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Summary of the Use of Hydroacoustics for Quantifying the Escapement of Adult Salmonids (*Oncorhynchus* and *Salmo* spp.) in Rivers

by

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Abstract

Many anadromous salmonid populations (*Oncorhynchus* and *Salmo* spp.) are declining in North America and Europe as pressure from over harvesting, habitat degradation, and other sources increases. In order to aid the management of these stocks, hydroacoustic techniques have been used since the 1960's to estimate adult salmonid escapement in nearly 50 rivers in North America and Europe. Initial evaluations used single-beam hydroacoustic techniques, with dual-beam techniques being introduced in the mid-1980's. Since 1992, digital split-beam hydroacoustic techniques have been used in over 50 studies in 17 rivers. Due in large part to it's improved spatial resolution and three-dimensional fish tracking capabilities, the split-beam technique has proven more useful than single-beam or dual-beam acoustic techniques for monitoring escapement and behavior at most sites. Monitoring in rivers is one of the more challenging applications for fisheries acoustics. Unlike typical marine mobile survey applications, riverine applications use stationary transducers with beams aimed in a relatively small water volume, surrounded by the acoustically reflective boundaries of the river surface and bottom. Rivers typically have uneven bottom bathymetry and nonlaminar hydraulics, requiring relatively sophisticated equipment and careful deployment, calibration, and testing. The major issues one must address in order to obtain reliable estimates of escapement included hydroacoustic equipment and techniques, site selection, transducer deployment, and fish behavior. Narrow-beam transducers are typically mounted near shore and aimed horizontally into the river, perpendicular to flow, monitoring migrating fish in side-aspect. A bottom substrate of low acoustic reflectivity (e.g., sand, small rocks) enables the acoustic beam to be aimed close to the bottom. In many cases, migrating salmonids are strongly shore- and bottom-oriented, where water velocities are slowest. Sites are sought where fish are actively migrating, not holding or milling. In addition to escapement counts, results include estimated fish sizes, diel distributions, spatial distributions, and velocities.

Introduction

Many anadromous salmonid populations (Oncorhynchus and Salmo spp.) are declining in North America and Europe as pressure from habitat degradation, harvesting, and other sources increases. In order to aid the management of these stocks, hydroacoustic techniques have been used since the 1960's to estimate adult salmonid escapement in nearly 50 rivers in North America and Europe (Johnston and Steig 1995).

Counting migrating fish in rivers is one of the more challenging applications for fisheries hydroacoustics. Unlike typical marine mobile survey applications (MacLennan and Simmonds 1992), migrating fish in rivers pass fixed transducers through a relatively small water volume, surrounded by the acoustically reflective boundaries of the river surface and bottom. Rivers typically have high reverberation levels, uneven bottom bathymetry, and nonlaminar hydraulics. Flow conditions can change rapidly, altering the area available for fish migration and increasing background noise. In addition, fish swimming characteristics, orientation, and position in the river may be variable.

Methods

The four major issues that must be addressed in order to obtain reliable counts of salmonids in rivers include hydroacoustic equipment and techniques, site selection, transducer deployment, and fish behavior.

Hydroacoustic Equipment and Techniques

Rarely are mobile survey evaluations used to count adult salmon escapement in rivers (Cheng et al. 1991). Fixed-location hydroacoustic techniques based on the deployment of stationary transducers are usually employed. Initial evaluations used single-beam hydroacoustic techniques, with dual-beam techniques being introduced in the mid-1980's (Table 1). A number of authors have reviewed single-beam and dual-beam fixed-location techniques applied to rivers (Johnston and Steig 1995, Mesiar et al. 1990), and for some riverine applications these may be adequate. The first application of split-beam acoustic techniques to adult salmonid escapement estimation occurred in 1992 on the Yukon River (Johnston et al. 1993). Since then, digital split-beam hydroacoustic techniques have been used in over 50 studies in 17 rivers (Table 2). For riverine monitoring, split-beam techniques (Ehrenberg 1983) offer several advantages over single-beam and dual-beam techniques (Ehrenberg and Torkelson 1996, Ransom et al. 1995).

Originally, the application of the split-beam technique for fisheries assessment was developed for providing *in situ* target strength (TS) estimates in order to scale echo integrator output from marine mobile surveys. In the early 1990's the split-beam acoustic technique was applied to riverine monitoring (Ehrenberg and Torkelson 1996, Johnston et al. 1993). By tracking the three-dimensional location of each fish in the beam at every ping (e.g., typically 10-20 times s^{-1}), selected echoes are grouped for individual fish, and mean TS calculated for each tracked fish. The lengths of individual fish can be estimated from the mean TS (Goddard and Welsby 1986, Love 1977). This improved split-beam spatial resolution results in improved TS estimates, as well as providing absolute direction of fish movement, permitting discrimination of upstream migrating fish from downstream fish. Ambiguous directional data are common with single-beam or dual-beam techniques (Harte 1993, Johnston and Hopelain 1990). In addition, split-beam techniques provide estimates of fish velocity, trajectory, and other behavioral parameters.

For any acoustic technique, excessive background noise can limit the accuracy of the fish TS measurements. The split-beam technique has better performance in the presence of noise, producing TS estimates that are more accurate and less variable than dual-beam estimates (Burwen et al. 1995, Traynor and Ehrenberg 1990).

Basic split-beam systems used in the studies described below included an HTI Model 240/243 Split-Beam Digital Echo Sounder, Model 340/343 Digital Echo Processor, Model 540 Split-Beam Transducers with cables, a Model 402 Digital Chart Recorder, digital audio tape recorder, oscilloscope, and remote rotators for aiming transducers. All systems operated at 200 kHz. Low side-lobe transducers with elliptical beams (e.g., 3° x 10°) were typically used. The elliptical-beams allowed more time for each target in the acoustic beam, and hence more data. Also, in order to maximize sample data, the systems employed ping rates up to 40 pings s^{-1}.

At the fish densities typically observed in rivers, the computer-based processing system was capable of tracking and counting individual migrating salmon in real time. Some projects employed manual tracking, using software that displayed echoes in echogram format and allowed viewing and selection of fish traces in the upstream/downstream plane. Automatic fish tracking programs recognized a fish by examining individual echoes to see if their amplitudes were above a predetermined threshold, if they had proper pulse width and shape (i.e., matching the transmitted pulse), and then tracked echoes in three dimensions. If there were enough sequential detections (typically 4-6), a series of echoes were grouped as a fish detection. For each fish detection the data collected included the fish's distance from the transducer, time of entry and exit from the beam, direction of travel, trajectory angle, and velocity.

With limited attention, systems operated for months at a time. In some cases, hydroacoustic systems were controlled and data and results transferred from the river to an office via modem, reducing the requirement for on-site labor.

Sample Site Selection

Virtually all of the salmon escapement evaluations to date took place at carefully selected sampling sites with smooth bottom profiles and relatively laminar flow (Johnston and Steig 1995, Ransom et al. 1995). Sites have typically been 1-20 m deep and 12-500 m wide (Table 3). Water velocities averaged approximately 1-2 m s^{-1}, with slower velocities observed near shore.

The ideal site has an acoustically "soft" (silt to small cobble) gently sloping bottom, with adequate velocity but minimum turbulence and entrained air. The site should have a triangular cross-section, such that the smallest angle of the triangle (and the transducer mount location) is at shore. The bottom should have an even and gradual gradient, with no protrusions.

