Statistical evaluation of turbine bypass efficiency at Wells Dam on the Columbia River, Washington

John R. Skalski, Gary E. Johnson, Colleen M. Sullivan, Edward Kudera, and Michael W. Erho

Abstract: The statistical and logistical aspects of conducting a rigorous hydroacoustic assessment of fish passage at a hydroelectric project are presented. A 3-year evaluation was conducted at Wells Dam (river km 830.1 Columbia River) to estimate bypass efficiency. Wells Dam has a unique hydrocombine structure where the spillway is located directly above the turbine intakes. Baffles placed in the spill intakes create attractant flow for bypassing downstream migrant salmon smolts. Fixed-location hydroacoustic techniques coupled with finite sampling methods were used to estimate bypass efficiency at the project using 25–29 transducers located in turbine and spill intakes. Spring bypass efficiency estimates ranged from 84.3 to 95.0% with a 3-year average of 89.4% (SE 3.1%). Bypass efficiency for summer migrants varied from 76.5 to 97.0% between years with a 3-year average of 89.0% (SE 6.3%).

Résumé : Ce résumé fait état des aspects statistiques et logistiques de l'évaluation hydroacoustique rigoureuse du passage des poissons aux ouvrages hydroélectriques. On a procédé à une évaluation, d'une durée de 3 ans, au barrage Wells (km 830,1 sur le Columbia) dont l'objectif était de déterminer l'efficacité de sa passe migratoire. Ce barrage a une structure unique situant l'évacuateur de crues directement au dessus des prises d'eau des turbines. Des chicanes à l'entrée de l'évacuateur créent un courant attrayant pour le smolt en dévalaison. Nous avons eu recours à des techniques hydroacoustiques statiques que nous avons combinées à des méthodes de prélèvement d'échantillons de taille finie pour estimer l'efficacité de la passe migratoire, au moyen de 25–29 transducteurs situés dans les prises d'eau des turbines et de l'évacuateur. Au printemps, cette efficacité a atteint, selon nos estimations, 84,3 à 95,0%, soit une moyenne sur 3 ans de 89,4% (écart-type de 3,1%). L'été, elle a varié entre 76,5 et 97%, selon les années, la moyenne sur 3 ans se chiffrant à 89,0% (écart-type de 6,3%).
[Traduit par la Rédaction]

Introduction

The past two decades have seen major attempts to modify and retrofit hydroelectric projects on the Columbia River to safely bypass salmonid smolts away from turbines on their way to the ocean. Mitigation activities have included installation of juvenile bypass facilities and traveling screens to divert smolts away from turbine intakes. Development of successful bypass facilities has taken years and many millions of dollars. For instance, development of the smolt bypass system at Wells Dam near Chelan, Washington state, U.S.A., was developed under provisions in Federal Energy Regulatory Commission (FERC) settlement agreements between 1980 and 1989, inclusive. Similar or longer developmental time frames have occurred at other hydroelectric facilities on the Snake–Columbia river system.

For a bypass to be successful, it must be highly efficient in diverting smolts away from the turbines with minimal flow requirements and safely return the fish to the river for continued outmigration. To date, few studies have evaluated the overall performance of smolt bypass systems in a statistically valid manner. One such study, the smolt survival study at Bonneville Dam, Second Power House (river km 234), indicated that smolt survival rates were lower than expected. This result led to modifications to the facility (Dawley et al. 1988, 1991; Ledgerwood et al. 1990, 1991). A second study was the estimation of bypass efficiency at Wells Dam during 1990–1992, following final installation of the smolt bypass facilities. However, these two studies underrepresent the mitigation activities at Columbia River hydroelectric projects and the need to evaluate the performance of installed facilities. An adaptive management approach to protecting salmonid runs on the Columbia River must be based on the best available scientific information to learn from both successes and failures for the benefit of the resource. Listing salmonid species in the Snake River as endangered under the U.S. Endangered Species Act will hasten the need for sound management decisions based on valid scientific investigation. The evaluation of bypass efficiency at Wells Dam will be used to illustrate what can be achieved when engineering, hydroacoustic, and statistical

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Table 1. Descriptive data for Wells Dam at reservoir elevation 237.4 m mean sea level.

River km at dam site	830.1 km
Drainage area	220 925 km^2
Historical flood (1894)	18.6 km^3
Spillway design flood	33.4 km^3
Gross head (maximum)	22.7 m
Reservoir storage capacity	10 479 km^3
Reservoir length	48.3 km
Dam length (overall)	1359.4 m
Hydrocombine length	344.4 m
Hydrocombine height	56.4 m
Generating units	10
Type of turbine	Kaplan
Maximum capability	820 000 kW

Note: In 1984, the reservoir was raised to 238.0 m mean sea level.

technologies are brought together to solve important mitigation problems.

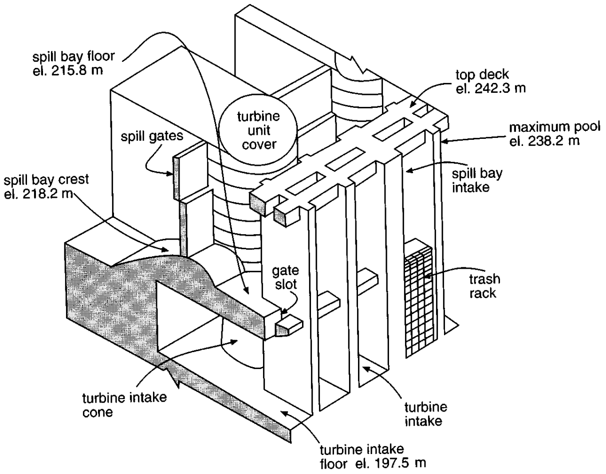
The purpose of this paper is to present statistical and logistical issues in designing a hydroacoustic study to estimate bypass efficiency (*B*) at a hydroelectric facility. Finite sampling theory will be used, taking into account the spatial and temporal variation in smolt migration as well as hydroacoustic measurement error. The study at Wells Dam illustrates the level of sampling precision that can be attained when the survey design takes into account the variance structure and sampling distribution of the migration. Studies at other hydroelectric facilities can benefit from the design concepts used in this study.

Study area

Wells Dam is located 830.1 km (Table 1) from the mouth of the Columbia River in Douglas County, Washington. Douglas County Public Utility District (DCPUD) owns and operates Wells Dam and is responsible for protecting runs of anadromous fish that migrate through Wells Dam because of Federal Energy Regulatory Commission (FERC) license conditions. Between 1980 and 1989, inclusive, provisions in FERC settlement agreements guided the development of the smolt bypass system at Wells Dam. As part of the settlement agreement, estimates of total project bypass efficiency for 3 consecutive years following final installation were required. The settlement agreement specified annual precision levels of ±10% at 90% confidence intervals (CI) if $\hat{\beta} > 85\%$ for spring run or $\hat{\beta} > 75\%$ for summer run, otherwise ±5% at 95% CI.

Wells Dam was designed as a hydrocombine (Fig. 1) to reduce the area of concrete structures founded on bedrock. Unlike conventional dams where the turbine units and spillways are distributed side by side, a hydrocombine dam has the spillways located directly above the turbine intakes. The spill bay and turbine intake floors are 22.3 and 40.5 m from the surface, respectively. The dam has 10 turbines and 11 spill bays (Fig. 2). All 11 spill bays are equipped with bottom spill gates. In addition, bays 2 and 10 also have surface gates that can be opened to generate top spill. Each turbine has three intakes (total 30) and, except for bays 1 and 11, each spill bay has three intakes. Water enters the spill intakes above water entering the turbine intakes because of the hydrocombine design. The smolt bypass system is built into the spillway.

