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Evaluation of juvenile salmon behavior at Bonneville Dam, Columbia River, using a multibeam technique

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Abstract − In recent years, with increased effort to bypass and guide fragile stocks of juvenile salmon in the Columbia Basin past hydroelectric projects, it has been increasingly important to obtain fine-scale fish behavior data in a non-intrusive manner. The Dual-Head Multibeam Sonar is an emerging technology for fisheries applications that addresses that requirement. It has two principal advantages over traditional hydroacoustic techniques: 1) it allows for simultaneous large-volume coverage of a region of interest, and 2) it affords three-dimensional tracking capability. The use of Dual-Head Multibeam Sonar in this study resulted in an unprecedented insight into fine-scale smolt behavior upstream of a prototype surface collector at the Bonneville Dam first powerhouse in 1998. Our results indicated that outmigrant juvenile salmon had an increased likelihood of milling or holding. This discovery will lead to better design criteria for future bypass and collector systems. Future fisheries multibeam sonar systems will likely be fully integrated systems with built-in real-time tracking capability. These systems may be used to track targets relative to physical guidance structures or other behavior-modifying stimuli such as light, turbulent flow, electrical/magnetic fields, or low-frequency sound and vibration. The combination of fine-scale fish behavior data and environmental parameters will yield better design criteria for the safe passage of listed or endangered species of Pacific salmon.

multibeam sonar / hydroacoustics / smolt / fish behavior / fish behavior / hydropower dams / fish tracking / three-dimensional visualization

Résumé − Évaluation du comportement des saumons juvéniles au barrage de Bonneville, sur le fleuve Columbia au moyen d'un sonar multifaisceaux. Ces dernières années, avec l'effort croissant d'aménagement pour faciliter et guider le passage des saumons juvéniles au niveau des barrages hydroélectriques du fleuve Columbia, il est devenu de plus en plus important d'obtenir des données précises sur le comportement des saumons sans provoquer de dommage corporel aux poissons. Le sonar multifaisceaux à deux têtes est une nouvelle technologie qui permet cette application. Il a deux principaux avantages sur les techniques hydroacoustiques traditionnelles : 1) de grands volumes peuvent être considérés simultanément, 2) il permet un suivi en trois dimensions. L'utilisation de ce sonar dans cette étude a permis d'observer pour la première fois le comportement, à petite échelle, des smolts en amont, au niveau d'un prototype d'un système de collecteur en surface. Nos résultats indiquent que les saumons juvéniles en migration ont une probabilité qui va croissante de se faire happer par les turbines ou piéger. Cette découverte conduira à mieux définir les paramètres des futurs systèmes de collecteurs et de passes à saumons. Les systèmes de sonar multifaisceaux utilisés en pêche devront intégrer des systèmes permettant le suivi des poissons en temps réel. Ces systèmes pourraient être utilisés pour guider des poissons avec des barrières physiques ou en utilisant des stimulus qui modifieraient le comportement tels que la lumière, des courants tourbillonnaires, des champs magnétiques ou électriques ou bien des vibrations et sons à basse fréquence. La combinaison entre des données de comportement des poissons à petite échelle et de paramètres environnementaux donneront de meilleurs critères pour la réalisation de passes à poisson pour les espèces en danger telles que le saumon du Pacifique.

sonar multifaisceaux / hydroacoustique / smolt / comportement des poissons / barrage hydroélectrique / suivi de poissons / visualisation 3D

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1. INTRODUCTION

1.1. Background

The Portland District of the U.S. Army Corps of Engineers (Corps) began developing surface flow bypass and collection systems in 1995, in response to the 1995 biological opinion on the operation of the federal Columbia River power system (National Marine Fisheries Service, 1995). Because of this mandate, the Corps began an aggressive, nontraditional development of surface flow bypass concepts with a sense of urgency for design, construction, and testing (U.S. Army Corps of Engineers, 1995; Johnson et al., 2000).