A bottom substrate of low acoustic reflectivity enables the acoustic beam to be aimed close to the bottom. Naturally occurring substrates of silt or mud frequently approach acoustic invisibility, relative to the higher reflectivity of the fish being monitored. Lacking this, gravel or small cobble is better than larger cobble, and smooth cobble is better than angular cobble. Large angular boulders or bedrock is the least desirable substrate.

Laminar flow with minimal entrained air is required for successful hydroacoustic monitoring. Turbulent water (e.g., immediately downstream from waterfalls or rapids) is difficult to monitor. The water velocity should be strong enough to discourage fish milling.

Occasionally, river beds have been artificially modified to facilitate aiming along a flat bottom. On the Fraser River, a sand bag substrate was laid evenly along the bottom where the acoustic beam was to be located.

Transducer Deployment

Elliptical-beam transducers were deployed with the long axis of the ellipse in the horizontal plane, with the transducer aimed across the river perpendicular to flow (Figure 1). The narrow axis of the beam was aimed close to the bottom, minimizing interference problems associated with the water surface and bottom structure. It is typical for medium-to-large rivers for opposing transducers to be deployed on each shore.

Fish Behavior

Adult salmon must be actively migrating past the sample site, not holding or milling. Sites that experience significant spawning should be avoided. Since behavior can be variable in areas of tidal influence, these areas should also be avoided.

For sites where the fish are highly shore oriented, small portable weirs are often placed just downstream of each transducer, extending from shore out into the river a short distance (Figure 1). These ensure that fish do not pass behind the transducer, in the near-field of the transducer, or where the sample volume would be too small for adequate detectability.

Results

The following examples of results were taken from studies conducted in the Chandalar River in 1994 monitoring chum salmon (O. keta) (Daum and Osborne 1995); the Fraser River in 1993 monitoring chinook salmon (O. tshawytscha), sockeye salmon, and pink salmon (Johnston et al. 1994); the Kenai River in 1994 and 1995 monitoring chinook salmon (Burwen and Bosch 1996, Burwen et al. 1995); and the Yukon River in 1992 monitoring chinook and chum salmon (Johnston et al. 1993).

Direction of Movement

At typical sites, fish traces on echograms were easily distinguished from background noise (Figure 2). The slopes of the traces were typically not reliable indicators of direction of movement. Typically 10-25% of the fish monitored were moving downstream, identifying a potential source of bias in escapement estimates for acoustic techniques not able to directly identify direction of movement.

In the Yukon River, 85% of the chinook and chum salmon monitored were travelling upstream. In the Chandalar River, 93% of chum salmon were travelling upstream.

Run Timing

Early in the season, daily fish passage estimates in the Kenai River were less than 500 fish day^{-1}, peaked at nearly 5000 fish day^{-1}, and then dropped off to less than 500 fish day^{-1} (Figure 3).

Seasonal hourly counts of chum salmon passing in the Chandalar River exceeded 75 fish hr^{-1} (Figure 4). Passage rates were relatively stable in 1994 until severe flooding caused an abrupt end to data collection on August 27.

During peak passage on the Fraser River, sockeye salmon passage rates exceeded 45 fish min^{-1} on one side of the river.

Spatial Distributions

To date, medium to large, fast flowing rivers typically observed shore- and bottom-oriented horizontal and vertical distributions for upstream migrating salmonids. Presumably this was the result of fish attempting to conserve energy by swimming upstream in areas of slower water velocity. In smaller rivers, distributions tended to be more dispersed (Iverson 1995, Steig et al. 1995).

Yukon River horizontal and vertical distributions for upstream-travelling chinook and chum salmon were shore and bottom oriented (Figure 5).

Upstream travelling chum salmon in the Chandalar River were shore oriented, while downstream targets were more evenly distributed across the river (Figure 6). Upstream fish were bottom oriented (Figure 7). During nighttime hours, fish tended to be located higher in the water column and nearer shore than daylight hours.

On the Fraser River, sockeye and pink salmon were strongly shore and bottom oriented, with most fish passing between the end of the diversion weir (extending out 4 m from the transducer) and a range of 10 m.

Spatial distributions can vary by species. On the Kenai River most chinook were located offshore, while smaller, more abundant sockeye were located predominantly near shore.

Diel Passage Rates

Differences in diel migration rates were observed. Chandalar River and Yukon River diel distributions were weighted toward nighttime (Figure 8). Diel distributions in smaller Deep Creek were similar (Iverson 1995).

Target Strength

On the Chandalar River, the overall mean TS for upstream fish from the right bank was -23 dB (Figure 9).

On the Fraser River, the daily average TS steadily decreased as the species composition shifted from larger chinook salmon to smaller sockeye salmon, then to even smaller pink salmon (Figure 10).

Fish Velocity

On the Yukon River, fish velocities (i.e. speed over ground) calculated using three dimensional target tracking techniques were within expected values as reported in Bell (1990), and were slightly higher for downstream travelling fish (mean = 0.9 m s^{-1}) than for upstream travelling fish (mean = 0.8 m s^{-1}). Fish with higher TS had significantly higher velocities.

Chandalar River fish velocities averaged 1.0 m s^{-1} and 1.5 m s^{-1} for upstream and downstream moving fish, respectively. Taking into account the water velocity at the site, these values fall within the upper range for cruising speeds and the lower range of sustained speeds reported by Bell (1990). A decrease in mean fish velocities corresponded to an increase in river flows.

Discussion

Hydroacoustics has been effectively used to monitor adult salmonid escapement in carefully selected rivers. Fish passage rates, direction of migration, diel distributions, spatial distributions, and velocities have been monitored.

While remaining a challenge, many of the problems associated with monitoring adult salmon escapement have been overcome by the availability of increasingly sophisticated hydroacoustic electronics and signal processing techniques, skilled operators, and careful selection of sample sites. Due in large part to it's improved spatial resolution and three-dimensional target tracking capabilities, split-beam techniques have been more useful than single-beam or dual-beam acoustic techniques for monitoring escapement and behavior at most sites.

The proximity of the beam to the bottom has been shown to be critical to enumerating salmon since upstream travelling fish frequently swim very near the bottom. Like all acoustic techniques, the split-beam technique can be susceptible to excessive reverberation. Unless sample sites are carefully selected, excessive turbulence and entrained air can limit the usefulness of hydroacoustics. Other limitations include the lack of direct species identification. However, one can frequently use behavioral and distributional evidence, coupled with periodic net sampling, to estimate species composition. Nevertheless, the unobtrusive nature of hydroacoustics and its high sample power makes it attractive for many riverine applications.

Potential improvements in riverine monitoring capabilities include quadrature demodulation for improved spatial resolution, and FM Slide/Chirp signals to increase the signal-to-noise ratios, both minimizing bias and variability around estimates.

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Table 1. Rivers where single-beam or dual-beam hydroacoustic techniques have been used to monitor salmonid escapement.