Fig. 1. Three-dimensional view of Wells Dam hydrocombine, which has spill intakes directly above turbine intakes, instead of horizontally displayed as occurs at more typical facilities.



The smolt bypass system at Wells Dam has five individual bypass units (Fig. 2). A bypass unit is formed by modifying a spill bay with sidewalls, gate slot plugs, and baffles (Fig. 2). Side walls installed between the pier noses and the turbine pit walls on each side of a spill bay prevent water from flowing between adjacent spill bays, thereby increasing the effect of the intake baffles on forebay flows. Gate slot plugs prevent flow between turbine intakes and the bypass units. The baffles are the most important feature in the design of the smolt bypass system at Wells Dam. After many years of testing, a vertical slot baffle opening placed in the center intake of the three intakes (Fig. 3) was selected (Johnson et al. 1992).

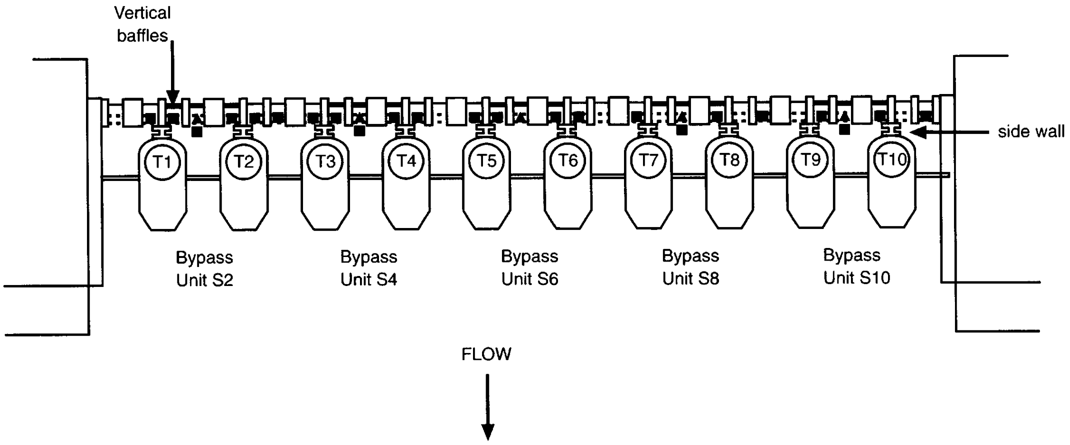
The principal salmonid species migrating past Wells Dam in spring are chinook salmon (*Oncorhynchus tshawytscha*), steelhead trout (*Oncorhynchus mykiss*), and sockeye salmon (*Oncorhynchus nerka*). Average fork lengths for migrating smolt are 10.3, 18.5, and 10.8 cm for chinook, steelhead, and sockeye, respectively. Wild spring chinook make up part of the spring outmigration whereas wild stocks make up virtually the entire summer migration. Wild subyearling chinook are produced in the Okanogan and Methow drainages. Spring chinook are raised and released at a U.S. Fish and Wildlife Service hatchery in Winthrup, Washington, 80 km upstream of Wells Dam. Steelhead are raised at the Wells hatchery and transported to upstream release sites. Summer chinook reared at the Eastbank hatchery are moved to ponds on the Similkameen and Methow rivers for volitional release (Table 2). About 2.1 million hatchery fish were released in the drainage above Wells Dam in 1992. Wild stocks of sockeye also migrate downstream past Wells Dam. These salmon migrate out of Lake Osoyoos, about 160 km upstream from Wells.

Methods

Hydroacoustics

Fixed-location hydroacoustic techniques were used to estimate bypass efficiency. The hydroacoustic studies at Wells Dam during 1990–1992 used three BioSonics® systems. Each system (Fig. 4) consisted of several 420-kHz transducers with cable, an echo sounder–transceiver, a multiplexer–equalizer, one or two chart

Fig. 2. Plan view showing the five bypass units (S2, S4, S6, S8, and S10) and the locations of turbine (T1, . . ., T10) intake transducers (■) at Wells Dam in 1990.



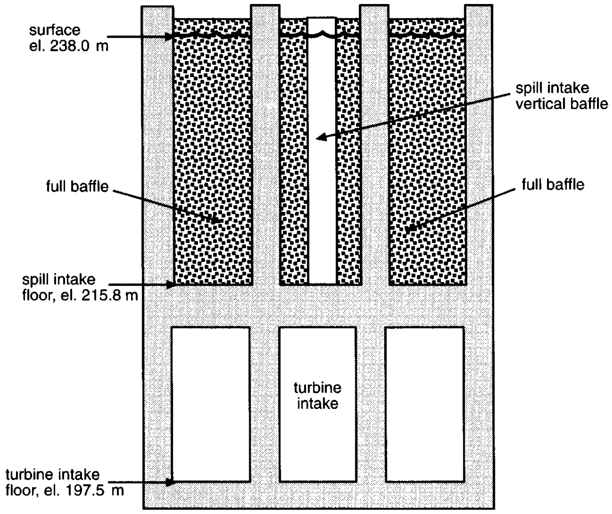
recorders, and an oscilloscope (Table 3). Beam widths of 6 to 15° were selected, depending on transducer location. Fixed-location scientific hydroacoustic techniques are explained by Thorne and Johnson (1993). Hydroacoustic techniques, in general, are explained by Mitson (1983).

A scientific hydroacoustic system works as follows. When triggered by the echo sounder, the transducer emits a short sound pulse in a relatively narrow beam aimed toward a water volume of interest. As these sound pulses encounter fish or other targets, echoes are reflected back to the transducer, which then converts the sound pressure to electrical signals. When received at the echo sounder, these signals are then amplified at a 40 log(R) + 2αR time-varied gain (TVG), where α is the absorption coefficient, which was set to zero in this study, and R is the range from target to transducer. This compensates for the loss of signal strength resulting from geometric spreading of the acoustic beam with distance from the transducer. Thus, targets that are equally sized on axis produce the same signal amplitudes at the echo sounder receiver output regardless of their distance (range) from the transducer. The range from the target to the transducer is determined from the time delay between the transmitted and received pulses.

The return signals are visually displayed on the oscilloscope and chart recorder to observe echo location, strength, and duration. Returns from individual fish and other signals are recorded on the chart recorder. The echogram provides a permanent record of all targets detected throughout the study. The threshold circuit on the chart recorder is adjusted to eliminate noise and signals below the level of interest. The chart recorder marks only targets with echo strengths greater than –56 dB on the acoustic axis of each transducer. This echo strength threshold was chosen so that even the smallest salmonid smolt returned an echo strong enough to mark the echogram but background noise would be minimized. From fyke net data, the smallest fish of interest was about 6.3 cm, corresponding to –49.1 dB (Love 1971). The echograms were the primary source of data for estimating bypass efficiency.

At least four successive echoes were required for a target to be classified as a fish. Most of the observed fish were detected more than four times in succession. This high redundancy occurred because of the relatively wide beam widths of the transducers and the high pulse repetition rates. This redundancy criterion also enhanced fish detectability in the presence of background interference. The requirement for multiple echos and a dramatic drop-off in the directivity pattern on the edge of the acoustic beam helps to ensure that valid targets were identified correctly. The signal-to-noise ratio in this study was typically 6 dB. On the basis of echogram trace types (i.e., the pattern of marks produced by successive detections), fish were classified as either migrants or wallowers. Wallowers (e.g., whitefish (*Prosopium spilonotus*), carp (*Cyprinus carpio*), squawfish (*Ptychocheilus oregonensis*)) produced marks consistent with large resident fish milling about in the forebay. Migrant trace types exhibited a change in range consistent with the smaller smolts. Only fish classified as migrants were included in the analyses. Further details of fish detection criteria for fixed-location hydroacoustics can be found in Carlson et al. (1981).