The Corps has conducted evaluations of surface flow bypass concepts for outmigrant juvenile salmonids for a number of years. One objective is to provide passive attraction or guidance flows to the salmonids and understand their behavior as they approach bypass structures, whether surface bypass structures retrofit to a dam or blocked trash racks and sluice chutes. Understanding the behavior of fish in front of these bypass and guiding structures will play a major role in helping engineers design permanent structures.

A number of different types of devices have been used in past years to try to understand the behavior of downstream-migrant fish. These include direct capture, video, radio telemetry, and sonic telemetry. Because many of the stocks in question are currently listed under the Endangered Species Act, techniques involving direct capture are limited. Video has met with limited success because of the relatively high turbidity levels associated with spring runoff. Video is best applied in close proximity to a structure, and thus, yields little information on the fish's approach behavior. Radio telemetry, while not functionally limited in range, does not provide the information necessary for fine-scale behavioral evaluations. In recent years, the emergence of tag tracking systems, suitable for freshwater applications, has gained favor with researchers. However, current tag technology requires use of a relatively large tag (7 mm × 16 mm), which may affect fish behavior, particularly for 0-age salmonid smolts. Because of the shortfalls of traditional methods and current limitations of new telemetry methods, it was desirable to pursue a new, non-intrusive technique for evaluating juvenile migrant salmon behavior near prototype bypass structures.

1.2. Purpose

This paper describes a new technique, Dual-Head Multibeam Sonar (U.S. Patent 6,084,827, issued July 4, 2000), for obtaining fine-scale fish behavior near prototype surface collector and guidance structures at hydropower projects.

2. METHODS AND MATERIALS

The two sonar heads used in this study were deployed from a floating platform moored in the forebay of the first powerhouse at Bonneville Dam (*figure 1*) approximately 18 m upstream of the test prototype surface collector (PSC). The dual-head sonar approach used in this study is similar to the Mill's Cross technique described in Urick (1975). Jaffe (1999) also applied a similar technique for examining the behavior of small aquatic animals in a marine environment and at a limited range. In our case, the Dual-Head Multibeam Sonar was deployed from a floating platform secured in place by two large upstream anchors attached to buoys and two tensioning lines attached to the test structure for stability. Two Simrad SM2000 sonar heads (multiple transducers and associated underwater electronics, Kongsberg Simrad Mesotech Ltd., Port Coquitlam, BC, Canada) were mounted near the end of a 6.0-m (3.5-m submerged) rigid pole and deployed from the floating platform. The two sonar heads were oriented perpendicular to each other with the center of each aimed at the region of interest. The orientation of the pole was monitored continuously by a KVH C100 fluxgate compass (KVH Industries Inc., Middletown, RI, USA) and a Crossbow CXTILT dual-axis tilt sensor (Crossbow Technology Inc., San Jose, CA, USA), respectively, attached to the top of the pole. The position of the floating platform relative to the test structure was monitored at 1-s intervals using an MDL Laser Radar Fanbeam MKIII (MDL Technologies Inc., Houston, TX, USA). Prisms were placed at both upstream and downstream extents of the floating platform for additional orientation data. Power, data telemetry, and actuator control lines were attached to a 0.635-cm insulated cable umbilical belayed to the PSC structure near pier nose 3BC (Turbine Unit 3, between intakes B and C). Cables were routed below the powerhouse deck to permit operation of the project gantry crane and the mobile crane used for changing PSC slot configurations (1.5-m and 6.0-m widths were tested).

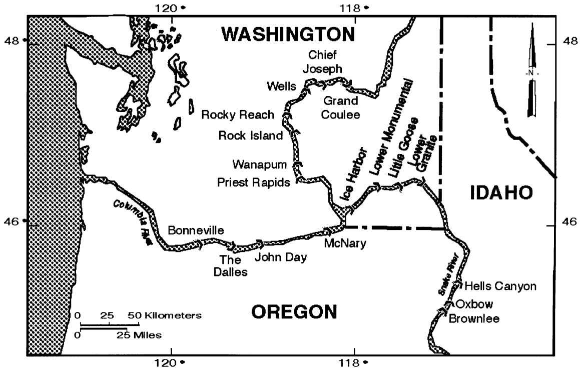

Figure 1. Location of Bonneville Dam in Washington State, USA.