River	Years	Species	Technique	Report
Andreafsky River, Alaska	1981-84	chum, pink, chinook	single-beam	Gaudet 1990
Aniak River, Alaska	1980-87+	chum, chinook	single-beam	Gaudet 1990
Anvik River, Alaska	1979-87+	chum, chinook	single-beam	Cousens et al. 1982, Gaudet 1990
Chandalar River, Alaska	1986-90	chum salmon	single-beam	Daum et al. 1992
Chignik River, Alaska	1986	sockeye	single-beam	Gaudet 1990
Chilkat River, Alaska	1981, 83	sockeye, chum	single-beam	Gaudet 1990
Copper River, Alaska	1978-87+	sockeye	single-beam	Gaudet 1990
Crescent River, Alaska	1979-87+	sockeye, chum	single-beam	Gaudet 1990
Fraser River, Canada	1980	sockeye	single-beam	Whitt et al. 1981
	1982	sockeye	single-beam	Cousens et al. 1982
	1984	sockeye	Doppler	NA
	1986	sockeye, chinook, pink	single-beam	Levy et al. 1991 Nealson and Murphy 1987
	1987	sockeye, chinook, pink	single-beam	Cheng et al. 1991
Kanektok River, Alaska	1982-87+	sock, chm, pnk, cho, chin, char	single-beam	Gaudet 1990
Kasigluk River, Alaska	1979	chum, chinook	single-beam	Gaudet 1990
Kasilof River, Alaska	1978-87+	sockeye, pink	single-beam	Gaudet 1990
Kenai River, Alaska	1967	sockeye	single-beam	Davis 1968
	1978-93	sockeye, pink	single-beam	Gaudet 1990
	1985-93	chinook	dual-beam	Eggers 1994, Eggers et al. 1995
	1985	chinook, sockeye	dual-beam	Johnston 1985, 1986
	1985-86	chinook, sockeye	dual-beam	Johnston et al. 1989
	1991	coho	dual-beam	Vaught et al. 1991
	1993	chinook	dual-beam	Burwen and Bosch 1995a
	1994	chinook	dual-beam	Burwen and Bosch 1995b
Keogh River, Canada	1985	pink, coho, chum	single-beam	Johnston et al. 1986
Klamath River, California	1986	chinook	dual-beam	Johnston and Harte 1987
	1987	chinook	dual-beam & Doppler	Johnston and Harte 1988 Johnston and Hopelain 1990
	1988	chinook	dual-beam	Harte and Johnston 1989
Kuichak River, Alaska	1979	sockeye	single-beam	Whitt et al. 1981
Kuskokwim River, Alaska	1980-81	chin, chum, coho, sock	single-beam	Cousens et al. 1982
Kwethluk River, Alaska	1978	chum, chinook	single-beam	Gaudet 1990
Melozitna River, Alaska	1981-83	chum	single-beam	Gaudet 1990
Moisie River, Quebec	1990	Atlantic salmon	dual-beam	Harte and McFadden 1991
	1991	Atlantic salmon	dual-beam	Harte and Kudera 1991
	1992	Atlantic salmon	dual-beam	Harte 1993a
	1993	Atlantic salmon	dual-beam	Harte 1993b
	1994?	Atlantic salmon	dual-beam	Harte 199?
Naknek River, Alaska	1967	sockeye	single-beam	Davis 1968
Noatak River, Alaska	1978-83	chum, pink, char	single-beam	Gaudet 1990
Nushagak River, Alaska	1980-87+	sockeye, chum, coho	single-beam	Cousens et al. 1982, Gaudet 1990
Ozette River, Wash.	1987	sockeye	single-beam	NA
Quinault River, Wash.	1983-97	sockeye	single-beam	Hendershot et al. 1984
Sacramento River, Calif.	1994	chinook	dual-beam	NA
Salmon River, California	1988	chinook	dual-beam	Written report not available
Sheenjek River, Alaska	1981-87+	chum	single-beam	Gaudet 1990
Stikine River, Alaska	1983-86	sockeye, chum, pink	single-beam	Gaudet 1990
Susitna River, Alaska	1979-87+	sock, chm, pnk, cho, chin	single-beam	Gaudet 1990
	1985	chinook, chum	dual-beam	Ransom et al. 1986
Tanana River, Alaska	1981	chum	single-beam	Gaudet 1990
River Tavy, England	1986	Atlantic salmon	dual-beam	Kubecka et al. 1996
Toklat River, Alaska			single-beam	NA
Unakleet River, Alaska	1982-83	chm, pnk, cho, chin, char	single-beam	Gaudet 1990
Wood River, Alaska	1967	sockeye	single-beam	Davis 1968
Yetna River, Alaska			single-beam	NA
Yukon River, Alaska	1982-87+	chinook and chum salmon	single-beam	Mesiar et al. 1990

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Table 2. Recent examples of split-beam hydroacoustic monitoring of adult salmonids in rivers.

River	Years	Species	Publication/Report
River Avon, England	1995	Atlantic salmon	Iverson et al. 1996
Chandalar River, Alaska	1994	chum salmon	Daum & Osborne 1995, Johnston & Daum 1995
	1995	chum salmon	Daum and Osborne 1996
	1996-1997	chum salmon	USFWS report in progress
Deep Creek, Alaska	1995	chinook salmon	Iverson 1995
	1996	chinook salmon	Iverson 1996
Fraser River, Canada	1993	sockeye, chinook, pink	Johnston et al. 1994
	1994-1997	sockeye, chinook, pink	DFO Canada reports in progress
Illinois River, Oregon	1993	steelhead	Johnston 1993
Kenai River, Alaska	1993	coho	Vaught and Skvorc 1993
	1994	chinook, sockeye, coho	Burwen and Bosch 1996
	1995	chinook, sockeye	Burwen et al. 1995
	1996-1997	chinook, sockeye	ADFG report in progress
River North Esk, Scotland	1996	Atlantic salmon	Bray et al. (in prep.)
Sacramento R., California	1994	chinook salmon	Nealson and Kumagai 1994
Ship Creek, Alaska	1996	chinook salmon	ADFG report in progress
River Spey, Scotland	1994	Atlantic salmon	Johnston and Ransom 1994
	1995	Atlantic salmon	Steig et al. 1995, Locke 1996
	1995-1997	Atlantic salmon	Laughton and Bray 1996, Bray et al. 1997
River Tavy, England	1995-1997	Atlantic salmon	Steig and Iverson 1995
River Teifi, Wales	1997	Atlantic salmon	Data collection in progress
Thompson River, Canada	1995	sockeye, chum	DFO Canada report in progress
Tornio River, Finland	1995	Atlantic salmon	Nealson and Johnston 1995
	1996-1997	Atlantic salmon	Romakkaniemi et al. 1997
River Torridge, England	1995	Atlantic salmon	Steig and Iverson 1996
Yukon River, Alaska	1992-1994	chinook and chum salmon	Johnston et al. 1993
River Wye, Wales	1994	Atlantic salmon	Ransom et al. 1995
	1994-1995	Atlantic salmon	Gregory and Gough 1995
	1995-1997	Atlantic salmon	Gregory et al. 1996

Table 3. Physical characteristics of representative rivers with hydroacoustic monitoring of salmon escapement.