Fig. 3. The upstream side (front view) of a bypass unit at Wells Dam with vertical baffle openings above turbine intakes.



Because only a portion of the cross-sectional area at a sampling location was ensonified, individual fish detections were multiplied by a weighting factor to estimate the total relative number of fish passing that location at that particular range and time. To account for the cone-shaped geometry of the acoustic beam, the weighting factor was defined as the ratio of the width at the sampling location to the width of the acoustic beam at the range of detection. (Sampling location widths were as follows: pier nose = 27.4 m; turbine intake = 6.9 m; bypass slot = 6.9 m; and bypass spill bay = 14.0 m). The weighting factor was

$$(1)\qquad z_{ij} = \frac{I_j}{2R_{ij}\tan(\theta_j/2)}$$

where z_{ij} is a weighted observation of fish i at location j, I_j is the width

Table 2. Species, locations, distances from Wells, dates, and sizes of releases of hatchery-raised juvenile salmonids upstream of Wells Dam in spring 1992.

	Release site	Distance from Wells Dam (km)	Date	Number
Spring chinook	Winthrop (yearling)	80.5	Apr. 15	624 771
Summer chinook (volitional release)	Similkameen (river km 3.2)	138.4	May 1–19	542 000
	Twisp	61.2	May 1–19	391 650
Summer steelhead	Methow (river km 16.1)	25.7	Apr. 20–May 1	395 350
	Okanogan (river km 45.1)	69.2	Apr. 23–27	66 645
	Similkameen (river km 8.0)	144.8	Apr. 14–22	47 215
	Omak Creek (river km 8.0)	66.0	Apr. 30	5 400
			Total	2 073 031

Note: Sources: B. Wallien (U.S. Fish and Wildlife Service) and S. Miller and D. Rapplejay (Washington Department of Fish and Wildlife).

Fig. 4. Block diagram of a hydroacoustic data collection system used at Wells Dam.

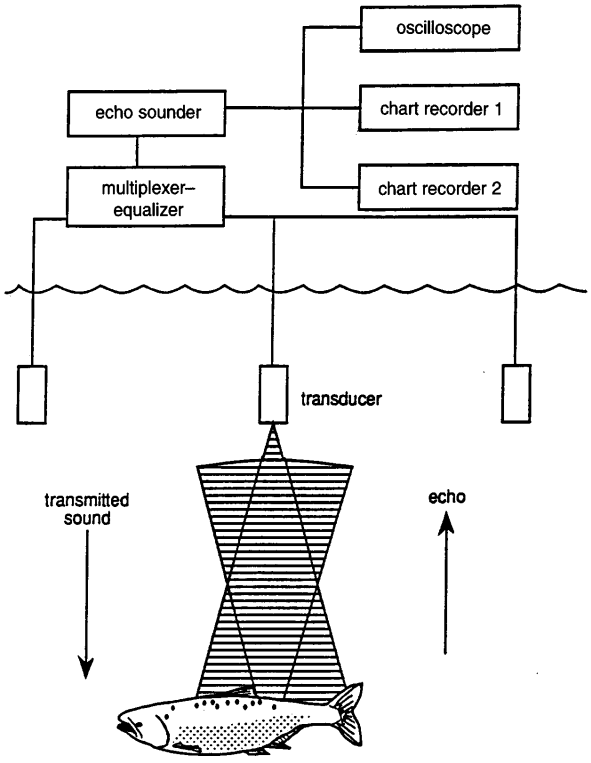


Table 3. Hydroacoustic system parameters used for studies at Wells Dam in 1990.

Component	Parameter
Echo sounder	Transmit frequency: 420 kHz
	Transmit power: 0 dB (for 1000 W power)
	Band width: 5 kHz
	Ping rate: 10–12 pps depending on year and location
	Pulse width: 0.4 ms
	TVG: 40 log(R) + 2αR
	Trigger source: thermal chart recorder
	On axis target strength: –50 dB
Chart recorders	Threshold: 0.1 V
	Target strength threshold: –56 dB

of location j, θ_j is the effective beam width (degrees) of the transducer at location j, and R_{ij} is the range of fish i from the transducer at location j.

Thus, fish detected closer to the transducer were weighted more (to represent more fish) than those detected further away. All subsequent analyses were based on these weighted fish detections. For a given migrant, the range from the transducer (R_{ij}) was the midpoint range of the echo trace as calculated by

$$R_{ij} = \frac{R_{\text{in}} + R_{\text{out}}}{2}$$

where R_{in} and R_{out} are the ranges at which the fish entered and left the acoustic beam, respectively.

Estimation of weighted fish counts using eq. 1 is based on the following assumptions. (*i*) Fish targets are uniformly distributed horizontally across the passage routes (i.e., no boundary or edge effects). (*ii*) Effective beam angle for each transducer is known accurately. (*iii*) An acoustic beam can be adequately modeled as a cone. (*iv*) Ranges of detected fish are measured accurately. (*v*) All fish that pass through the acoustic beam are counted.

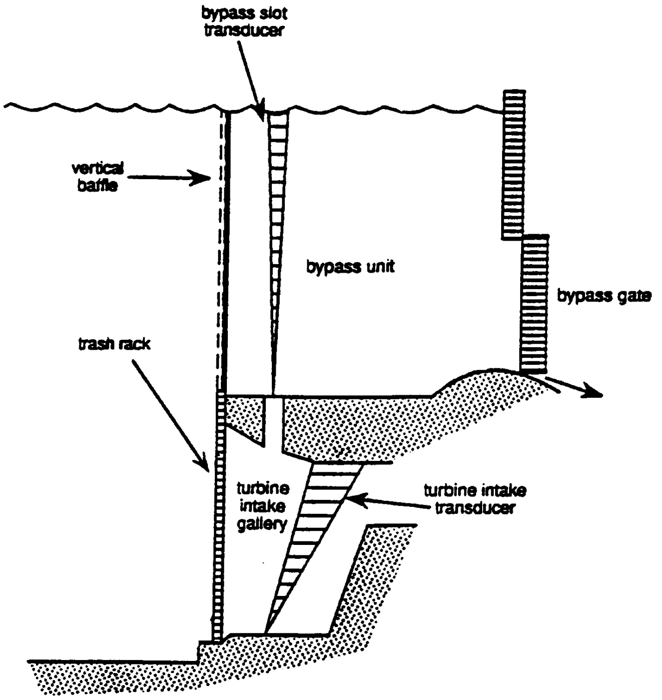
Weighted fish counts from eq. 1 are expanded by the reciprocal of the sampling fraction of the acoustic beam within a passage route. The portion of the bypass intake ensonified was 15% and the portion of a turbine intake ensonified was 23%.

The assumptions behind eq. 1 appeared to be reasonably fulfilled in this study. Data from the fyke net samples in 1990 showed roughly uniform distribution of the fish in the turbine and bypass intakes. The effective beam width could also be accurately measured by the ½ power angle of the directivity pattern ascribed to each transducer. Furthermore, the transducers were selected to have small acoustic side lobes and a dramatic drop-off in the directivity pattern to more closely approximate the assumed cone shape. The low side lobes and dramatic drop-off in the directivity pattern also helped ensure that fish outside the theoretical cone had voltages below the threshold and would not be counted. The relatively low fish densities (approximately 5 fish/1000 m^3) in the forebay (Johnson 1995) also helped ensure that individual fish targets would be accurately counted. Together, these factors helped ensure the reliability of the hydroacoustic measurements.