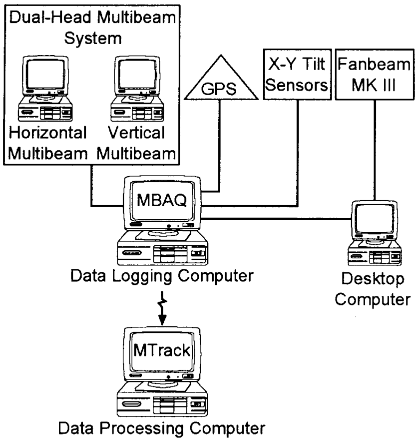

Figure 2. Schematic of major components of the Dual-Head Multibeam Sonar System.

The floating platform was positioned approximately 18.5 m from the face of the PSC. That position precluded bottom interference and placed the transducer in the shadow of the PSC to avoid turbine interference. The Dual-Head Multibeam Sonar collected data 24 h·day^{-1} from 2.0 m in front of the transducers (blanking range) to the face of the PSC. Both horizontal and vertical coverage was approximately 9.9 m at the maximum range.

The control and logging side of the Dual-Head Multibeam Sonar was housed in an equipment trailer positioned on the deck of the dam near Turbine Unit 5. The system comprised two Simrad SM2000 surface processor units, a control computer running Seismic Positioning System Software for the MDL Laser Radar Fanbeam MKIII, and a third computer running Battelle's Multibeam Data Acquisition Software (MBAQ) for logging all data (*figure 2*). Additionally, a Garmon global positioning system (GPS) was mounted on the roof of the powerhouse, and the MDL Laser Radar Fanbeam MKIII was positioned at the northern-most end of the PSC. An additional prism was attached to the handrail of the upstream side of the PSC to provide a quality control reference point for platform positioning. An actuator control switch was positioned near the surface units for remote aiming of the sonar heads. The operator could thereby view the sonar displays while adjusting the aiming angle for optimal positioning or exploration.

2.1. MTrack fish tracking software and analysis

Some multibeam files collected at the dam were processed onsite. The majority of the files collected at Bonneville Dam during the sampling period were sent to the Pacific Northwest National Laboratory in Richland, Washington, for processing. Binary files received from the dam were subdivided and manually processed by data technicians. MTrack software developed at Battelle was used to filter out permanent dam structures and to group targets together based on their proximity in space, time, and angle units through a visual user interface. Once MTrack had grouped tracks together in a meaningful way, technicians manually selected fish targets from the noise. MTrack applied further algorithms to retain only fish targets that overlapped in the horizontal and vertical transducer beams. The resulting fish track data were output as text files.

The text files resulting from fish tracking were read into a series of Fortran programs that calculated exact fish positions within the forebay sampled region (converting polar coordinates to the x, y, z planes). These programs corrected for fish location according to transducer location, tilt, and aspect. The data were then loaded into a database, and an instantaneous velocity was calculated for each tracked target. Average positions and average speed were also calculated for individual fish.

A number of analyses were then applied to the tracked fish data with various origins. A search of the literature produced useful results from areas as diverse as particle-diffusion theory (Parrish and Hamner, 1997; Turchin, 1998), multiple target tracking (Bar-Shalom and Li, 1998), spherical statistics (Zar, 1984), geology (Davis, 1986), and animal behavior (Parrish and Hamner, 1997; Turchin, 1998).

3. FISH TRACKING RESULTS

In this section, we provide examples of the types of results that may be derived from the multibeam sonar data, including: direction of travel, track characteristics, and visualization. These examples were taken from our evaluations of the Bonneville Dam first powerhouse prototype surface collector in 1998. Other data routinely collected but not shown in this paper include: sonar coverage, spatially-specific depth distributions, and tracked target kinematics.

