bilinear spline interpolation was used to interpolate hydraulic information at nearest nodes to the old position of each sequential fish position pair. A bilinear spline was used for computational simplicity, but its use restricted the analysis to linear interpolation. Therefore, curvilinear changes in hydraulic conditions represented as straight lines by this interpolation scheme may produce unrealistically sharp gradients as fish move across cell boundaries. This problem may be particularly acute across sharp hydraulic gradients. A better interpolation scheme will be employed when the methods used to merge the hydraulic and biological data sets are improved.

Parameterizing Fish Movement

The following logic was used to mathematically describe juvenile salmon swimming behavior. A single fish trace can be represented as a sequence of position pairs in which each pair is comprised of an initial (or old) position at time $t_{i\text{-}1}$ and a second (or new) position at t_i. For each vector direction, the change in position from $t_{i\text{-}1}$ to t_i is comprised of two components: passive transport and volitional swimming (Figure 8). Change in position for the *X*-direction is represented as:

$$X_{t=i} = X_{t=i\text{-}1} + (\Delta t * (U + U_{\text{fish}})) \quad (1)$$

where:

Δt = time step,

$X_{t=i}$ = new (updated) position on X-Direction at time $t=i$,

$X_{t=i\text{-}1}$ = old (initial) position on X-Direction at time $t=i$-1,

U = velocity in X-Direction (passive transport) at time $t=i$ -1, and

U_{fish} = velocity of volitional swimming in X-Direction at time $t=i$-1.

A similar approach would be employed to depict change in position for the Y-direction and Z-direction. Using Equation 1, volitional swimming is zero for a passive, neutrally buoyant particle in a hydraulic field. In contrast, passive transport is zero for a fish embedded in a nonmoving volume of water (i.e., where u=0.0, v=0.0, and w=0.0) and any changes in position by the fish reflect active movement. Equation 1 was also used to delete observations from the hydroacoustics data set. In addition to deleting traces having one or more pings out of bounds, traces were also deleted in which one or more interpreting volitional velocities exceeded 2.0 m s^{-1}.

It is not possible to explain or predict movement behavior of individual juvenile salmon, even in a perfectly repeatable experimental setting, because of individual variability in degree of smoltification, physiological state, influence of secondary variables, maturity, size, antecedent history, and stochasticity associated with the dynamics of neural processing. Even the same fish may respond differently when repeatedly presented with exactly the same hydraulic field. Therefore, a more realistic representation is to consider that volitional swimming is comprised of an additional component, a velocity term, $U_{RN,}$ represented as a random number, that reflects the uncertainty inherent in predicting or explaining the movement behavior of individual organisms (Equation 2). The random number representing velocity should be scaled so that the resultant total velocity obtained by adding it to volitional swimming cannot exceed the accepted maximum swimming speed of the species life-stage being examined. As presented in a subsequent subsection entitled “Statistical Issues”, hydraulic fields are considerably less than ideal experimental settings. An additional term reflecting the inherent statistical biases that characterize fish position data and hydraulic field data must be considered, yielding the following representation of fish moving within a hydraulic grid (visualized in Figure 8):

$$X_{t=I} = X_{t=i\text{-}1} + (\Delta t * (U + \underline{U_{\text{fish}}} \; \underline{+ \; U_{RN}} + \text{Biases})) \quad (2)$$

where:

Δt = time step,

$X_{t=i}$ = new (updated) position on X-Direction at time $t=i$,

$X_{t=i\text{-}1}$ = old (initial) position on X-Direction at time $t=i$-1,

U = velocity in X-Direction (passive transport) at time $t=i$ -1, and

U_{fish} = velocity of volitional swimming in X-Direction at time $t=i$-1,

U_{RN} = random velocity component at $t=i$-1, and

Biases = biases inherent in the analyses.

Ideally, the random number should maintain its sign from the previous time-step except, perhaps, when the absolute value of volitional swimming exceeds the absolute value of the random number of opposite sign (see Figure 7 for explanation). This convention reflects field and laboratory observations of juvenile salmon in which their movement is characterized by relatively long traces in which direction does not often change instead of being characterized as a random walk. Thus, swimming patterns of juvenile salmon may be best represented as long exploratory runs in which they maintain their direction of swimming until an obstacle or repelling hydraulic feature is encountered or when their direction

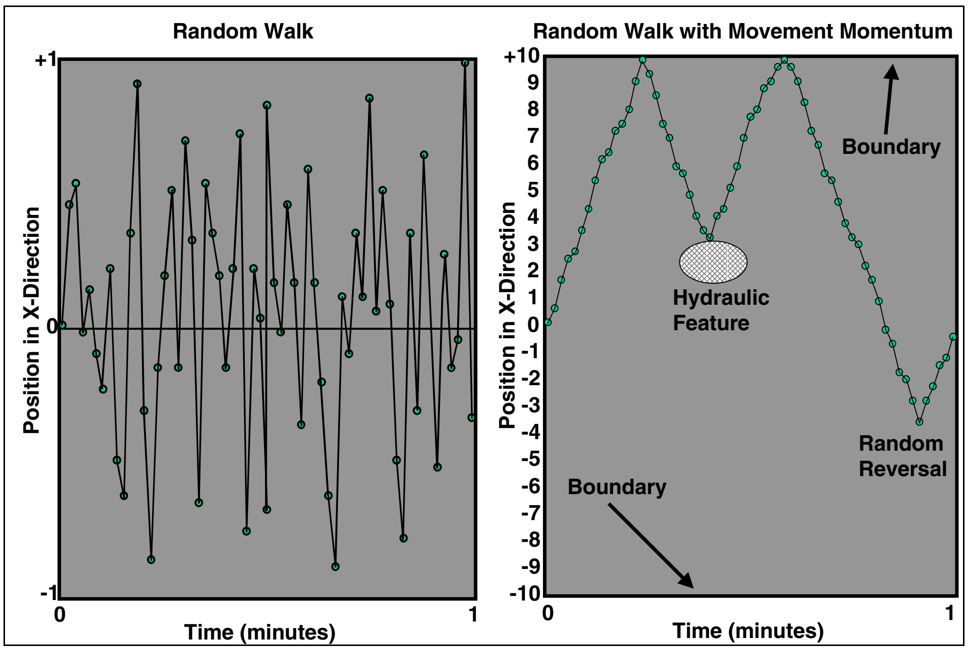

Figure 7. Comparison of traces expected from modeling movement as a random walk (left subplot) versus modeling movement as random process in which the distance traveled is random but direction of movement is conserved between one steps (right subplot). Direction of movement will change when either a repelling hydraulic feature is encountered or when a random reversal in movement occurs.