Transducer locations and orientations

The size of the hydroelectric project and the mandated precision requirements necessitated more transducers than had ever been deployed in a hydroacoustic study at a dam before. Transducers were deployed in both bypass intake slots and turbine intake galleries. For the bypass evaluation, five transducers (nominal beam width 6°) were placed in bypass intake slots: S2, S4, S6, S8, and S10 (Figs. 2 and 5). The bypass slot transducers were deployed in the gate slot immediately downstream from the vertical baffle opening. This location is at

Fig. 5. Side view of a bypass unit at Wells Dam showing transducer sampling areas.



the center of a bypass spill bay. These transducers rested at the bottom of the bypass and were aimed straight up toward the surface (Fig. 5). The range in the bypass slots was approximately 19.8 m. In 1990, transducers were also placed at the surface and aimed downward; the results showed fish distributed in the upper 5 m, or at a range of 15–20 m from the uplooking transducer (Kudera et al. 1990). The pulse rate was 12 pulses/s (pps) in 1990. The five bypass slot transducers sampled fish passage into all five bypass intakes of the smolt bypass system during each year, 1990–1992.

For the 1990 bypass evaluation, transducers (nominal beam width 15°) were deployed in 20 of 27 available turbine intakes (Figs. 2 and 5); at any time, 3 turbine intakes of 1 turbine were not available because of turbine runner replacement. These transducers were mounted on the bottom and aimed upward and 10° downstream toward the intake ceiling (Fig. 5). Previous data showed fish predominately distributed at a range of 12 m or greater, or within 3 m of the turbine intake ceiling (Johnson et al. 1992). The pulse rate was 12 pps. At least two of three intakes at each turbine unit were randomly selected for transducer placement (Table 4). At two turbine units (units 1 and 2), all three intakes were sampled; these two units were selected because previous data showed relatively high fish passage rates (Johnson et al. 1992). The third transducer in turbine intake 3A was moved to turbine intake 1C on May 5, after initial data showed higher fish passage rates in that unit.

For 1991 and 1992, tranducers sampled fish passage in 24 of 30 turbine intakes (nominal beam width 15°). These transducers were mounted the same as in 1990 but with a pulse rate of 10 pps. At least two of three intakes at each turbine unit were randomly selected. In 1991, at four turbine units (units 1, 2, 5, and 10), all three intakes were sampled. In 1992, six turbine units were sampled at all three intakes (units 1, 2, 3, 4, 5, and 10).

Fyke net sampling

During 1990, species composition data were collected from inside turbine intake 4C using fyke nets. Net data were collected at least once per week from April 5 to August 30, 1990. Sampling usually lasted 8 h. For the first 3 months of the study, sampling was done only at night. During July and August, day and night samples were collected. The entire cross-sectional area of the turbine could be sampled by the array of three nets across by seven nets down. Only the center column of seven nets was fished. Each net opening was 2.13 m wide and 2.06 m high. Each net was 3.96 m long with 4.53-mm stretch mesh and 6.35-mm mesh cod end. The fish were categorized as follows: yearling chinook, zero-age chinook, sockeye, steelhead, whitefish, and other. Fish counts were divided by sample time to produce number passing per unit time.

Statistical methods

The overall sampling design for estimating bypass efficiency at Wells Dam is characterized by separate designs for bypass units and turbine units. The results of the separate sampling schemes are then combined to provide the estimate in bypass efficiency (B). Total project bypass efficiency is defined as

$$(2)\qquad B = \frac{Y}{Y + X}$$

where Y is the total passage of smolt through bypass facilities over the course of the study and X is the total passage of smolt through turbine units over the course of the study. However, the true bypass (Y) and turbine (X) passages are not known. Instead, estimates of passage, $\hat{Y}$ and $\hat{X}$, must be used in estimating bypass efficiency, where

$$(3)\qquad \hat{B} = \frac{\hat{Y}}{\hat{Y} + \hat{X}}$$

Using the delta method (Seber 1982, pp. 7–9), the overall variance of the estimate of bypass efficiency $\hat{B}$ can be expressed as a function of the variances for bypass and turbine passage estimates. The variance of B is

$$(4)\qquad \mathrm{Var}\,(\hat{B}|B) + B^2(1 - B)^2\left(\frac{\mathrm{Var}\,(\hat{Y}|Y)}{Y^2} + \frac{\mathrm{Var}\,(\hat{X}|X)}{X^2}\right)$$

or

$$(5)\qquad \mathrm{Var}\,(\hat{B}|B) = B^2(1 - B)^2(\mathrm{CV}(\hat{Y})^2 + \mathrm{CV}(\hat{X})^2)$$

where CV denotes the coefficient of variation expressed as a decimal. Unlike variances for typical ratio estimators (Cochran 1977), the covariance between $\hat{Y}$ and $\hat{X}$ is not incorporated in the variance of $\hat{B}$ because separate hydroacoustic sampling schemes were used in monitoring bypass and turbine passage. The specific form of the estimator and its variance will depend on the sampling schemes used to estimate $\hat{Y}$ and $\hat{X}$. The sampling error associated with the estimate, $\hat{B}$, includes three sources of error: hydroacoustic measurement error and subsampling error associated with sampling only a fraction of the total spatial and temporal dimensions of the emigration through Wells Dam. In particular, the temporal sampling includes both days within season and time periods within hours during the outmigration. By sampling every day of the study period, the statistical design was simplified and a major source of variation (i.e., day to day) was eliminated. Independent estimates of the spring bypass efficiency ($\hat{B}$) and summer bypass efficiency ($\hat{B}$) were derived for each year. The sampling designs were the same for both seasons.

The spatial sampling schemes consisted of sampling all 5 bypass units and all 10 turbine units at Wells Dam. However, at each turbine unit, a minimum of two of three turbine intakes was randomly sampled. For some turbine units, all three turbine intakes were sampled to eliminate intake to intake variance. Turbine units with high fish passage were selected to receive transducers in all three turbine intakes. The temporal dimensions of the sampling design consisted of daily sampling during designated spring and summer study periods. The spring period lasted for 30–41 days and the summer period lasted for 15–17 days (Table 4). The spring season began shortly after chinook smolts were released upstream at Winthrop hatchery. Sampling occurred 24 h/day during the course of the seasons. The basic unit of

Table 4. Turbine intake sampling locations and dates for the 1990–1992 studies at Wells Dam (ns, not sampled).