3.1. Direction of travel

Using bin-based fish tracking data, we produced observed-flow-vector plots to relate the direction of travel to the flow conditions within particular bins of water for the 1.5-m and 6.1-m slot configurations, respectively (*figure 3*). The 'observed' vector component represents the direction of movement relative to the structure under test. The 'flow' vector is the average flow measured in a physical model at the Waterways Experiment Station in Vicksburg, MS. The 'effort' vector is the result of the observed minus flow vectors by vector arithmetic.

3.2. Track characteristics

Track characteristics were quantified using an index of tortuosity (τ). The index of tortuosity is an inverse linearity term (linearity is an algorithm used histori-

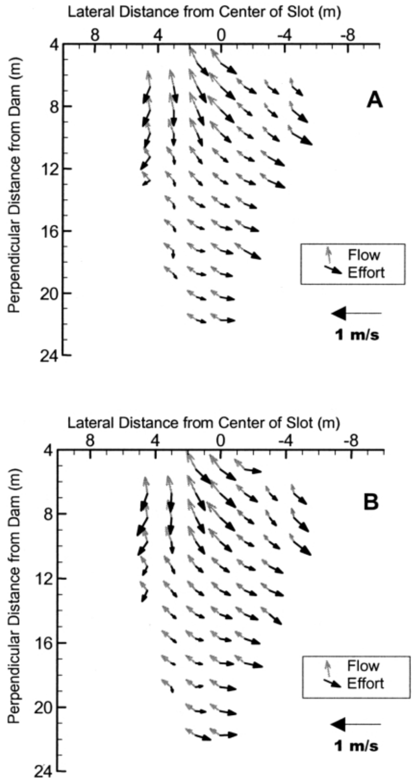

Figure 3. Top view (x–z) of observed, flow, and effort vectors for the 1.5-m and 6.1-m configurations.

cally in single-beam hydroacoustics as well as other disciplines), where:

$$\tau = \left(\frac{\text{Distance Traveled}}{\text{Straight Line Distance}} \right) \qquad (1)$$

Distance traveled is the sum of the small distances a target moved between each record along a track. The straight-line distance is the difference between the target's first and last recorded positions. Using this equation (1), a fish traveling in a straight line will have an index of tortuosity equal to 1.0. Fish traveling more circuitous paths will have index values greater than 1.0. Examples of fish track plots at various tortuosity levels representing the range of values in this study are shown in *figure 4*.

One of the more difficult aspects of the analysis has been track characterization, or behavioral classification. Several metrics were devised to represent individual fish behavior. In this example, a high degree of tortuosity may suggest fish holding or milling behavior. *Figure 5* shows that the degree of tortuous behavior increased similarly for the 1.5-m and 6.1-m test configurations in 1998. One might deduce that the fish exhibited increased tendency to hold or mill, with increased proximity to the test structure.

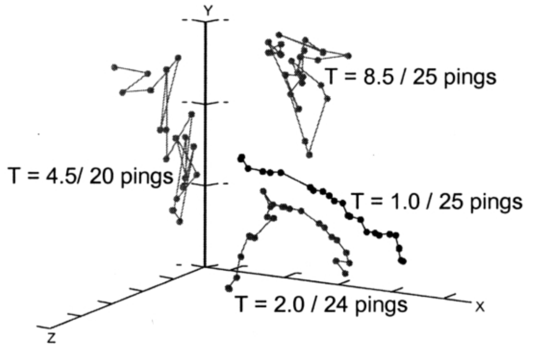

Figure 4. Examples of index of tortuosity values between 1.0 and 9.0 (data from single tracked fish targets at Bonneville Dam in 1998).