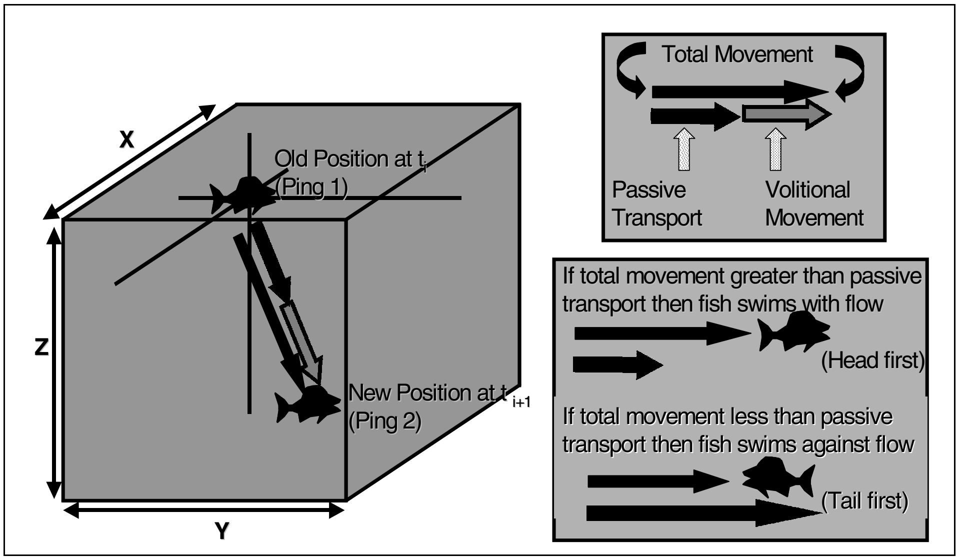

Figure 8. Hydraulic conditions interpolated to the position of the fish can be used to transport the fish through the CFD grid as though it were a neutrally buoyant, passive particle. The predicted location of the fish under passive transport can be subtracted from the known position of the fish at the next ping. The difference between the two distances represents the direction and extent of volitional swimming and the random velocity component by the fish.

changes through the influence of an environmental feature (e.g., a diving bird) not represented in the model and best simulated as random process (Equation 3). We are presently working on using Equation 3 as the basis of the statistical analysis, but presently, all of our results are based on use of Equation 2.

$$X_{t=i} = X_{t=i-1} + (\Delta t * (U + U_{fish} + (S_{t=i-1} * |U_{RN}|) + \text{Biases})) \quad (3)$$

where:

Δt = time step,

$X_{t=i}$ = new (updated) position on X-Direction at time $t=i$,

$X_{t=i-1}$ = old (initial) position on X-Direction at time $t=i-1$,

U = velocity in X-Direction at time $t=i$ -1, and

$S_{t=i-1}$ = sign of random movement from timestep $t=i-1$,

U_{fish} = velocity of volitional swimming in X-Direction at time $t=i-1$,

U_{RN} = a velocity represented as a random number for time $t=i-1$, and

Biases = biases inherent in fish position and hydraulic field data.

The passive transport predicted location of the fish can be subtracted from the fish's known next position obtained from the multi-beam hydroacoustics data set to determine that component of the fish's movement that is volitional (not caused by passive transport) along each axis of the coordinate system (Figure 8) by rearranging Equation 1 and solving for U_{fish}. Subtraction of a fish's known future position from passive transport provides an estimate of the bearing and range of its volitional swimming.

Once the volitional swimming component of a fish's change in location is known, then the underlined portion of Equation 2 (highlighted in Figure 9) becomes the basis of a multiple regression analysis. Multiple regression is used to estimate volitional swimming (U_{fish}) and the random velocity component (U_{RN}) as a function of the various independent variables mined from the hydraulic data set.

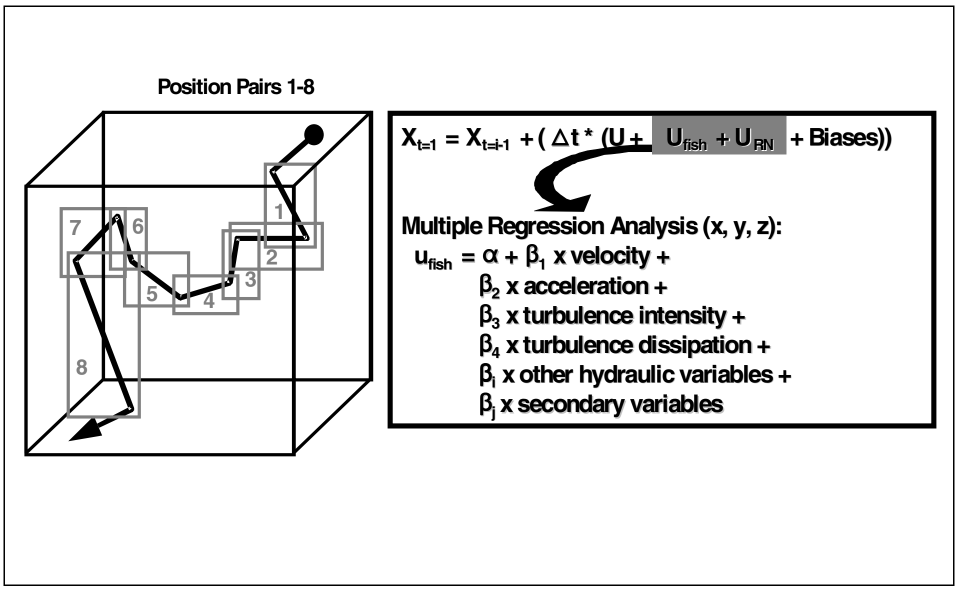

Figure 9. Analyses of volitional swimming are based on multiple regression analysis of the volitional swimming component of total movement using position pairs (in this case, 8 position pairs would be employed).

In addition to volitional swimming, the variables responsible for reorientation, i.e., the variables responsible for headfirst vs tailfirst swimming orientation in each direction can be determined using multiple regression or discriminate analysis.

Several categories of independent variables were developed for regression analysis:

d. Variables defined at the location of the fish for each direction are velocities and accelerations. Scalar variables defined at the fish location are turbulent dissipation and turbulent energy. These variables are directly calculated by interpolation from the output of the CFD model.

- Variables defined as gradients passing through the location of the fish for each direction such as the gradient in turbulent dissipation or the gradient in turbulent energy. These variables are calculated from beginning and ending values of lines passing through the location of the fish paralleling X, Y, and Z and end at planes defining opposing faces of the cell.

- Absolute variables such as the absolute value of the gradient of turbulent energy or turbulent dissipation passing through the location of the fish.

The analysis procedure described above also facilitates evaluation of non-hydraulic variables. Additional variables can be added to the analysis, such as magnetic field strength, electrical field strength, or sound pressure levels if values from these fields can be interpolated to coincide with the locations of the nodes used to describe hydraulic characteristics. An expanded analysis could be used to explore and assess the contributions of non-hydraulic variables to the patterns of fish movement.

Initially, the results of multiple regression analysis are be used to develop preliminary "fish traffic rules". A preliminary "fish traffic rule" uses the R-Square to weight the estimate of U_{fish} (i.e., the extent to which movement is deterministic). For example, an R-Square of 0.30 is interpreted to mean that 0.3 of the average distance that fish swim is based on the traffic rule. The remaining 0.7 is based on the selection of a random number from a scaled, uniform distribution to estimate U_{RN}. Thus, when the results are used in a predictive context, the model output could ranges between being totally stochastic when the R-Square approaches zero and being totally deterministic when the R-Square approaches 1.0.