	1990		1991		1992	
Location	Spring	Summer	Spring	Summer	Spring	Summer
1A	Apr. 19–May 18	July 9–24	Apr. 14–May 24	July 8–22	Apr. 17–27	ns
1B	Apr. 19–May 18	July 9–24	Apr. 14–May 24	July 8–22	Apr. 17–27	June 26–July 12
1C	May 4–18	July 9–24	Apr. 14–May 24	July 8–22	Apr. 17–27	June 26–July 12
2A	Apr. 19–May 18	July 9–24	Apr. 14–May 24	July 8–22	Apr. 27–May 26	June 26–July 12
2B	Apr. 19–May 18	July 9–24	Apr. 14–May 24	July 8–22	Apr. 27–May 26	June 26–July 12
2C	Apr. 19–May 18	July 9–24	Apr. 14–May 24	July 8–22	Apr. 17–May 26	ns
3A	April 19–May 4	ns	Apr. 14–May 24	July 8–22	Apr. 17–May 26	June 26–July 12
3B	Apr. 19–May 18	July 9–24	ns	ns	Apr. 17–May 26	June 26–July 12
3C	Apr. 19–May 18	July 9–24	Apr. 14–May 24	July 8–22	Apr. 17–May 26	June 26–July 12
4A	Apr. 19–May 18	July 9–24	Apr. 14–May 24	July 8–22	Apr. 17–May 26	June 26–July 12
4B	Apr. 19–May 18	July 9–24	Apr. 14–May 24	July 8–22	Apr. 17–May 26	June 26–July 12
4C	ns	ns	ns	ns	Apr. 17–May 26	ns
5A	May 3–18	July 9–24	Apr. 14–May 24	July 8–22	Apr. 17–May 26	June 26–July 12
5B	May 3–18	July 9–24	Apr. 14–May 24	July 8–22	Apr. 17–May 26	June 26–July 12
5C	ns	ns	Apr. 14–May 24	July 8–22	Apr. 17–May 26	June 26–July 12
6A	Apr. 19–May 18	July 9–24	Apr. 16–May 2	ns	Apr. 17–May 26	June 26–July 12
6B	Apr. 19–May 18	July 9–24	Apr. 14–May 24	July 8–22	Apr. 17–May 26	June 26–July 12
6C	ns	ns	Apr. 14–May 24	July 8–22	ns	ns
7A	Apr. 19–May 1	ns	Apr. 14–May 24	July 8–22	Apr. 17–May 26	June 26–July 12
7B	ns	ns	Apr. 14–May 2	ns	Apr. 17–May 26	June 26–July 12
7C	April 19–May 1	ns	Apr. 14–May 24	July 8–22	Apr. 17–May 26	June 26–July 12
8A	Apr. 19–May 18	July 9–24	Apr. 14–May 24	July 8–22	Apr. 17–May 26	June 26–July 12
8B	ns	ns	Apr. 14–May 24	July 8–22	ns	ns
8C	Apr. 19–May 18	July 9–24	ns	ns	Apr. 17–May 26	June 26–July 12
9A	ns	ns	Apr. 14–May 24	July 8–22	ns	ns
9B	Apr. 19–May 18	July 9–24	Apr. 16–May 2	ns	Apr. 17–May 26	June 26–July 12
9C	Apr. 19–May 18	July 9–24	Apr. 14–May 24	July 8–22	Apr. 17–May 26	June 26–July 12
10A	Apr. 19–May 18	July 9–24	May 3–24	July 8–22	Apr. 17–May 26	June 26–July 12
10B	ns	ns	May 3–24	July 8–22	Apr. 17–May 26	June 26–July 12
10C	Apr. 19–May 18	July 9–24	May 3–24	July 8–22	Apr. 17–May 26	June 26–July 12

inference was a turbine or bypass unit-hour. Within a unit-hour, systematic sampling was conducted for a total of 12 min/h on the basis of three 4-min samples.

Bypass sampling design

By sampling at all bypass units, the bypass to bypass variation was eliminated in estimating bypass efficiency. The resulting sampling design at the bypass units is a single-stage sample design using stratified sampling of unit-hours across the dam and through time. Within a unit-hour, a systematic sample was collected during the hour and repeated each hour of the survey. The starting times for the systematic samples were rerandomized at the beginning of each day to avoid any systematic bias. In constructing the estimator, variance, and estimated variance of the estimator, sampling was assumed to be stratified random sampling. Skalski et al. (1993) showed that the variance formula for random sampling tends to overestimate the variance of hydroacoustic surveys based on systematic sampling.

Terms are defined as follows: y_{ijkg} is the weighted number of fish detected (i.e., estimated number of fish) in the gth sampling unit ($g = 1, 2, \ldots, l_{ijk}$) in the kth hour ($k = 1, 2, \ldots, 24$) at the jth bypass ($j = 1, 2, \ldots, 5$) on the ith day ($i = 1, 2, \ldots, D$); L_{ijk} is the number of time intervals in the kth hour ($k = 1, 2, \ldots, 24$) at the jth bypass ($j = 1, 2, \ldots, 5$) on the ith day ($i = 1, 2, \ldots, D$); and l_{ijk} is the number of time intervals sampled in the kth hour ($k = 1, 2, \ldots, 24$) at the jth bypass ($j = 1, 2, \ldots, 5$) on the ith day ($i = 1, 2, \ldots, D$). Then the estimate of total bypass passage (Y) is

$$\hat{Y} = \sum_{i=1}^{D}\sum_{j=1}^{5}\sum_{k=1}^{24}\sum_{g=1}^{l_{ijk}}\left(\frac{L_{ijk}}{l_{ijk}}y_{ijkg}\right) \tag{6}$$

The variance of Y follows directly from stratified random sampling where

$$\mathrm{Var}\,(\hat{Y}|Y) = \sum_{i=1}^{D}\sum_{j=1}^{5}\sum_{k=1}^{24}\left(L_{ijk}^{2}\left(1-\frac{l_{ijk}}{L_{ijk}}\right)\frac{S^{2}_{y_{ijk}}}{l_{ijk}}\right) \tag{7}$$

and where

$$S^{2}_{y_{ijk}} = \frac{\sum_{g=1}^{L_{ijk}}\left(y_{ijkg}-\overline{y_{ijk}}\right)^{2}}{(L_{ijk}-1)} \tag{8}$$

and where

$$\overline{y_{ijk}} = \sum_{g=1}^{L_{ijk}} y_{ijkg}/L_{ijk} \tag{9}$$

The sampling within a bypass unit-hour was three 4-min samples per hour such that the sampling fraction was

$$\frac{l_{ijk}}{L_{ijk}} = \frac{3}{15} = 0.20$$

Variance for $\hat{Y}$ was estimated by substituting the sample values of eqs. 8 and 9 into eq. 7. Skalski et al. (1993) showed, in general, that variance estimates were reduced by using smaller, more frequent sampling intervals within the hour.

Turbine sampling design

The estimate of total turbine passage is based on a two-stage sampling scheme. The first stage of sampling is the random selection of two of three turbine intakes in each turbine unit to be sampled throughout the season. The second stage of the sampling design is the stratified random sampling of each unit-hour. As was the case in estimating bypass passage, in practice, a systematic sample within the unit-hour was used in estimating total turbine passage. The anticipated consequence of using a systematic sample in conjunction with a variance formula based on random sampling is to overestimate the true variance (Wolter 1984; Skalski et al. 1993).

Define the following terms, where x_{ijklg} is the number of fish detected in the gth sampling unit ($g = 1, 2, \ldots, h_{ijkl}$) in the lth hour ($l = 1, 2, \ldots, 24$) during the kth day ($k = 1, 2, \ldots, D$) in the jth intake ($j = 1, 2, 3$) of the ith turbine unit ($i = 1, 2, \ldots, 10$); H_{ijkl} is the number of time intervals in the lth hour ($l = 1, 2, \ldots, 24$) of the kth day ($k = 1, 2, \ldots, D$) in the jth intake ($j = 1, 2, 3$) of the ith turbine unit ($i = 1, 2, \ldots, 10$); h_{ijkl} is the number of time intervals sampled in the lth hour ($l = 1, 2, \ldots, 24$) of the kth day ($k = 1, 2, \ldots, D$) in the jth intake ($j = 1, 2, 3$) of the ith turbine unit ($i = 1, 2, \ldots, 10$); T_i is the number of turbine intakes in the ith turbine unit (3), and t_i is the number of turbine intakes sampled in the ith turbine unit. Then the estimate of total turbine passage is

$$(10)\qquad \hat{X}=\sum_{i=1}^{10}\left(\sum_{j=1}^{t_i}\frac{T_i}{t_i}\left(\sum_{k=1}^{D}\sum_{l=1}^{24}\sum_{g=1}^{h_{ijkl}}\left(\frac{H_{ijkl}}{h_{ijkl}}x_{ijklg}\right)\right)\right)$$