3.3. Three-dimensional visualization

An animated, three-dimensional visualization tool was also developed to view fish movement in the context of a dam. The visualization includes user controls for manipulating the scene graphic, speed of data playback, and display of track histories. These

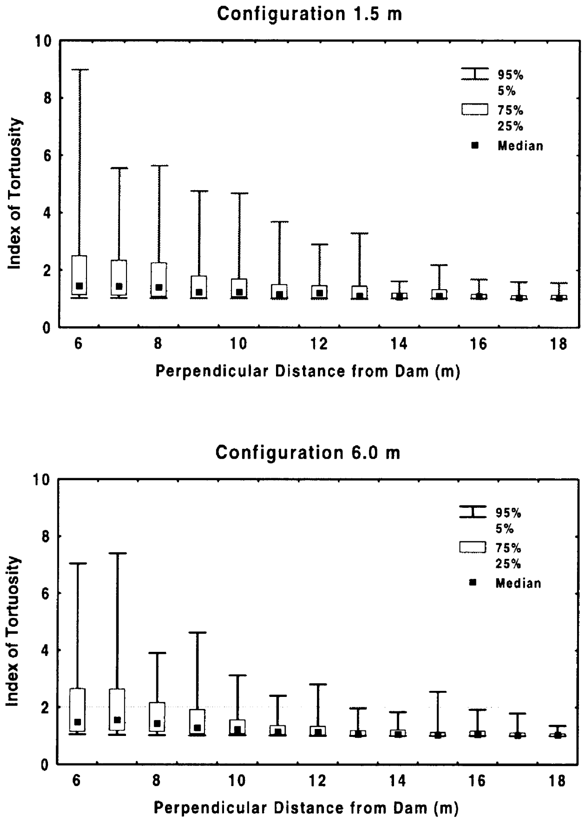

Figure 5. Box and whisker plots of the index of tortuosity with range for two configurations of the prototype surface collector at Bonneville Dam in 1998.

visualizations were used for qualitative examination of trends and anomalies in the dataset before and during data analysis to elicit an increased understanding of target dynamics and for quality control.

4. DISCUSSION

Traditional methods of evaluating fish behavior using nets or other direct capture techniques are no longer acceptable in the Columbia River basin because many of the stocks under investigation are currently listed under the Endangered Species Act. Thus, studies of fine-scale fish behavior (tracking resolution of ≤ 1 m) in the past three years have focused on hydroacoustic evaluations, coupled with radio telemetry studies using hatchery stocks. In past years, our analyses of juvenile salmon behavior data involved the use of vector graphics based on splitbeam hydroacoustics. Fixed-splitbeam hydroacoustics provided the necessary volumetric resolution to allow fine-scale tracking, but suffered from limited sample volume. In recent years, several metrics were developed to describe the behavioral characteristics of smolts as they approached a guidance or collection structure. More recently, a combination of splitbeam and multibeam techniques was used to increase coverage very near the structure and provide estimates of fish target strength.

The hydrographic industry has used narrow-beam echosounding since the 1960s, and it has developed as a tool of preference within that industry (Vilming, 1998). Multibeam swath bathymetry has emerged in recent years and has the advantage of large swath coverage with relatively fine resolution for bottom mapping and seabed classification. Only within the past few years has multibeam sonar been considered a viable tool for fishery research (Mayer et al., 1998; Gerlotto et al., 1999). The primary reason for using multibeam is to increase sample volume and target-position resolution. It is likely that future scientific hydroacoustic tools will have a multibeam architecture coupled with the attributes of existing hydroacoustic tools.

With the advent of real-time digital beam forming, it became possible to sample volumes that were ten times or more that of traditional sampling techniques by using a multibeam approach. Multibeam sonar has also been recommended by researchers in the past to help address biases associated with estimates of school size in the marine environment based on the small sample volume of traditional echosounding techniques (Gerlotto et al., 1999). In 1998, the Portland District of the Corps opted to deploy this new technology at Bonneville Dam to conduct three-dimensional tracking of individual fish over a relatively large volume of water. The Dual-Head Multibeam Sonar used was a unique application of the multibeam concept by deploying two sonar heads positioned on a fixed mount. The sonar heads were oriented at a 90-degree angle to each other, referenced to the primary axis of the two beams, which produced horizontal and vertical components within the overlap zone. The overlap region of the two sonars was the volume sampled for fish tracking.