Statistical Issues

Three statistical problems occur in the analysis, auto-correlation, lack of independence in the observations, and uncertainty about the distribution of the random numbers that would represent the stochastic processes that contribute to fish behavior. Auto-correlation of fish location data must occur since positions are determined sequentially. However, auto-correlation also occurs in the hydraulic data set (Table 4) because the following pattern exists in the hydraulic data. For the Lower Granite Dam simulation, the absolute value of velocities, accelerations, and turbulence intensities will increase in the downstream direction. This increase occurs because the total cross-sectional area of the downstream boundary (turbine intakes and openings to the surface collector) is significantly less than that of the upstream boundary. Therefore, velocities at the downstream exit boundaries must, on average, be greater than the velocities of the upstream entry velocities. As a consequence, spatial auto-correlation in the CFD output may produce spurious relationships between fish movement and flow field features or result in inflated estimates of significance. Auto-correlation between dependent and independent variables is also a concern in the analysis because volitional swimming as calculated using Equations 1 or 2 is calculated by subtracting out the passive transport component of position change. Passive transport is a correlate of all of the independent variables calculated by the CFD model.

Observations collected from real or simulated contiguous water bodies (i.e., hydraulic fields) will not be statistically independent of one another. Independent observations from a hydraulic field are impossible to obtain because water is only slightly compressible. That is, in a largely incompressible fluid medium, any local disturbance will immediately propagate throughout the field. Therefore, no part of a hydraulic field can be independent of any other part of the field. Lack of independence affects the results of a statistical analysis by inflating the number of observations (n) which in turn will inflate significance levels and estimates of regression and correlation coefficients.

Random numbers are selected to represent inherently stochastic processes associated with simulating fish movement. The characteristics of the distributions from which the random numbers are selected will partially determine fish movement predictions. In the future, we anticipate carrying over the sign associated with a random number selected from a previous time step (Equation 3). This new convention has an impact on the error distribution assumed for multiple regression.

Overcoming Statistical Shortcomings

The goal of this report is to develop a process-based description of fish passage dynamics to supplement the treatment-based approach that presently dominates fish passage studies in the region. The shift in perspective requires that the difference in the two modeling frameworks commonly used in process-based modeling be understood.

Table 4
Pearson Product Moment Correlation Coefficients Between Velocity and Position for Each Axis Showing Auto-Correlation in Output from CFD Modeling. All $p<0.0001$ and $N=578,151$

	X-Position	Y-Position	Z-Position	X-Velocity	Y-Velocity	Z-Velocity
X-Position		-0.08	-0.17	0.26	-0.30	-0.22
Y-Position			0.01	0.19	-0.46	-0.14
Z-Position				-0.48	-0.45	0.05
X-Velocity					0.13	-0.19
Y-Velocity						0.14

Most process-based models (i.e., non-treatment models) can be broadly separated into those utilizing an Eulerian frame of reference and those employing a Lagrangian frame of reference. The CFD model utilizes an Eulerian frame of reference in which a grid composed of multiple cells remains fixed in space and material flows through the grid. Individual packets of material or particles are averaged into each cell as they move across the cell boundaries so that their individual integrity is lost. Therefore, any model using only an Eulerian frame of reference cannot supply information directly to describe a process such as fish movement, in which the integrity of each individual must be maintained as it moves through the grid (Nestler and Goodwin 2000). In contrast, fish location data utilizes a Lagrangian frame of reference in which a packet of material or a particle is tracked in 3-dimensional space without losing its individual integrity.

A Lagrangian framework by itself does not present a framework suitable for describing information in fields, such as a flow field. In the context of process-based modeling, merging the CFD data set with the fish position data set creates a Coupled Eulerian-Lagrangian Hybrid (CEL Hybrid) frame of reference (Figure 10). The term "hybrid" acknowledges that the resulting coupled framework has some attributes of CFD modeling, a tool commonly employed by engineers, and some attributes of fish position determination, as commonly employed by fisheries biologists using telemetry or acoustical methods. Coupled frames of reference are particularly good at exploring and simulating complex processes (e.g., Tran-Son-Tay et al. 1998) that have attributes that require both frameworks for accurate representation. The Eulerian module of the coupled system provides discrete (data are presented at cell nodes or cell faces only) representations of a flow field or a water quality field. The Lagrangian module of the coupled system provides a framework necessary for depicting movement of individual

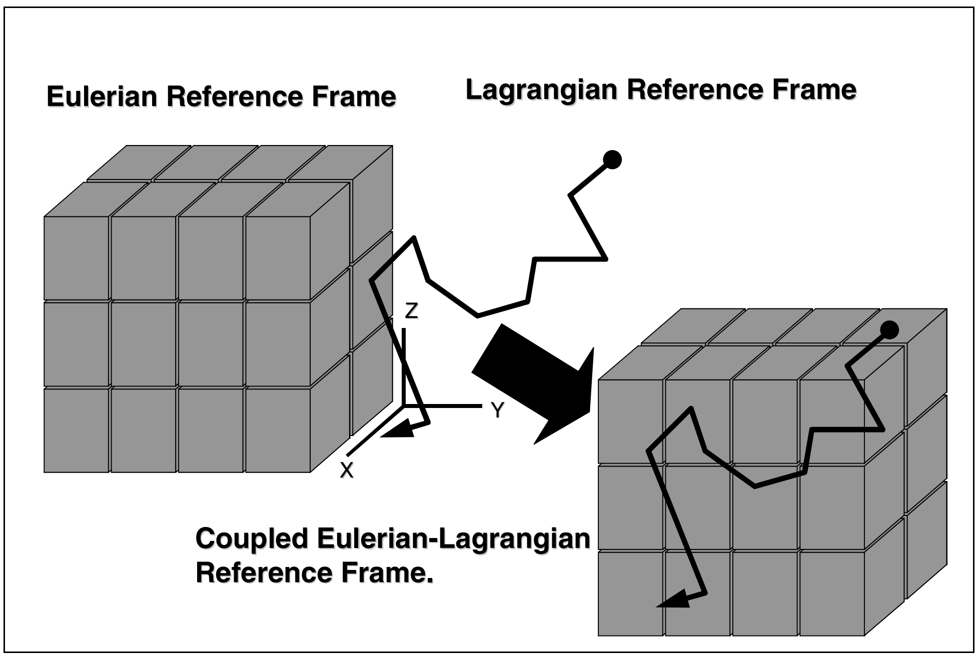

Figure 10. Merging data collected using an Eulerian reference frame with data collected using a Lagrangian reference frame generates a coupled Eulerian-Lagrangian frame of reference capable of simulating complex processes. Coupled Eulerian-Lagrangian models can be used to create virtual systems that spatially and temporally duplicate relevant processes of real systems. The virtual systems can be "sampled" like real systems and the resulting data statistically analyzed to determine how well relationships between independent and dependent variables are being captured by the statistical analysis.

fish. CEL Hybrid modeling systems have the potential of providing relatively complete descriptions of complex systems. As such, they can be viewed as providing surrogate "virtual" representations of real systems in which all relevant processes can be simulated in their totality. That is, a CEL Hybrid model can be viewed as a simulator of a complex system in the same way that a flight simulator can realistically simulate certain important aspects of the flying environment. See Nestler and Goodwin (2000) for a more complete explanation and discussion of CEL Hybrid modeling approaches.