Since $\hat{X}$ is based on two-stage sampling, the variance of $\hat{X}$ can be expressed as

$$(11)\qquad \mathrm{Var}\,(\hat{X}|X)=\sum_{i=1}^{10}\frac{T_i^2}{t_i}\left(1-\frac{t_i}{T_i}\right)S^2_{x_{ij}}+\frac{T_i}{t_i}\sum_{i=1}^{10}\sum_{j=1}^{3}\sum_{k=1}^{D}\sum_{l=1}^{24}\left(H^2_{ijkl}\left(1-\frac{h_{ijkl}}{H_{ijkl}}\right)S^2_{x_{ijkl}}\right)$$

where

$$(12)\qquad S^2_{x_{ij}}=\frac{\sum_{j=1}^{3}\left(X_{ij}-\bar{X}_i\right)^2}{(3-1)}$$

$$(13)\qquad S^2_{x_{ijkl}}=\frac{\sum_{g=1}^{H_{ijkl}}(x_{ijklg}-\bar{x}_{ijkl})^2}{(H_{ijkl}-1)}$$

and where

$$(14)\qquad X_i=\sum_{j=1}^{3}X_{ij}/3$$

$$(15)\qquad x_{ijkl}=\sum_{g=1}^{H_{ijkl}}x_{ijklg}/H_{ijkl}$$

Variance estimates were computed by substituting sample values for the terms in eqs. 12–15 into eq. 11. The sampling fraction for each turbine transducer was $h_{ijkl}/H_{ijkl} = 0.20$. When all three turbine intakes within a turbine unit were sampled (i.e., $t_i = T_i = 3$), the first term in the variance formula 11 becomes zero for that unit. The hourly sampling sequence was systematic. The start times for the systematic samples at each turbine intake were randomized at the beginning of each sampling day (08:00).

Measurement error

Formulas 6 and 10 used in estimating bypass and turbine fish passage, respectively, are based on the analysis of weighted estimates of fish passage using eq. 1. The weighted fish counts have inherent measurement error that contributes to the overall variance of total project bypass efficiency. Sources of nonsystematic hydroacoustic measurement error can include (*i*) target strength variation, (*ii*) pattern recognition error in interpreting the fish traces, and (*iii*) spatial subsampling because of the geometry of the acoustic beam (eq. 1) (see Thorne and Johnson 1993 for detailed discussion). However, this hydroacoustic measurement error is largely incorporated in variance formulas 7 and 11.

For example, let the hour be divided into N equal time intervals of length $60/N$ min. Then, if a random sampling scheme monitors n of these N intervals, an unbiased estimate of total passage during that unit hour (Z) is

$$\hat{Z}=\frac{N}{n}\sum_{i=1}^{n}\hat{z}_i$$

where $\hat{z}_i$ is the number of fish estimated to have passage through the unit during the ith interval by the hydroacoustic apparatus, provided $\hat{z}_i$ is an unbiased estimate of z_i, the actual fish passage in the ith interval.

The variance of $\hat{Z}$ will consist of both sampling error and hydroacoustic measurement error. To see how these error sources contribute to the overall variance, the total variance formula is used, where

$$\begin{aligned}\mathrm{Var}\,(\hat{Z})&=\mathrm{Var}_{z_i}(E(\hat{Z}\mid z_i))+E_{z_i}(\mathrm{Var}\,(\hat{Z}\mid z_i))\\&=\mathrm{Var}_{z_i}\left(E\left(\frac{N}{n}\sum_{i=1}^{n}\hat{z}_i\mid z_i\right)\right)+E_{z_i}\left(\mathrm{Var}\left(\frac{N}{n}\sum_{i=1}^{n}\hat{z}_i\mid z_i\right)\right)\\&=\mathrm{Var}_{z_i}\left(\frac{N}{n}\sum_{i=1}^{n}z_i\right)+E_{z_i}\left(\left(\frac{N^2}{n^2}\sum_{i=1}^{n}\mathrm{Var}\,(\hat{z}_i\mid z_i)\right)\right)\end{aligned}$$

$$(16)\qquad \mathrm{Var}\,(\hat{Z})=\frac{N^2}{n}\left(1-\frac{n}{N}\right)S^2_{z_i}+\frac{N^2}{n}\overline{\mathrm{Var}\,(\hat{z}_i\mid z_i)}$$

where

$$S^2_{z_i}=\frac{\sum_{i=1}^{N}(z_i-\bar{z})^2}{N-1}$$

In a sample survey of fish passage, the Var($\hat{Z}$) would be estimated by

$$\mathrm{Var}\,(\hat{Z})=\frac{N^2}{n}\left(1-\frac{n}{N}\right)s^2_{\hat{z}_i}$$

where

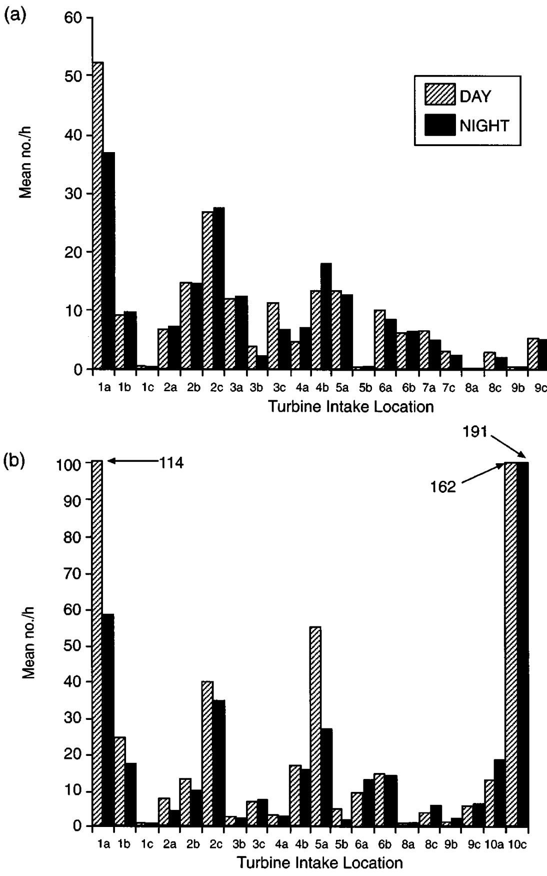
$$s^2_{\hat{z}_i}=\frac{\sum_{i=1}^{N}\left(z_i-\hat{\bar{z}}\right)^2}{n-1}$$

This estimate of the variance has the expected value

$$\begin{aligned}(17)\qquad E\left(\frac{N^2}{n}\left(1-\frac{n}{N}\right)s^2_{\hat{z}_i}\right)&=\frac{N^2}{n}\left(1-\frac{n}{N}\right)E\left(s^2_{\hat{z}_i}\right)\\&=\frac{N^2}{n}\left(1-\frac{n}{N}\right)S^2_{\hat{z}_i}+\frac{N^2}{n}\left(1-\frac{n}{N}\right)\overline{\mathrm{Var}\,(\hat{z}_i\mid z_i)}\end{aligned}$$

Hence, the empirical variance, $s^2_{\hat{z}_i}$, implicitly incorporates both the subsampling error and the hydroacoustic measurement error. Comparison of variance formulas 16 and 17 shows, however, that the variance estimator (eq. 17) is negatively biased. The second term in formula 17 has the additional factor of $1 - n/N$, which variance formula

Fig. 6. Horizontal distribution of turbine passage indices (mean number/h by location) for day and night separately at Wells Dam during (*a*) spring, April 19 – May 18 and (*b*) summer, July 9–24, 1990.