River	Maximum Depth (m)	Width (m)
Chandalar River, Alaska	3.8	130
Deep Creek, Alaska	0.9-1.5	12-15
Fraser River, Canada	10-20	130-180
Illinois River, Oregon	2-5	35-60
Kenai River, Alaska	4-8	90-120
River Spey, Scotland	2.5	51
Tornio River, Finland	3-9	250-500
River Wye, Wales	2-3	60

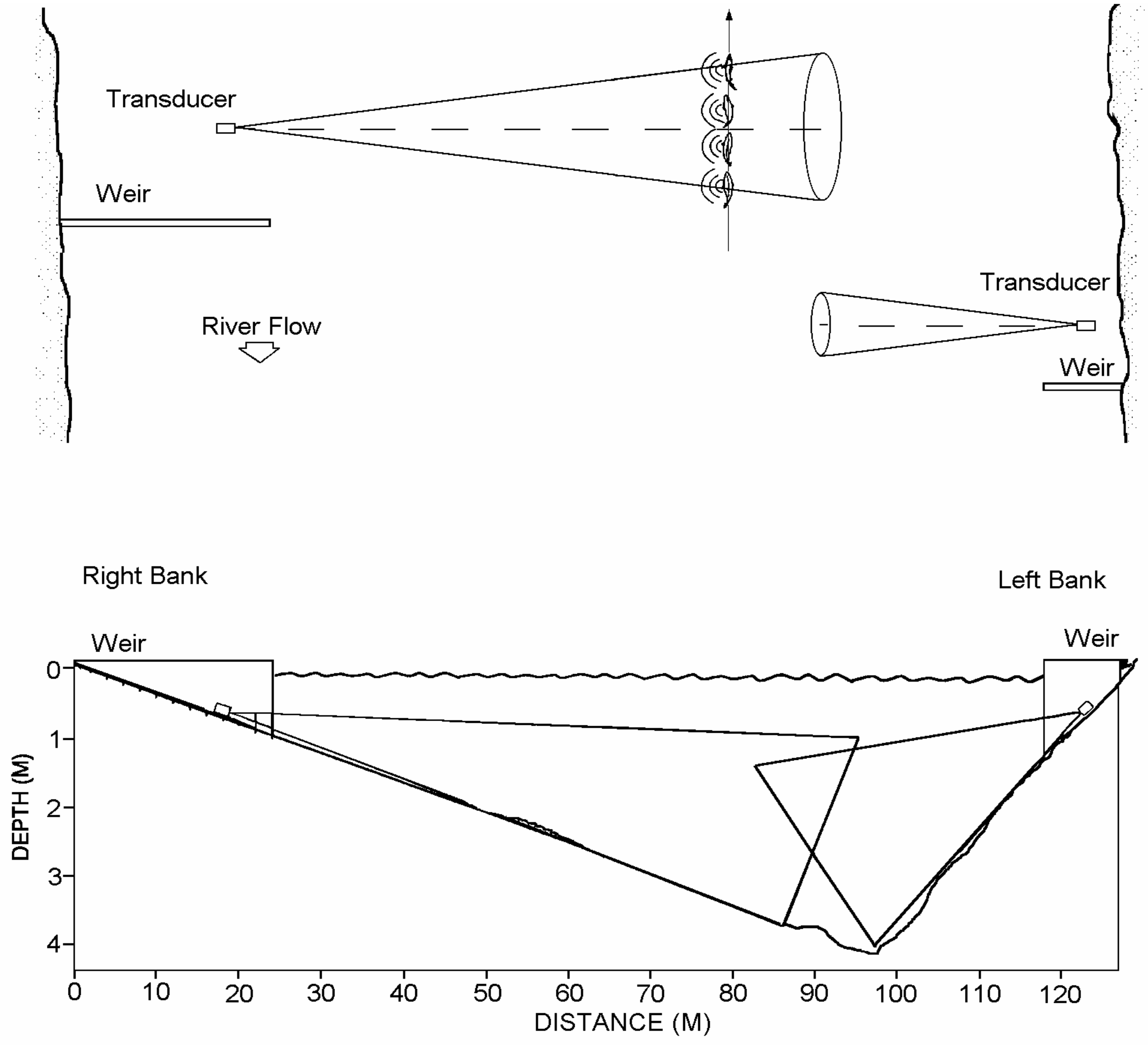


Figure 1. Typical riverine deployment in plan view, showing four acoustic ensonifications on an upstream migrating fish passing through the acoustic beam, and elevation view.

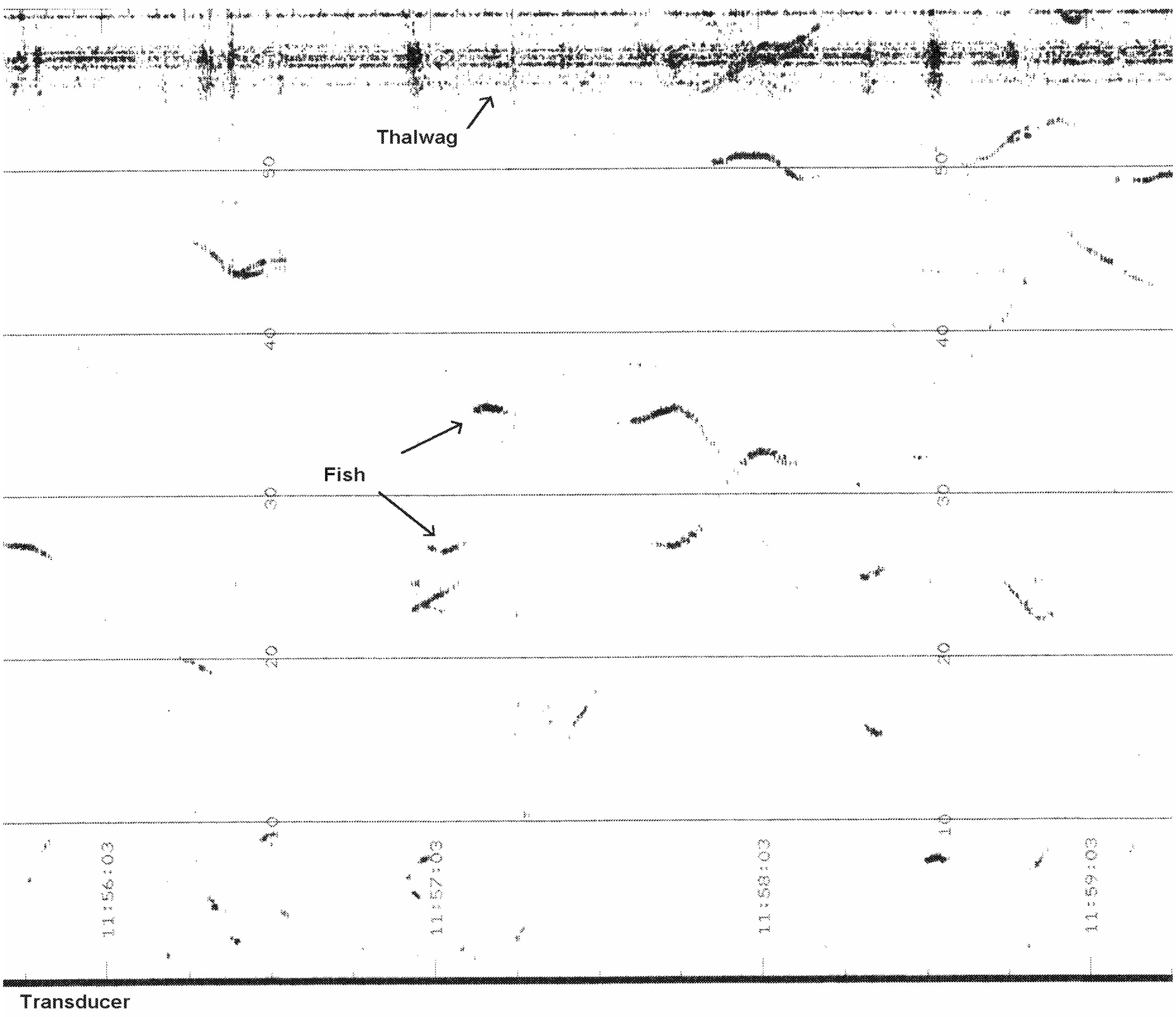


Figure 2. Kenai River echogram showing traces from chinook salmon (Burwen et al. 1995).