One of the desirable attributes of CEL Hybrid models is that they can be virtually "sampled." Sampling algorithms used to explore the virtual system may be mathematically formulated to contain the same biases, assumptions, errors, and uncertainties as the sampling procedures used to sample the real world. Therefore, biases, sampling assumptions, errors, and uncertainties (stochasticities) of the real world can be represented in the virtual system. The accuracy of the virtual system (or degree to which the virtual system duplicates the real system) can be determined by comparing the statistical properties of a virtual representation using virtual sampling with the statistical properties of the real world using real sampling (Figure 11). For example, multiple regression can be used to sample both the real and virtual systems. If the virtual system exhibits the similar rankings of variables, R-Squares, probabilities, and pattern in the residuals as analysis of the real system, then it will be reasonable to consider that the behavior patterns exhibited by real fish have been largely captured by the model within the constraints of the assumptions of the analysis (Figure 12).

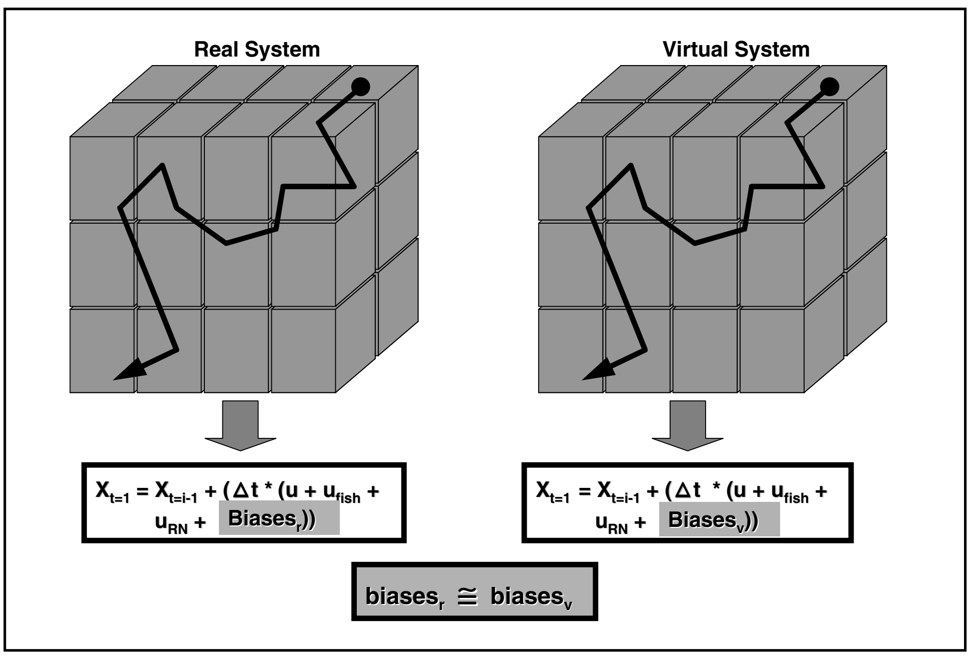

Figure 11. It is not necessary to eliminate biases in coupled Eulerian-Lagrangian models. It is only necessary that these models exhibit similar biases to the real system.

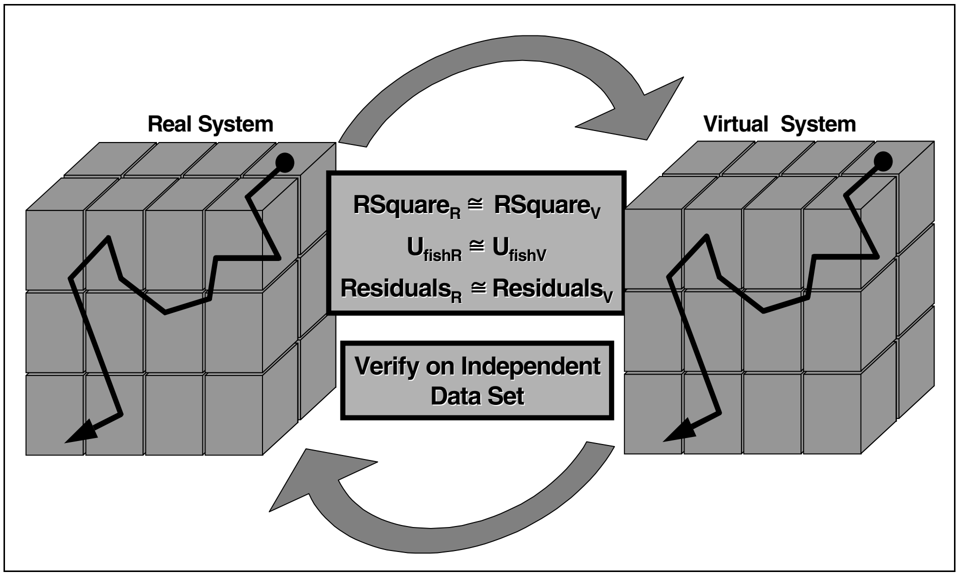

Figure 12. Future methods for calibrating behavior models. In a coupled Eulerian-Lagrangian framework, the adequacy of the simulation can be determined by how well the results of statistical analysis of the virtual system matches the statistical analysis of the real system in terms of R-Square, variables and their weights, and behavior of the residuals.

Initial coefficients describing fish movement obtained from the regression analysis can be used to parameterize a fish movement model that can be used in a predictive context. The results of the statistical analysis are not the final product, but simply the entry point into process simulation. Model performance criteria are used to determine the adequacy of the relationships developed between fish behavior and flow field features instead of the results of statistical analysis. The initial parameters used to create the virtual system world and can be optimized using parameter estimation processes typically employed to simulate complex processes such as groundwater movement. However, in the case of CEL Hybrid models, parameter estimation is expanded to not only optimize to a goodness-of-fit criterion, such as deviations between predicted and observed values, but also to fit the statistical characteristics of the real system with the virtual system. This latter point is extremely important. It is neither possible nor desirable to remove the various biases inherent in analyzing highly auto-correlated, non-independent data inherent in flow fields and sequential tracks of fish movement. Optimum simulation and understanding result when the biases of the real world are recreated in the virtual system. In this logic, results from statistical analysis of movement data become the initial parameter estimates for confirmatory, process-based modeling.

In summary, process-based studies must utilize methods designed to optimally simulate complex processes. In this context, the results of the statistical analysis of fish movement provide only the initial or preliminary fish traffic rules. The preliminary fish traffic rules obtained from statistical analysis are coded into a post-processor particle-tracking algorithm where they will be iteratively developed and evaluated from this starting point. Evaluation will then be based on performing similar statistical analysis on both the real and virtual systems until the statistical characteristics of the virtual system converge to the statistical characteristics of the real system.