16 does not possess. Typically, it is believed that the measurement error (i.e., $\mathrm{Var}(\hat{z}_i \mid z_i)$) is small relative to $S_{z_i}^2$, so the bias will be small. Furthermore, the bias is proportional to $1 - n/N$, which for the Wells Dam study will be 0.80, close to the required 1.0 in formula 16. A conservative but always valid estimator of the true variance can be obtained by ignoring the finite population correction (i.e., $1 - n/N$).

Systematic hydroacoustic measurement errors in estimating X or Y could potentially bias estimates of bypass efficiency (B). If turbine and bypass transducers have similar rates of false detections or avoidances, the biases would cancel in estimation of B. However, different systematic errors at the two locations could bias B in either direction. Careful calibration of the systems is used to help avoid such errors that may affect $\hat{B}$ and (or) Var $(\hat{B}|B)$.

Results

Horizontal distribution of smolt passage showed that the highest rates of turbine passage were generally at the far ends of the dam for both spring and summer studies (Fig. 6). The observed horizontal pattern showed considerable variability between slots within a turbine, and the variance increased as mean passage increased. This distributional pattern was the reason for redistributing a third transducer from turbine unit 3 to that of turbine unit 1 shortly after the 1990 season began. In 1991 and 1992, the number of turbine units with all three turbine slots sampled increased to four and six, respectively. The addition of the two or four additional transducers in 1991–1992 was the reason for improved precision in subsequent years (Table 5).

Table 5. Spring and summer estimates of total project bypass efficiency and associated standard errors for the years 1990–1992 and weighted average.

Year	Season	Dates	B (%)
1990	Spring	Apr. 19 – May 18	84.3±4.1
	Summer	July 9–24	76.5±2.4
1991	Spring	Apr. 14 – May 24	95.0±0.3
	Summer	July 8–22	97.0±0.2
1992	Spring	Apr. 17 – May 27	89.0±0.3
	Summer	June 26 – July 12	93.4±0.4
Overall	Spring	1990–1992	92.0±2.1
	Summer	1990–1992	96.2±1.5

The annual estimates of bypass efficiency in spring varied from 84.3 ± 4.1% (mean ± SE) to 95.0 ± 0.3. A weighted mean, weighting inversely proportional to the variance, provides an overall estimate of $\hat{B}_w = 92.0 \pm 2.1$ across all 3 years, 1990–1992 (Table 5). The annual estimates of bypass efficiency during the summer varied from 76.5 ± 2.4 to 97.0 ± 0.3%. A weighted mean across years resulted in an overall estimate of $\hat{B}_w = 96.2 \pm 1.5\%$ (Table 5). Weighted averages are appropriate 3-year summaries if bypass efficiency is static and interannual variation is solely the result of sampling error. Alternatively, unweighted means may be more appropriate if interannual variation is largely the result of variation in river flow and migration conditions. For the spring seasons, average sampling error was $\overline{\mathrm{Var}(\hat{B}_i|B_i)} = 5.66$ whereas the component for interannual variation was estimated as $\sigma_{B_i}^2 = 23.10$. The larger variance component for natural variation suggests the arithmetic mean of $\hat{\bar{B}} = 89.4 \pm 3.1\%$ may be the most appropriate estimate of general bypass efficiency in spring. Similarly, variation between bypass estimates during summers 1990–1992 suggests that the system was not static ($\sigma_{B_i}^2 = 117.8$; $\overline{\mathrm{Var}(\hat{B}_i|B_i)} = 1.99$). Hence, the arithmetic mean of $\hat{\bar{B}} = 89.4 \pm 6.3\%$ is the best estimate of general bypass efficiency during summer months.

Daily estimates of bypass efficiency showed a general trend of increased bypass efficiency as the migration progressed during spring seasons (Fig. 7). However, no obvious trend was apparent during the summer seasons (Fig. 8) except for data collected early in 1990. These trends do not seem to be strongly associated with species composition data collected in concurrent fyke net samples (Figs. 9 and 10).

Discussion

Wells Dam was the first hydrocombine dam constructed in the United States. A second hydrocombine dam, the Cowlitz Falls Dam located on the Cowlitz River, Lewis County, Washington, only recently became operational in 1994. The surface flow bypass for salmonid smolts at this dam was modeled after the one used at Wells Dam. The high bypass efficiency rates at Wells Dam (>89%) have also prompted development of prototype surface flow bypass systems at other mainstem Columbia and Snake River hydroelectric projects. The bypass efficiency at Wells Dam is much higher than efficiencies at other dams with turbine intake screens. For example, the bypass efficiency for submersible traveling screens in the Columbia Basin is

Fig. 7. Estimates and 90% confidence intervals for daily bypass efficiency for spring (*a*) 1900, (*b*) 1991, and (*c*) 1992.

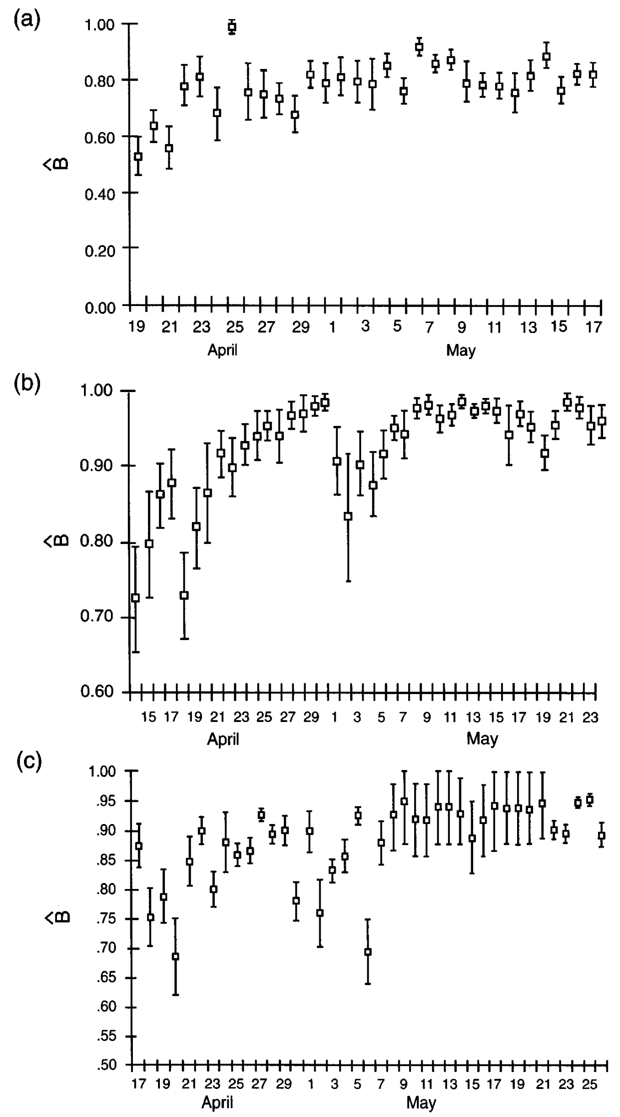
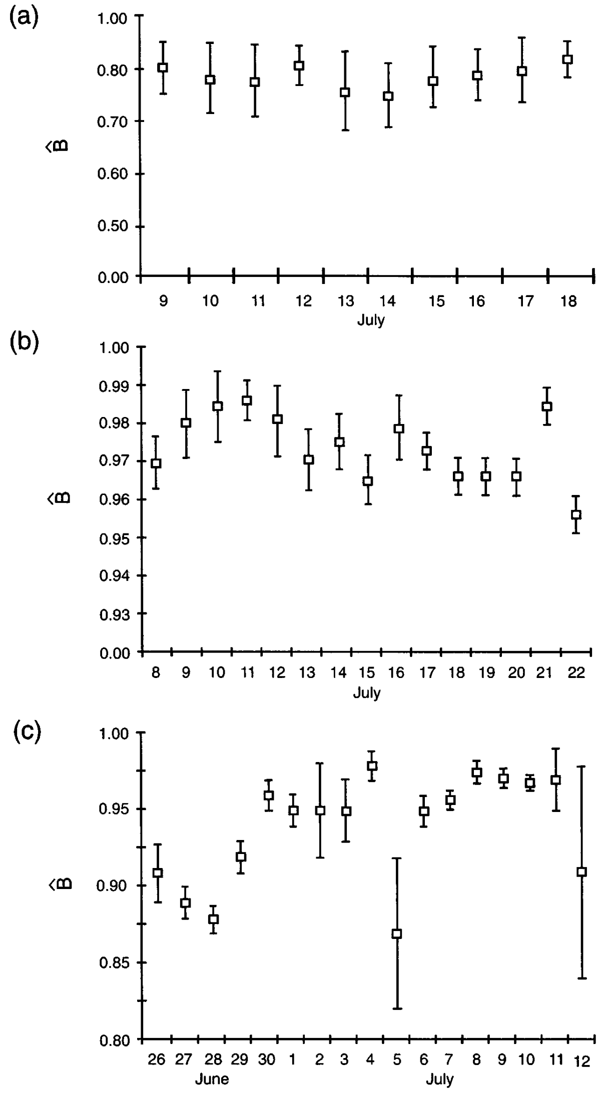