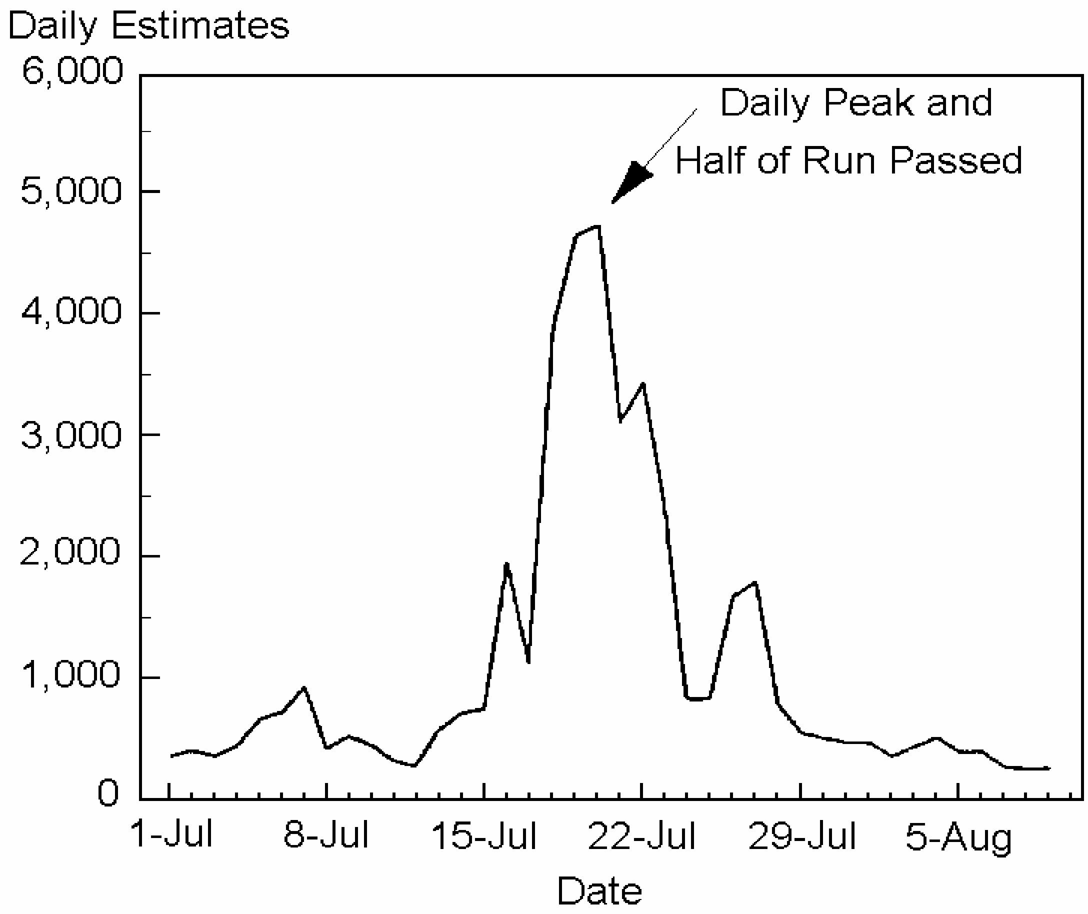


Figure 3. Daily fish passage rates for upstream migrating chinook salmon in the Kenai River during 1995 (Burwen and Bosch 1996).

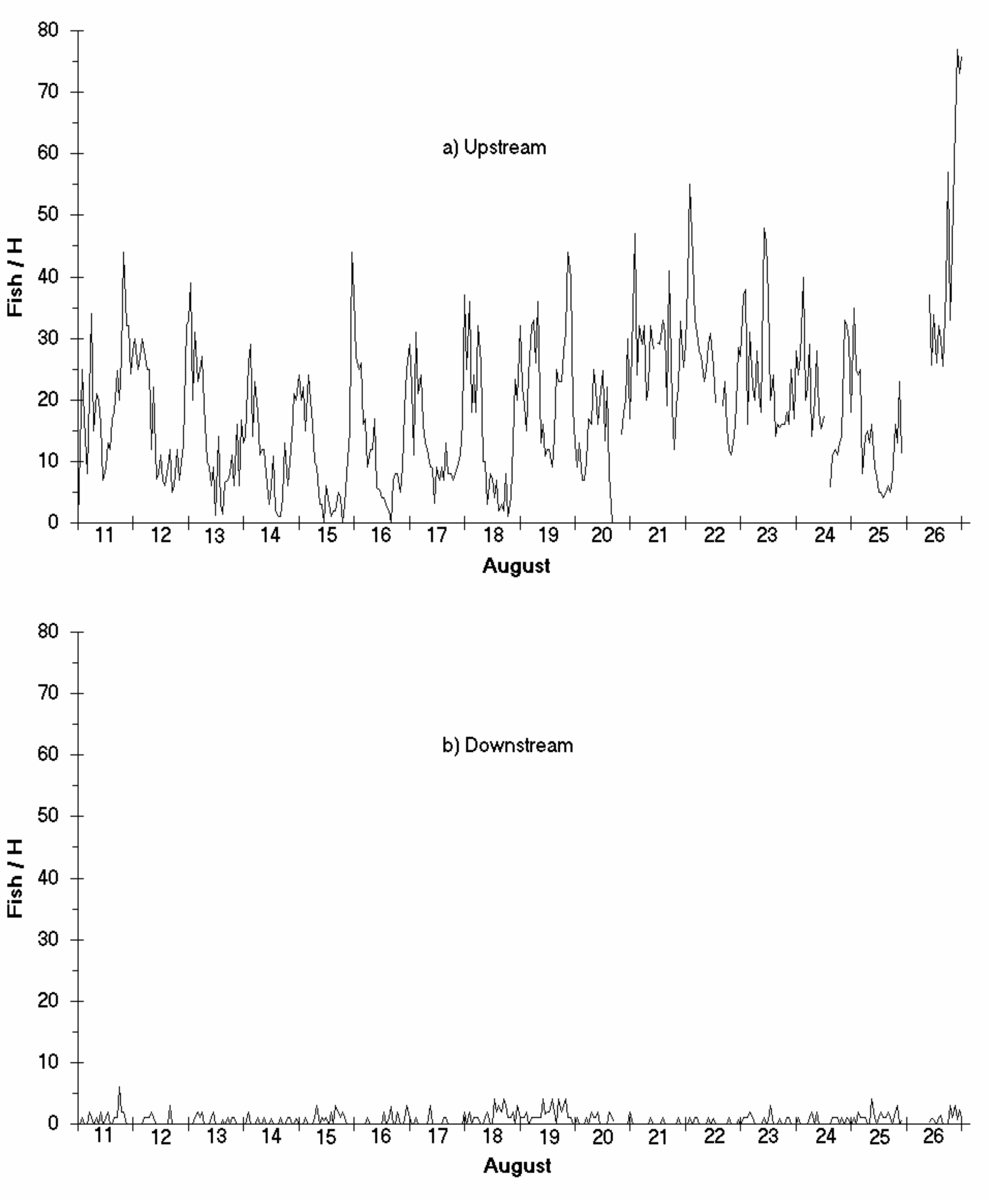
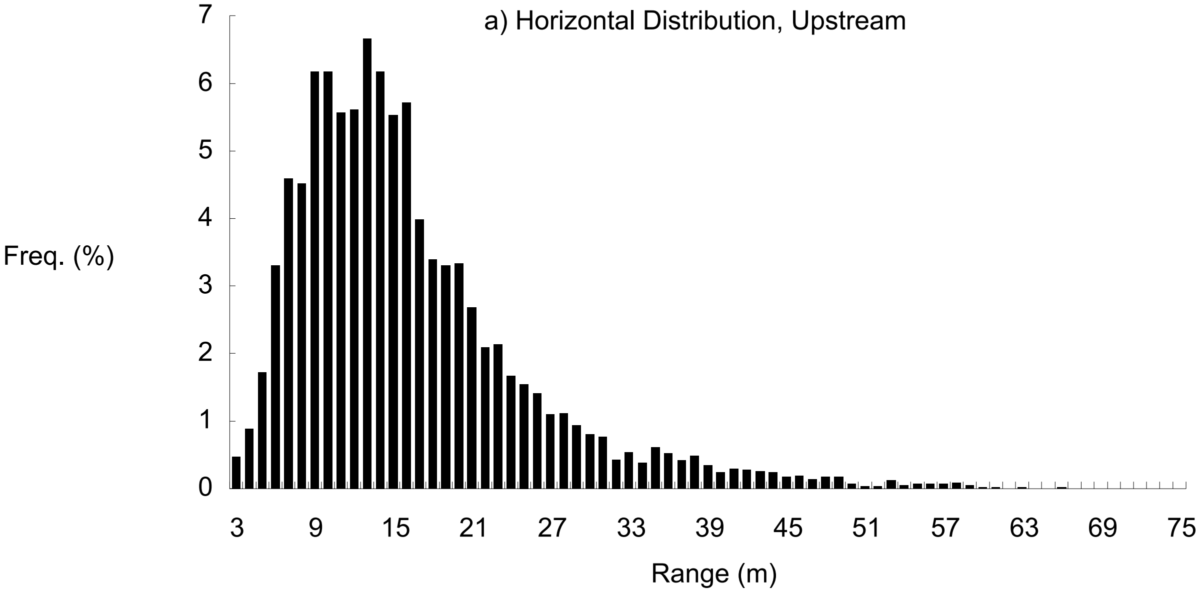