Modeling of Juvenile Salmon Behavior

Background

Particle tracking algorithms allow neutrally buoyant, passive particles to be transported through a hydraulic field (Martin, J. L., and S. C. McCutcheon. 1999). Applying "fish traffic rules" developed through multiple regression to the passive particles allows the creation of virtual fish that can be introduced into the hydraulic field to simulate fish swim-path selection. The NFS can be used in three different ways. First, the model can be used in a Quality Control – Quality Assurance context. That is, the NFS is run with the same hydraulic output used to develop the rules, but the initial distribution of virtual fish is randomized. The traces generated by the NFS are then statistically evaluated to ensure that the predictions of the NFS match the results of the statistical analysis. During this phase, the "fish traffic rules" developed as previously described are explored and tested to better understand the relationship between hydraulic patterns and fish swim-path selection. Second, the NFS can be programmed with hypotheses about swim-path selection. For example, a prevailing regional hypothesis of "fish prefer not to sound" can be programmed as a rule into the NFS and evaluated to see if the hypothesized rule fits observations about fish behavior. Third, the NFS can be run in a predictive mode in which a hydraulic data set representing a new design or operation is used to run the NFS. In all three applications, the NFS can be run with a CFD output data set or measured hydraulic data representing a particular design/ operation. If measured data are available for parts of the physical domain of interest, then measured data can be substituted. The NFS can then make predictions about the percentage of fish using each possible exit way through the dam. In this way, the NFS can be used to estimate fish passage effectiveness of new design or operational alternatives that can be simulated hydraulically but for which no biological information is available.

Estimating volitional swimming requires that the part of the fish's change in position accounted for by passive transport must be estimated. Velocity information from the CFD model interpolated to the location of a fish (Figure 6) can be used to passively transport fish as though they were neutrally buoyant, passive particles in the flow field (Figure 8). The step of estimating passive transport forms the foundation of the NFS that is expanded to later explore and predict juvenile salmon swimming behavior.

The dynamic or passive transport component of the NFS model is the particle tracking module and its supporting hydrodynamic input processing routines. The particle tracking model is a modification of that developed for the U.S. Army

Engineer Research and Development Center's three-dimensional, boundary-fitted coordinate, free surface hydrodynamic model CH3D. Particle tracking within the CH3D boundary-fitted grid is performed on a transformed grid in order to take advantage of the unit square computational cell and contravariant velocity field (Figure 13). The details of the two-dimensional planar grid coordinate transformations are presented in Johnson et al. 1991 and Chapman et al. 1996.

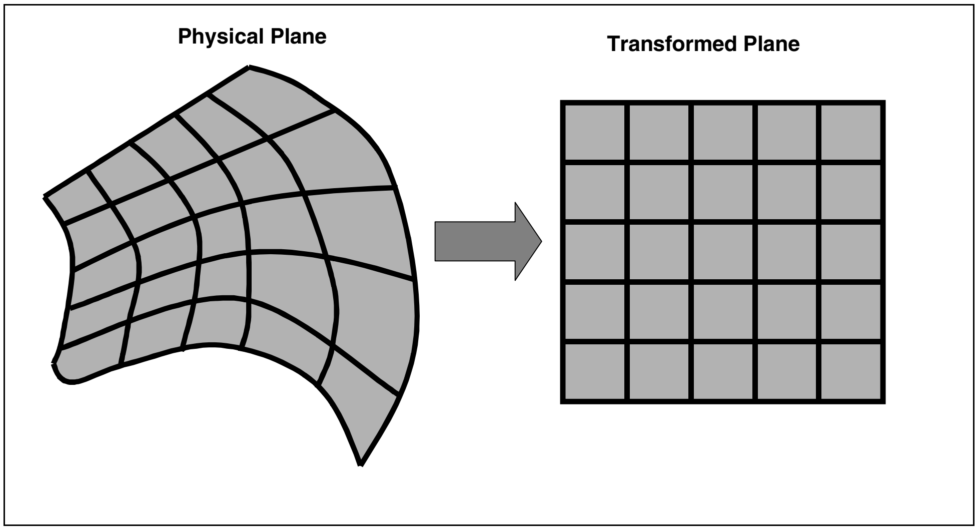

Figure 13. Transforming physical space to contravariant space allows all computations and georeferencing to be performed in unit square space for planes and unit cubed space for volumes. Use of contravariant space for biological data collection will considerably ease data merging.

The NFS, however, requires fully three-dimensional coordinate transformations in order to accommodate the IIHR U^2RANS hydrodynamic data. As a result, the mathematical formulation presented in the CH3D model documentation has been extended to coordinate transformations that map to a three-dimensional unit cube grid. Similarly, the transformation used to convert physical space to contravariant space can be applied to the biological position data. This allows both the biological data and the hydraulic data to be stored in the same matrix structure, which considerably increases the speed and efficiency in which the biological and hydraulic data are merged. This allows hydraulic data to be identified with each ping in addition to the eight points of the cell within which it occurs. The addition of more points allows the use of more accurate nonlinear interpolation methods to estimate hydraulic conditions at the interior of the cell.

The basic function of the particle tracking module is that particle positions x_k are updated from time level i to i+1 as follows:

$$x_k^{i+1} = x_k^i + u_k^i \Delta t \tag{4}$$

in which,

u_k = three-dimensional contravariant velocity vector,

k = vector index = 1,2,3, and

t = time step.

The interpolation of the contravariant velocity components within the three-dimensional transformed grid is accomplished by biquadratic interpolation on each horizontal grid cell and a two point linear interpolation between vertical layers (Hildebrand, 1956). At the end of a desired output interval, the contravariant position vectors are transformed to Cartesian coordinates prior to being output. A complete description of the particle tracking methodology is presented in Chapman et al. 1994.

The overall objective of the particle tracking development effort was to build and test a particle tracking module capable of handling multi-block hydrodynamic data provided by the IIHR U^2RANS model. The initial step was the development of a single zone linkage processor program and particle tracking module that reads the three dimensional non-orthogonal curvilinear coordinate geometry and hydrodynamic output file produced by the IIHR U^2RANS model and performs passive transport within the hydrodynamic field. The processor program performs the following operations: 1) Cartesian velocity components are transformed to contravariant velocity components mapped to a unit cube grid, 2) computes the three-dimensional metric coefficients required for transforming the contravariant position vectors back to Cartesian coordinates, and 3) writes the contravariant velocities and transformation arrays to a file consistent with the particle tracking routine within the NFS model.