The Dual-Head Multibeam Sonar approach to quantifying fish behavior is not without limitations. First, the system is difficult to calibrate in the laboratory because of the large number of beams associated with each sonar head. Laboratory calibration will be necessary before the system can be used to assess stock size or to estimate passage rates. Our method of field calibration involves the use of a standard target (target strength = –45 dB) that is routinely transected across the beams, both horizontally and vertically. Although this technique is sufficient for setting minimum and maximum thresholds for detectability in our behavior studies, it is not adequate for biomass estimation or passage estimation. Second, the system has an inherent range-dependent decrease in angular resolution. In our current application, where we are relatively close to a structure, this has not presented a major problem. We are currently exploring the use of interpolation algorithms that will permit increased, within-beam resolution. Within-beam interpolation will result in greater range capability for fine-scale fish tracking. The technique is best applied in areas with high signal-to-noise ratio, although filters may be used to extract fish tracks from uncorrelated noise. Improvements in transducer design are also needed to minimize the side lobe interference and combine the heads into a single unit to remove parallax effects.

The analysis of fine-scale fish tracks can be segregated into two broad categories of spatial-temporal analytical methods: Lagrangian individual-based models, including individual tracks and behavioral classification, and Eulerian stochastic particle models, including diffusion theory and population trends. The individual-based Lagrangian techniques are more mechanistic and provide more information about individual movement than the Eulerian approach, which is primarily aimed at the population level (Turchin, 1998). In many instances in behavioral ecology, researchers are forced to use the Eulerian approach simply because the individual-based detail is not available (Pitcher, 1993). With the development of the Dual-Head Multibeam Sonar technique, the capability to use Lagrangian techniques has become a reality because individual targets or fish may be tracked in relatively fine spatial and temporal scale. Additional analyses, beyond those presented in this paper, are currently being explored to better describe the behavior of juvenile salmon near-surface collection and bypass structures.

It has been commonly thought that outmigrant juvenile salmon follow the flow of the river as they move toward the sea. This is probably a reasonable deduction for the bulk-flow regime. However, when they approach a barrier to their migration, such as a hydropower dam, our results indicated that they had an increased likelihood of milling or holding, even at an opening designed to provide passage flow. This behavior was noted for both narrow and wide slot configurations tested during the study. The holding tendency may be alleviated by improved design of the bypass structure. On-going research will address the physical environmental factors that may be causing the holding behavior, whether it is hydraulics, low-frequency noise, light, or other physical phenomena.

5. CONCLUSION

This study demonstrated that the Dual-Head Multibeam Sonar can provide fish behavior data for evaluation of prototype fish passage structures. This can be accomplished using off-the-shelf multibeam sonar sets employing special modifications that permit them to synchronize operation coupled with special software to handle the combined datasets. The study demonstrated the ability to detect fine-scale changes in juvenile salmon behavior and to quantify that behavior using individual-based Lagrangian techniques for behavior classification. These discoveries will lead to establishing improved design criteria for future surface flow bypass structures and ultimately result in increased smolt passage through relatively benign passageways at hydropower facilities.

The multibeam system of the future will be an integrated system with a single controller and the capability of extracting target strength directly from the system. The system will be designed with very low side-lobes (< –27 dB). It will also incorporate within-beam interpolation algorithms for improved target tracking resolution at longer ranges.

Although the focus of this paper has been on hydropower projects, the technique described here may be applied to other research where fine-scale fish behavior monitoring and evaluation is desirable. Examples of other applications include predator/prey interactions, stimuli avoidance or attraction (fish guidance evaluations), and general ecological studies to name a few. The Dual-Head Multibeam Sonar system, with minimum modification, may also be used to track sonic tags for species-specific evaluations.

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