Figure 4. Hourly fish passage rates for a) upstream and b) downstream migrating chum salmon on the Chandalar River (left bank) during 1994 (Daum and Osborne 1995).



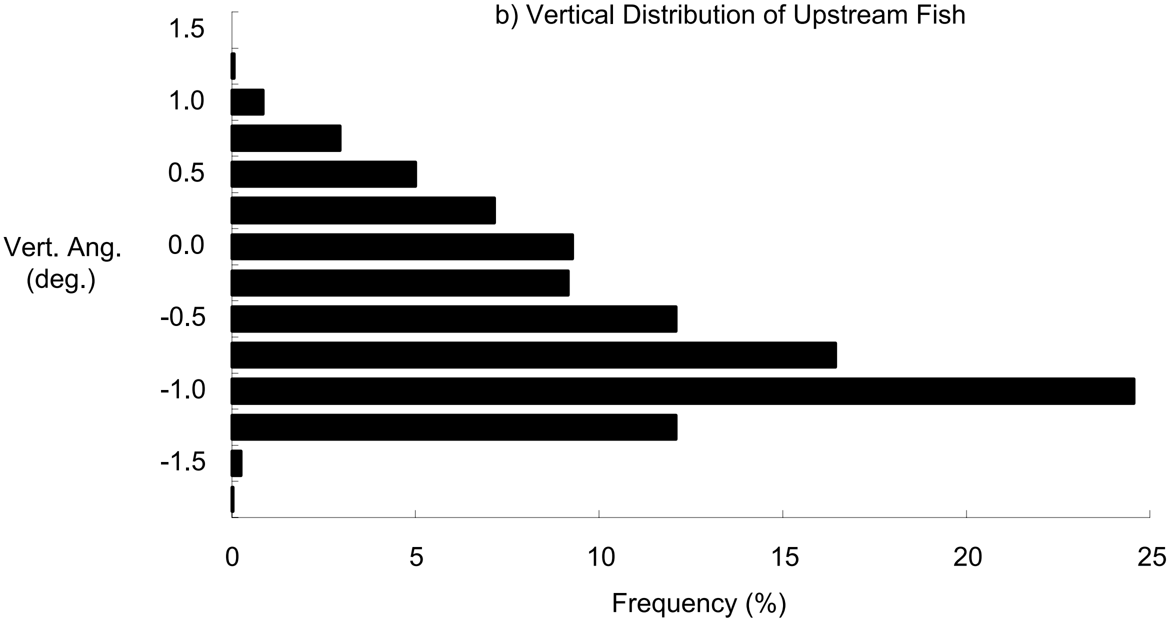


Figure 5. Yukon River a) horizontal distribution (across river), and b) vertical distribution of 5751 upstream travelling fish on the right bank, during 1992 (Johnston et al. 1993).