The linkage and particle tracking routines were tested using four grid configurations. The first two were simple 10 x 10 x 10 Cartesian grids. The first had constant uniform grid spacing in all the three dimensions. The second used a geometric increase in grid spacing in all three dimensions. The use of these grids served a number of purposes. First, they afforded a manageable way to insure that the grid, velocity, and transformation data were correctly exchanged among the various linkage and particle tracking subroutines. Second, the constant and variable grid space Cartesian grids have analytic metric transformation coefficients and as a result, the transformation data provided by the processor program could be checked exactly. Next, the output of the particle tracker was again checked analytically using a constant speed and direction defined individually in the X, Y, and Z directions. The third grid configuration was a subset of the IIHR U^2RANS data set, which consisted of a $10 \times 10 \times 10$ grid in the vicinity of the intake structure. This subsetted data set allowed the hand checking of the input to linkage and the particle tracking module. In addition, the particle tracks provided by particle tracking routine were compared with the Cartesian velocity field. The final set of test simulations utilized the entire Lower Granite forebay data set. The forebay simulations resulted in particle trajectories that followed the streamlines of the flow field, which is the expected result for passive transport . We have developed TecPlot graphics of trajectories and velocity vectors for a single block. An example of a TecPlot representation of the flow field is presented in Figure 15.

The description above applies only to single block depictions of the physical domain being represented by the CFD model. Complex geometries are best fitted by multi-block depictions of the physical domain, in which different parts of the physical domain are represented by individual blocks. Multi-block depiction of a complex domain allows for improved representation of the complex geometries but requires the creation of the system described below to insure that hydraulic information and particle tracks can be passed across block boundaries without loss of accuracy. With this goal in mind, the development of the multi-block version of the NFS particle tracking module was undertaken.

Multi-block processor program

A multi-block extension of the previously discussed hydrodynamic data processor and particle tracking programs (Chapman, 1997 and 1999) was then developed and tested. The original processor program was modified so that the individual three- dimensional geometry and hydrodynamic data files are read and processed for each block to provide input files for the multi-block particle tracking module.

Multi-block linkage processor program

A linkage program that provides boundary information for the multi-block particle tracking module has been designed, implemented and tested. A number of operations are performed by the linkage program. First, it reads a multi-block input grid connection file which is derived from the IIHR U^2RANS hydrodynamic grid. This file provides the total number of zones, the dimensions of each zone, zone linkages that indicate which zones share a common boundary, and zone connection pairs that identify the common I,J,K coordinates of grid points that define the common boundary. Utilizing these data, the linkage program next assigns block to block grid index connection arrays. These arrays are used by the particle tracking module to allow the passage of particles among the individual blocks.

Multi-block particle tracking programs

The multi-block particle tracking module consists of two programs. An external driver program manages input, transfers files to the particle tracking routine, accounts for active versus inactive particles within each zone, and writes particle coordinate positions to an output file. In addition to importing the geometric and hydrodynamic data for each block, the driver program establishes initial particle positions and particle activation switches. Multiple blocks are accommodated by referencing particle positions and activation switches to block number as well as particle number. The second program performs the particle position and block updates. Individual block grid and hydrodynamic data are passed to this routine where the particles are moved utilizing Equation 4. A series of boundary tests are then performed to determine if a particle has moved from one block to another or if it has left the entire system. If either of these cases occurs, the particle activation switches and total particle numbers for that block are updated. Subsequent to the update of all particle positions within a block, control is passed back to the driver program. This entire procedure is repeated until either all of the particles have left the system or a predetermined simulation end time has been reached. A TecPlot compatible input file is provided by the multi-block particle tracking module at prescribed intervals for visualization purposes.

Linkage and particle tracking testing

To verify the integrity of the boundary linkage arrays, a number of simplified grid tests were performed. Specifically, combinations of 10 x 10 x 10 and 5 x 5 x 5 unit cube grids were oriented so that all possible boundary connections were generated in the X, Y, and Z directions. Subsequent to visual inspection of these arrays, multi-block, constant velocity particle tracking simulations were performed. These simulations showed that the inflow, outflow, and solid wall boundary flags worked properly using both positive and negative flow field directions. In addition, the correct transition of particles between blocks was verified. A series of test simulations were performed using the multi-block Lower Granite hydrodynamic model setup provided by IIHR after the completion of the multi-block transformation and linkage and particle tracking programs. Specifically, various combinations of forebay, SBC, and turbine inlet structure blocks were utilized to test the entire modeling system. Specifically, block to block particle transfers were validated in all three directions and among several blocks along with the SBC and outflow boundary configurations.

4 Results

As described earlier in this report, study results are of unknown quality because of uncertainties in both the CFD model output and multi-beam fish location data. Presentation of detailed results cannot occur until the uncertainties in the foundation data sets are quantified or corrected. We describe the uncertainies in both data bases below and present results in general terms so that the form and utility of the results can be seen.

Uncertainties in hydroacoustics need to be considered relative to the use of this gear for evaluating fish position. Ordinarily, hydroacoustics are employed to monitor and estimate various guidance efficiencies in which the information of interest is the proportion of total fish using a particular exitway through the dam. Workers using this gear reasonably assume that the errors in the analysis are approximately equal between the numerator and denominator terms used to estimate guidance efficiency. However, in multi-beam acoustics, there are no separate numerator and denominator terms. Consequently, errors or biases in the data cannot be assumed to cancel out. For example, the presence of "out-of-bounds" traces implies that there are errors in stationing during data collection. There is no spatial closure information to estimate the degree to which uncertainty in location may bias the analysis. Therefore, the effect of stationing uncertainty on the analysis cannot be determined. In addition, the presence of unrealistically high fish swim velocities within a single trace implies that there are instances in which two or more separate fish are being processed as a single fish trace. When this occurs within the analysis, the transition from fish one to fish two is treated as the movement of one fish using least squares methods. Least squares methods are heavily affected by the presence of outliers, and outliers that are invalid data points may heavily bias the results of the analysis. There presently are no methods available to estimate the potential bias introduced by incorrectly accepting a trace as being produced by a single fish when, in fact, it is produced by two or more fish or to estimate how often a double- for triple-fish trace occurs in the data base. Conversely, arbitrarily deleting traces based on a criterion such as "traces exhibiting changes in ping locations associated with a velocity greater than 2 m s^{-1} (6.6 ft s^{-1})" may also bias the analyses by dropping examples of extreme reaction of fish to important flow field features.

In addition, relatively few fish traces were available within the immediate hydraulic influence of the dam. We understand that telemetry antennae used to acquire information about radio tagged fish interfered with the acquisition of multi-beam data near the orifices. Consequently, that part of the hydraulic field having the greatest management interest and the widest range of hydrualic features had relatively few numbers of fish traces (about 12% of the total number of fish with the majority of these fish occurring between the orifices).

The rating curve used to estimate flow through the SBC was based on the rating curve for the Tainter gate. Measurement of flow through the SBC indicated that model flow through the SBC was underestimated by about 25 percent. This error, in turn, causes the calculation of the passive transport, particularly near the SBC, to be underestimated. Underestimating passive transport will bias the calculation of volitional swimming as well as cause the independent variables to be in error. The analysis presented in this report has errors in both the independent and dependent variables. Consequently, results can only be presented in general terms to show their form and utility.

Data Subsetting

Preliminary analysis of data obtained for Lower Granite indicates that data must be subset by day versus night, range from the dam, and orientation of the fish (Figure 14). Note that R-Squares increase substantially when the analysis is subsetted by orientation and range of the targets from the dam, and relatively little improvement in R-Square occurs when the data are subsetted by day vs night or by Run09 vs Run12. Consequently, it is unlikely that the response of juvenile salmon can related to flow successfully unless fish orientation is considered.