Fig. 8. Estimates and 90% confidence intervals for daily bypass efficiency for summer (*a*) 1990, (*b*) 1991, and (*c*) 1992.



about 35–75%, depending on screen configuration and other factors (Swan et al. 1990). It is yet to be seen whether similar success can be achieved at a conventionally designed dam. Nevertheless, in the interim, well-crafted hydroacoustic studies will be needed to assess the advantages of using surface flow bypass in improving the migration success of salmonid smolts.

The high precision of the surface flow bypass evaluation at Wells Dam is the result of a number of purposeful decisions. Elements lending to the success of the study include (*i*) preliminary hydroacoustic data during years of prototype development that provided estimates of variance components (i.e., bypass within hour $S^2_{y_{ijk}}$, intake to intake $S^2_{x_{ij}}$, and turbine within hour $S^2_{x_{ijkl}}$) for sample size calculations; (*ii*) high level of sampling effort spatially, with 25–29 transducers in a total of 35 potential intake sites; (*iii*) high level of sampling effort temporally, with daily sampling and a sampling fraction of 0.20 within hours; and (*iv*) knowledge of the horizontal distribution of smolts passing the facility.

These elements worked together to help ensure the sampling precision (±4.1 and ±2.9% at 95% CI, spring and summer, respectively) of the bypass evaluation study to achieve and exceed the levels of precision specified in the FERC settlement agreement (i.e., ±10% at 90% CI or ±5% at 95% CI depending on the value of the point estimate). Johnson et al. (1994) investigated the sampling efficiency at other hydroprojects and also found favorable levels of precision with reasonable sampling effort.

In designing a hydroacoustic study, it is crucial to take into consideration the temporal and spatial distribution of the data. Standard statistical methods, which base their design and analysis on assumptions of normal distribution and constant variance, are inappropriate when analyzing fish passage data. With fish counts, the variance increases as mean passage number increases (e.g., more reminiscent of Poisson or negative binomial distribution). Hence, the horizontal distribution

Fig. 9. Catch per hour of chinook (age-0 and yearlings combined), sockeye, and steelhead in the fyke nets at Wells Dam in 1990 for night only.

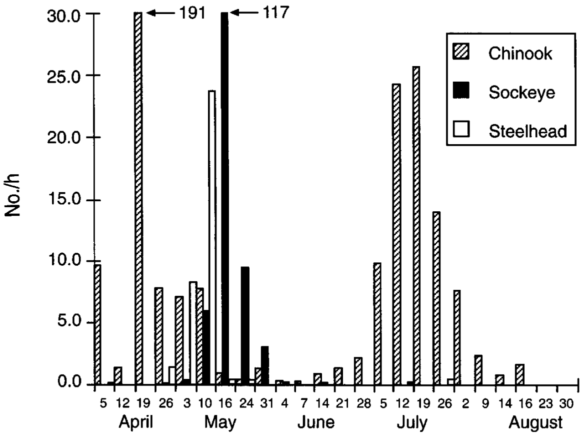
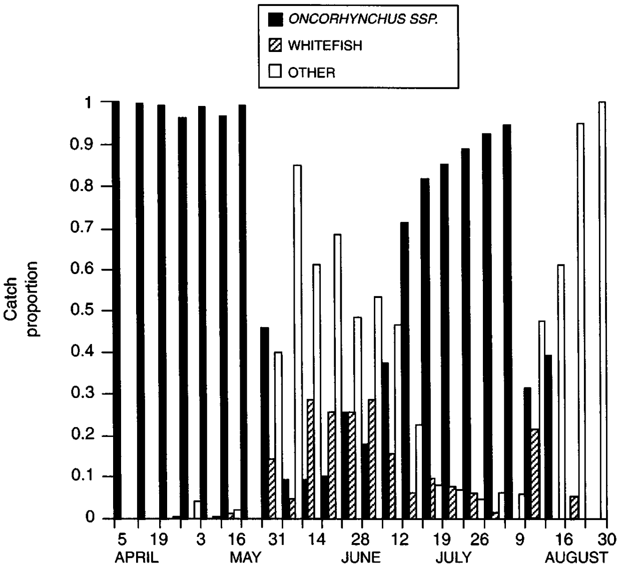


Fig. 10. Proportions of the total catch from fyke net samples at turbine intake 4C at Wells Dam in 1990 for night only.



of the data (Fig. 6) provided key information on where the contribution to the variances of Y and X (eqs. 7 and 11) would be the greatest and where sampling effort should be focused.

Furthermore, the variance in total turbine passage (eq. 11) is composed of two types of variance components: the variance in passage among intakes within turbines (i.e., $S^2_{x_{ij}}$), and the variance in passage between sample intervals within a unit-hour (i.e., $S^2_{x_{ijkl}}$). The relative magnitude of $S^2_{x_{ij}}$ for turbine units with high passage numbers was large enough that placement of strategic transducers at key units, such as T_1, T_2, T_5, and T_{10} (Fig. 7), substantially improved the precision of $\hat{B}$. The relocation of a transducer from turbine unit 3 to the third slot in turbine unit 1 reduced the SE ($\hat{B}$) by a factor of at least 2 in 1990. The addition of a third transducer to the turbine intakes of four or six units in 1991 and 1992 instead of just two intakes as was the case in 1990 further reduced the SE ($\hat{B}$) by a factor of 10 (Table 5). These types of gains in precision can only be attained when the variance structure of the estimator of bypass efficiency is known and preliminary hydroacoustic data are used to guide sampling design decisions. The cost of this hydroacoustic study was high (e.g., each year generated over 29 km of chart recordings that required manual reading). However, the costs of redoing the studies because of poor precision would have been even greater. These potential costs are further overshadowed by the social and environmental value of our aquatic resources and the potential harm caused by the misdirection of efforts aimed at enhancing and protecting valuable fisheries without sound scientific information.

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