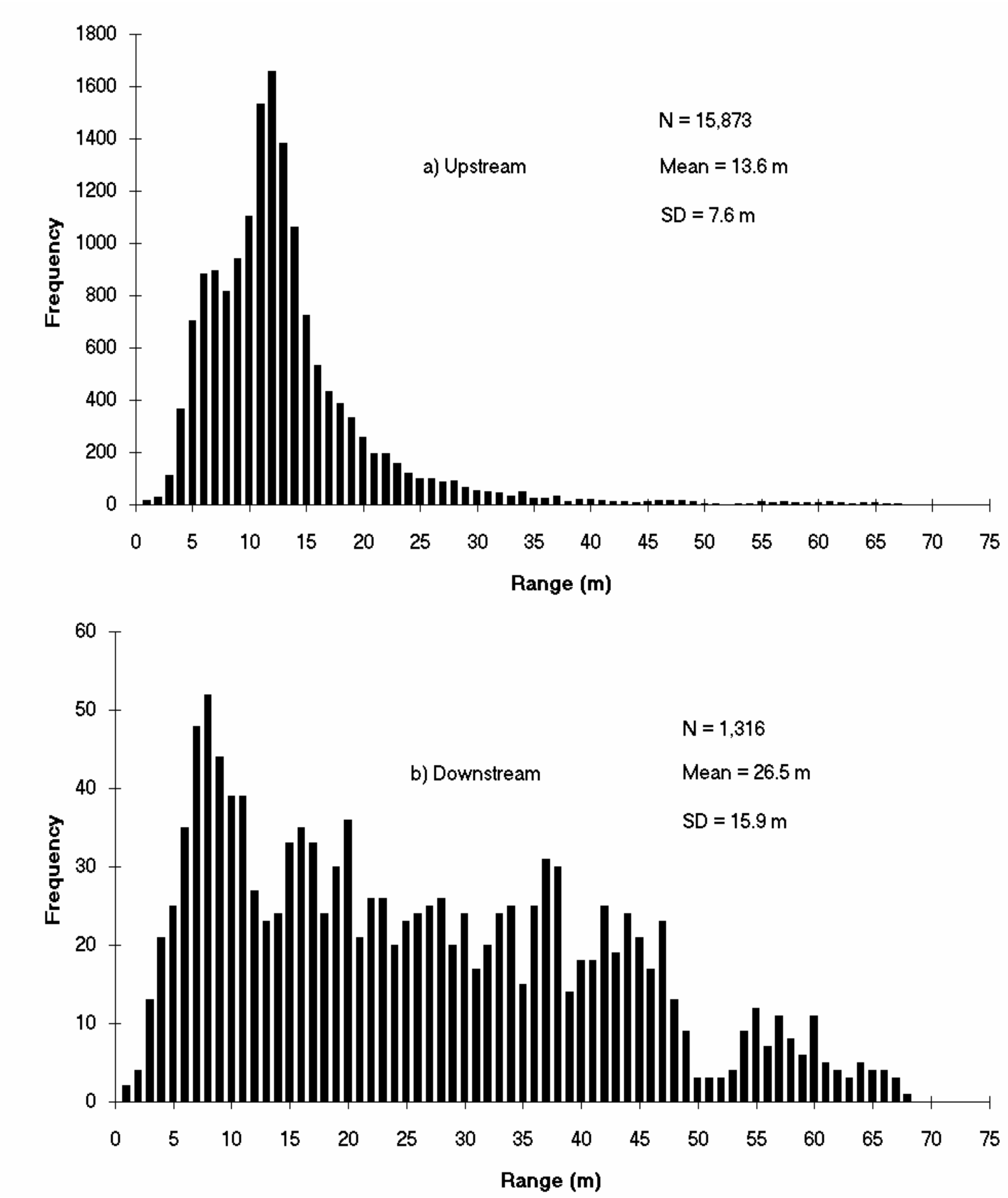


Figure 6. Horizontal distribution of a) upstream and b) downstream travelling chum salmon on the Chandalar River at the right bank (Daum and Osborne 1995).

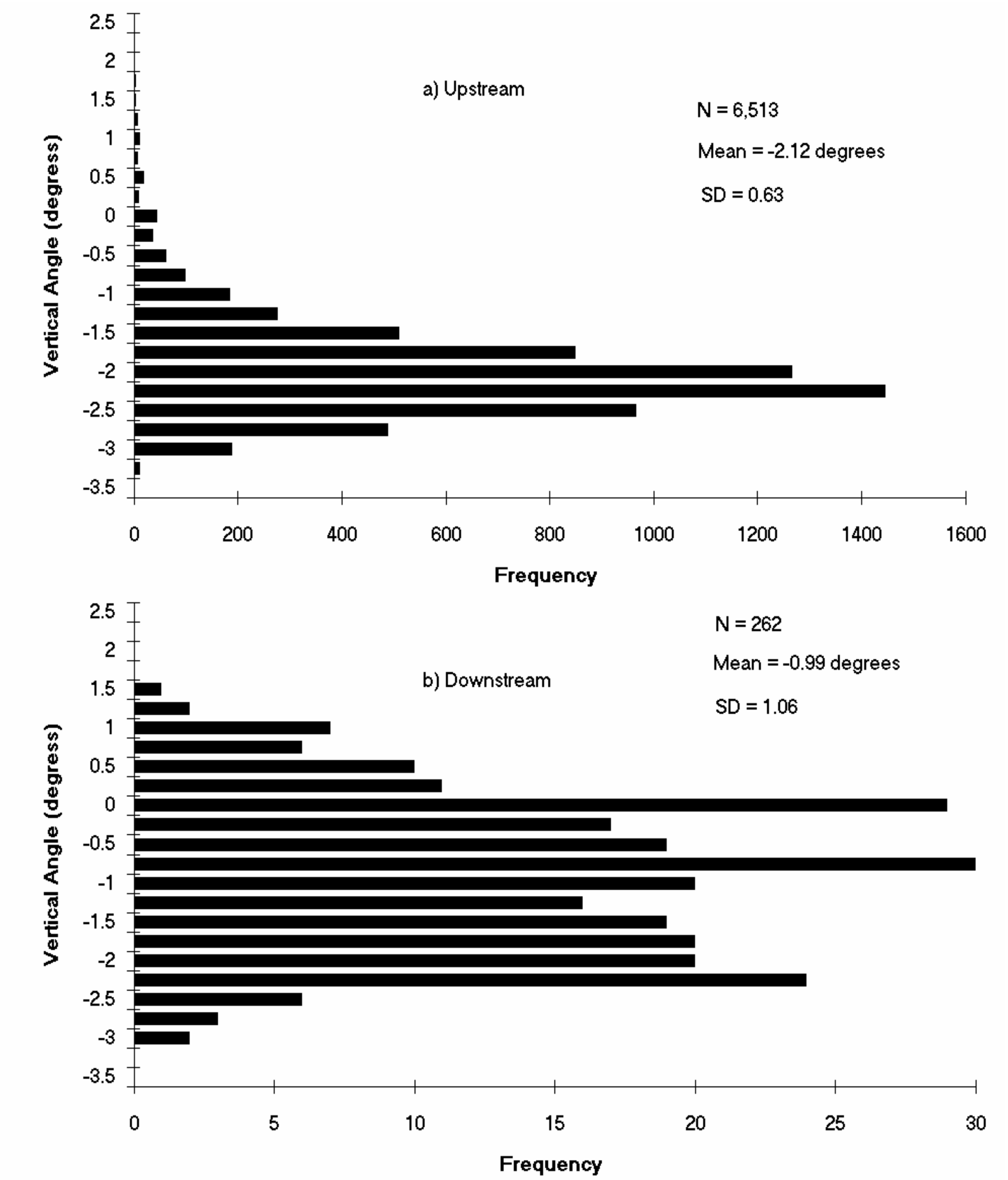


Figure 7. Vertical distribution of a) upstream and b) downstream travelling chum salmon on the Chandalar River left bank (Daum and Osborne 1995).