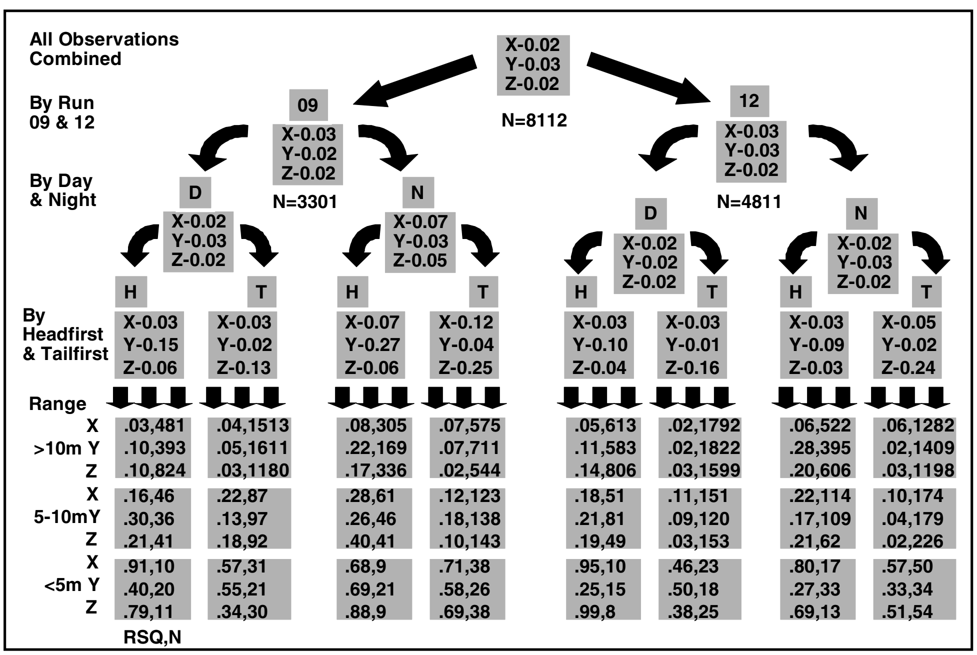

Figure 14. Nested subsetting of the analysis based on maximum R-Square multiple regression. Note that R-Square values increase substantially when the analysis is subsetted by range and orientation.

Statistical Relationships

Regression analysis of volitional swimming yielded the following general results (Table 4). The first row of the table is presented in some detail as an example of how the table should be used. During the day, within 10 m of the dam, in the X-direction, and for head into the current swimming, volitional swimming was negatively related to vertical (Z) acceleration, negatively related to vertical jerk (the derivative of acceleration), positively related to the absolute value of jerk in the vertical direction, and negatively related to increasing turbulent intensity. This can be interpreted to mean that juvenile salmon will swim away from downward accelerating flow and away from increasing turbulent intensity. R-Square values ranged from less than 0.01 to 0.389 over a range of observations (degrees of freedom plus 1) from 109 to 3447. Generally, highest R-Squares were also associated with the smallest number of observations

Table 5
Summary of Variables Identified by Multiple Regression Analysis That Affect Volitional Swimming

Class[1]				Statistics[2]		Independent Variables[3]				Absolute Value[4]					
1	2	3	4	RSQR	DF	VEL	ACC	JRK	TR-D	TR-K	VEL	ACC	JRK	TR-D	TR-K
D	C	X	H	0.294	108		-Z	-Z					+ZG		-XG
		X	T	0.260	233	+Z	-Y							-YG	+XG
		Y	H	0.153	111		-Z		+YG						
		Y	T	0.135	230	-Y,+YG			-YG						
		Z	H	0.383	96	-XG	YG					+YG,+ZG			
		Z	T	0.194	245	+XG	+Y				XG				XG
	F	X	H	0.018	1106	-Z				-ZG		-XG			
		X	T	0.018	3446	+Y	-X		-						
		Y	H	0.089	986	+Y	-Y,-X,-Z								
		Y	T	0.024	3566	-Y,+X			-F	+F					
		Z	H	0.121	1665	+Z,+X				+ZG,+F					
		Y	T	0.023	2887	-Z,+X	+Z,+Y								
N	C	X	H	0.389	197		-Y		+F		-YG				
		X	T	0.104	339	-X			+ZG			+ZG			-XG
		Y	H	0.146	182	+X,+YG				-ZG				+XG	
		Y	T	0.056	354		-Z			+YG				-YG	+XG
		Z	H	0.208	111		+Y			-F				-YD	+YG
		Z	T	0.268	425	-XG			-F,-ZG					+XG	
	F	X	H	0.064	866	-Y	+X,+Y				+YG				
		X	T	0.047	1972	+Y	-X,-Y			+F					
		Y	H	0.214	591	+Z	-Y,-Z			+XG					
		Y	T	0.022	2247	-Y	+Z								
		Z	H	0.183	998	+XG,+Y	-X,+XG								
		Z	T	0.008	1840	-Z,+X									

Legend: D=Day, N=Night, C=Combined (within 10 m of SBC), F=Far (greater than 10 m of SBC), X=X-direction, Y=Y-direction, Z=Z-direction, H=Head into current, T=Tail into the current, RSQR=R-Square, DF=Degrees of Freedom, VEL=Velocity, ACC=Acceleration, JRK=_____, TR-D=Turbulence dissipation, TR-K=Turbulence intensity further highlighting the need to increase the number of observations near the dam. Velocity and acceleration were identified most frequently as the variables influencing volitional swimming, although the turbulence variables occurred occasionally. The absolute values of the hydraulic variables were less important than when their sign was maintained. Additionally, R-Squares were consistently higher nearer the SBC than further from the SBC, although effects of nearness to the SBC and small numbers of observation are confounded. The results should be viewed only in the most general of terms because of the problems in the analysis described earlier.

Decision-Support Module

A decision-support shell can be built on to the NFS after the completion of confirmatory modeling. For Lower Granite Dam, the decision support system tallies the number of out-migrating juvenile salmon utilizing different exit ways. For example, the decision-support shell of the NFS can summarize the predicted numbers of fish using spillway, turbine, or surface collectors to pass the dam based on a particular "fish traffic rule" (Figure 15). For this example, fish are counted as passing into a particular opening when they have crossed a plane covering that opening. More sophisticated tallying code can be produced to duplicate the limitations or assumptions of different sampling methods used to measure entry of fish into the different exits.

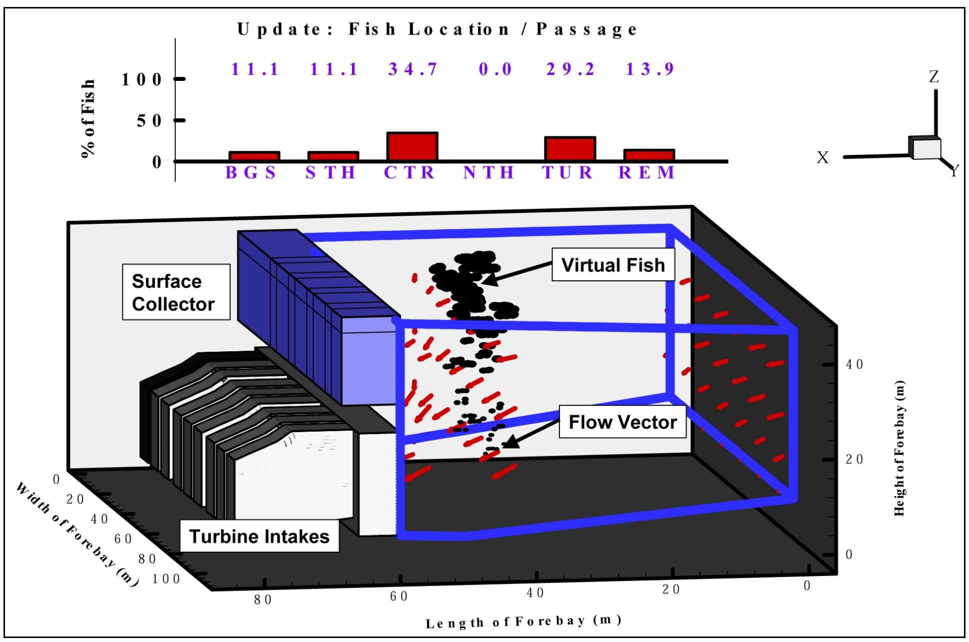

Figure 15. Example of the decision-support shell that can be used to evaluate different fish passage designs or operational plans. Legend: BGS = surface collector opening nearest the behavioral guidance system, STH = south opening to the SBC, CTR = center opening of the SBC, NTH = north opening to the SBC, TUR = turbines, REM = remaining fish in the simulation.

5 Discussion

Archive Knowledge

The approaches described in this report can be used to effectively integrate data commonly collected by hydraulic engineers or design engineers with data collected by biologists insuring that all data are used for decision-making. The approaches documented in this report also provide a framework to systematically archive knowledge about the behavior of the different species and life stages of salmon in the basin using the same tools that will be used to select dam designs and operations. Using this framework, it will be possible to compare relationships between projects or between different years of the same project. Differences can be reconciled by refining the behavioral rules used to simulate fish swim path selection, by exploring for secondary variables that may be confounding results from different studies, or by better understanding possible changes in behavior during the smoltification process. Most importantly, the approaches offer a rigorous method that can be employed to minimize the use of the “build and test” paradigm.

Develop Large Project Optimum Designs

The scale, complexity, and highly dynamic nature of the hydraulic environment at major dams is one of the major challenges that limit the ability of designers to build successful fish passage structures. Unlike smaller facilities, like irrigation withdrawal systems, simple hydraulic design criteria cannot be formulated for large dams. The approaches described in this report offer one of the few tools that can be applied in a systematic way to design fish passage structures. Once swim path selection rules have been formulated, then it is possible to use engineering tools to evaluate competing designs or operations for their effectiveness to attract approaching fish to the entrance to the system with a minimum of delay and minimize the number that pass through the turbines.

Suggested Improvements

We offer the following recommendations to improve the process developed in this report:

First, the statistical and analytical pass through the biological information should use the same higher order nonlinear interpolation scheme used in the NFS. Presently, the statistical and analytical pass uses a simple bilinear spline interpolation. Consequently, error is introduced during the phase in the study in which the virtual ecosystem is sampled and the results compared to the real system. Two separate interpolation schemes were originally used because of the difficulty in matching up sequential location information with the proper node points of the model. This presently requires a run time of around 8 hours on a 300 mHz Pentium II PC for merging one CFD data set with one medium sized biological data set. Using a nonlinear interpolation scheme would require that additional nodes beyond the nearest 8 nodes would have to be identified and merged requiring substantial increases in run time. Implementing this recommendation will require that the transformation used to map the Cartesian grid to a contravariant (unit cubed space) grid must also be applied to the biological poistion. Once the biological information is transformed to contravariant space then the proper nodes in the CFD output data set can be directly identified by their matrix addressing.

Second, fish behavior should be referenced to stream lines and not the arbitrary origin and axis orientation of the CFD grid. That is, the selection of the origin and axis direction of the CFD grid probably has little or no biological significance. It may be more reasonable for fish to be oriented to the prevailing local streamline than to the origin and axis orientation of the CFD code. This suggestion may be difficult to implement and should be considered as a long-term goal.

Third, a verification data set from another year with different flows and different operations should be used to confirm the relationship between flow and fish behavior. Hydrodynamic fields are characterized by highly autocorrelated data which effectively reduces the degrees of freedom in the analysis.

Fourth, other statistical methods, such as discriminate analysis or canonical discriminate analysis, should be considered to explore the relationship between flow and fish swim path selection.

Fifth, a change to a Markov Chain representation of fish behavior, including continuous time Markov Chain depiction of swim-path selection, should be explored to determine the approach that best captures and summarizes fish swim selection. This also is a long-term suggestion.

Sixth, the relationship between fish behavior and the grid spacing used in the CFD and the time step used in the NFS should be described. Results obtained from relatively coarse CFD grids and long timesteps of the NFS will probably differ from finer CFD grids and shorter time steps of the NFS.

6 Conclusions

The results of this study demonstrate that it is possible to integrate CFD model output and biological information in a mathematically rigorous manner using a CEL Hybrid Model approach. Methods were identified to overcome some of the shortcomings inherent in using highly auto-correlated and non-independent data sets.

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14. ABSTRACT

New tools have become accepted within the Columbia River Basin that provide detailed information on the hydraulic environment (e.g., Acoustic Doppler Current Profilers – ADCP and Computational Fluid Dynamics – CFD) and biological responses (e.g., multi-beam hydroacoustics and acoustic tracking). Unfortunately, the new information provided by these tools cannot presently be integrated into a unified framework to support regional decision-making. The overall goal of this research is to develop and apply an approach for integrating biological and hydraulic information to support selection of optimum designs and project operations for Surface Bypass at Lower Granite Dam. The tools and relationships developed for Lower Granite Dam may have application to other sites within the basin. The specific goal for FY99 was to develop the approach and apply it in a preliminary, proof-of-concept context in anticipation that the ideas and concepts will be more fully developed in FY00. We present an approach based on the following steps: 1) evaluation of the CFD and biological data sets for integration potential, 2) adjustment of coordinate system and georeferencing system of the biological data sets so they could be overlaid on CFD output, 3) development of a mathematical framework describing fish swim path selection, 4) development of an analytical/statistical process relating the response of juvenile salmon to specific flow field variables, 5) development of a confirmatory modeling process (Numerical Fish Surrogate) that can be used to explore and verify the results from step 3 or to simulate new conditions, and 6) development of a decision-support module that can be used to summarize the performance of specific design or operational alternatives. Preliminary results of the analytical/statistical phase indicate that juvenile salmon during the times sampled move through the waterscape in a fully three-dimensional manner in which they avoid repelling hydraulic features in on dimension by escaping in other dimensions.

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