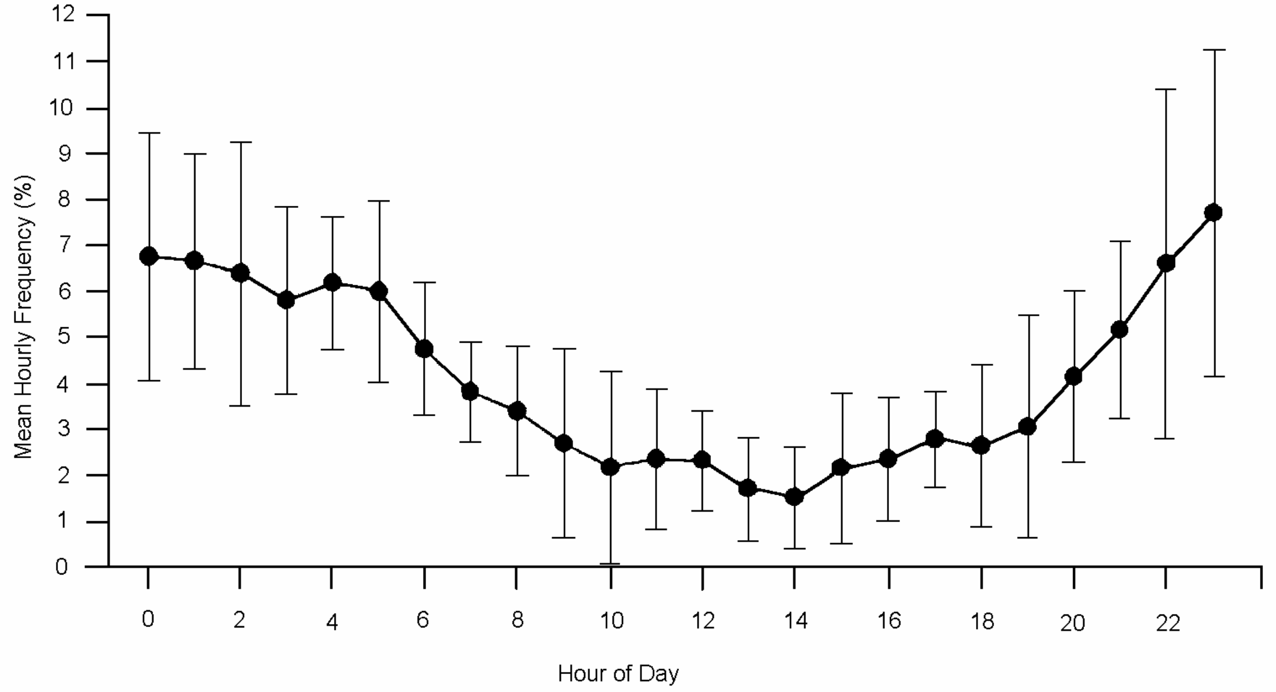


Figure 8. Diel distribution of chum salmon on the Chandalar River (left bank) during 1994 (Daum and Osborne 1995).

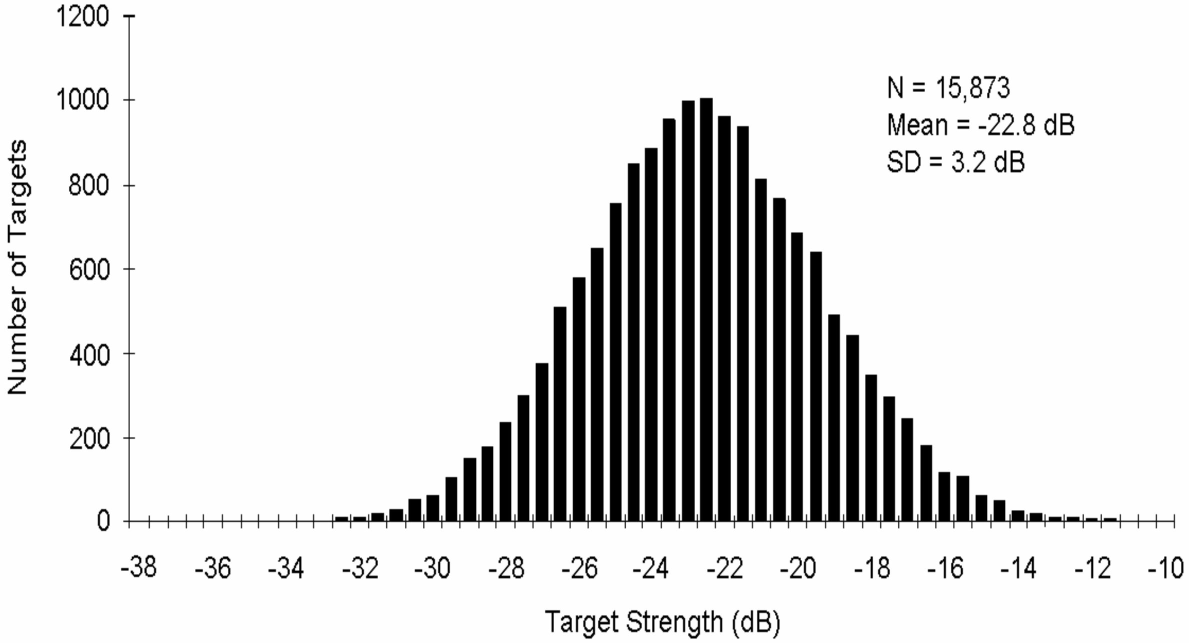


Figure 9. Target strength frequency distribution for upstream travelling chum salmon in the Chandalar River (right bank) during 1994 (after Daum and Osborne 1995).

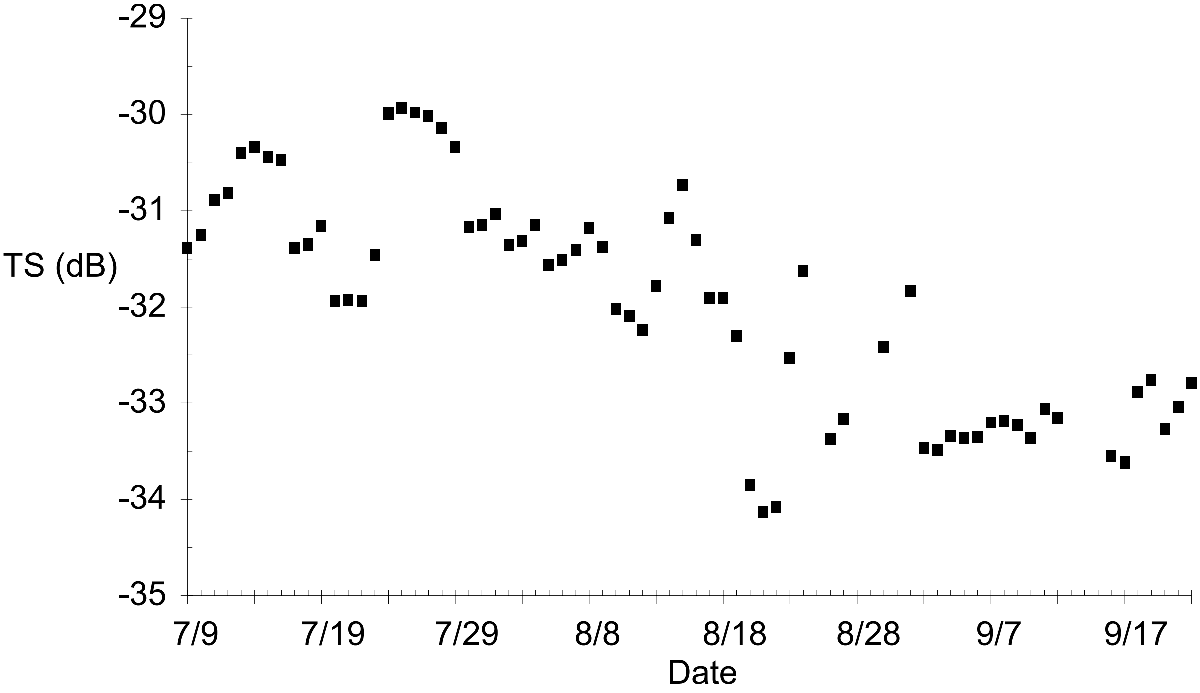


Figure 10. Daily mean target strength of upstream travelling fish on the Fraser River, British Columbia, during 1993 (Johnston et al. 1994).