Potential Impacts of Pile Driving on Juvenile Pink (*Oncorhynchus gorbuscha*) and Chum (*O. keta*) Salmon Behavior and Distribution

by

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Abstract

POTENTIAL IMPACTS OF PILE DRIVING ON JUVENILE PINK (*ONCORHYNCHUS GORBUSCHA*) AND CHUM (*O. KETA*) SALMON BEHAVIOR AND DISTRIBUTION

by Blake E. Feist

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A pilot study assessed the potential effects of pile driving activities at the Everett Homeport site (near the mouth of the Snohomish River) on the behavior and distributions of schools of juvenile pink (*Oncorhynchus gorbuscha*) and chum (*O. keta*) salmon. School size, frequency of occurrence, species distribution, and general fish behavior were measured. Individual fish were sub-sampled for total length, weight, and stomach contents. On sampling days, tidal stage, weather conditions, salinity, and the underwater acoustic environment were also measured.

Within the range of salmonid hearing, the sound field generated by pile driving activities had a radius of at least 300 m. Pile driving operations apparently affected ,the general behavior and distributions of schools about the site. Nearly twice as many fish schools were found on the construction side of the site on non-pile driving days compared to driving days. Fish schools were typically in water <1.5 m, within 2 m from shore, and surface oriented. Fish school distances from shore did not change significantly as a result of pile driving. The average total length of fish did not increase significantly over the study period, suggesting fish were either transient and/or not growing. However, stomach content analysis indicated that most fish were feeding. Salinity and tidal stage did not appear to have an effect on fish behavior or distribution.

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I would like to thank Dr. James Anderson for his support and guidance and for allowing me to take the reins of this research; most Masters students do not have the opportunities I had to experience the “big picture” of conducting research. Doctor Thomas P. Quinn was responsible for initiating this whole project, and I am indebted. I would also like to thank all of my observers who spent so many hours judiciously looking into the water, especially Kevin Kumagai for his undaunting dedication to this project. Cheryl Morgan identified the stomach contents of my fish samples, for which I am indebted. Robert Miyamoto, Mark Stoermer, and Mike Macauley from the Applied Physics Laboratory, were instrumental in carrying out the acoustic survey of this study. Their commitment, often without pay, cannot go unrecognized. Geri Byrne was exceptionally tolerant of the emotional stresses I encountered during this project and should be commended, I could not have done this without her support. Finally, I would like to thank my parents, William and Thora, for their unconditional support throughout this project. My mother is no longer with us but her spirit is and always will be an inspiration. This research was funded, in part, by the Washington State Department of Transportation, Manson Construction and Engineering, and General Construction.

INTRODUCTION

Pacific salmon (*Oncorhynchus* spp.) in the Northwest United States are confronted with seemingly endless challenges imposed by destruction and alteration of migration routes, and spawning and rearing habitats. Mitigation of these human induced changes often have limited efficacy. In order to avoid additional “scratches” on the backs of Pacific salmon, the Washington Department of Fisheries (WDF) prohibits pile driving activities in Puget Sound (Washington) waters from March 15 to June 15 each year. The rationale is that migrating juvenile Pacific salmon might be driven towards deeper water in order to avoid the disturbance created by pile driving activities. This premature departure from the protective confines of the nearshore area could place juvenile salmon at a disadvantage by prohibiting optimal foraging opportunities and by exposing juveniles to predators.

The regulation allegedly hinders the progress of shoreline construction companies, who claim only anecdotal evidence supports the hypothesis of the WDF pile driving prohibition rule. Therefore, pile driving construction companies initiated this study in order to ascertain the impacts of their activities on the distribution and behavior of juvenile Pacific salmon. The hypothesis of WDF and this research is that sounds produced by pile driving rigs alter the abundance, behavior, distribution, and/or general ecology of juvenile pink and chum salmon at the Everett Homeport, Everett, WA. To test this hypothesis, I first characterized the underwater acoustic environment at the Everett Homeport to determine if sounds in the area were within the audible range of juvenile pink and chum salmon. Secondly, I measured the abundance, behavior, and distribution of juvenile pink and chum salmon at the Everett Homeport, with and without pile driving. The information from this study has direct application to decision making at WDF and other management agencies concerned with the welfare of aquatic organisms in the Puget Sound area. In the following section, I will review the pertinent literature on juvenile salmonid ecology in the nearshore estuarine areas, underwater acoustics, and fish audition.

Estuarine ecology of juvenile pink and chum salmon

Pink and chum salmon typically migrate soon after emergence from their natal streams to the estuary (see Kobayashi and Abe 1977; Healey 1979; Godin 1982). Once in the estuary, they occupy nearshore, shallow water areas until they reach a total length (TL) of 50-60 mm (Manzer 1956; Gilhousen 1962; see Kirkwood 1962; LeBrasseur and Parker 1964; Neave 1966; Kaczynski et al. 1973; Groot 1982), upon which they move into the neritic zone. Juvenile pink and chum salmon in the Puget Sound area typically migrate from their natal streams between early February and late May, with peaks of abundance occurring from late March to mid-May for pink salmon, and late March to early May for chum salmon.

Individual estuarine residence times for juvenile chum salmon vary considerably, with estimates ranging from 0 to 32 days (Mason 1974; Healey 1979; Salo et al. 1980; Chitwood 1981; Congleton et al. 1981; Simenstad and Eggers 1981; Levy and Northcote 1982; Schreffler et al. 1990). Individual residence times for pink salmon are not known.

Newly emerged juvenile pink and chum salmon occupying nearshore waters of Puget Sound have a feeding preference for epibenthic invertebrates, with a subsequent transition to more pelagic prey as they grow larger and move into deeper water (Bax et al. 1978; Simenstad and Kinney 1978; Fresh et al. 1979; Meyer et al. 1981; Weitkamp and Schadt 1982). However, there is considerable variation in the diet as a function of species, time of year, and geographical location. Kaczynski et al. (1973) found that juvenile pink salmon (mean TL 39 mm) sampled in nearshore waters of Port Susan, WA, primarily fed on barnacle nauplii, invertebrate eggs, and mysis larvae, whereas juvenile chum salmon with mean TL 43 mm, primarily fed on epibenthic harpacticoid copepods and gammarids.

Feller and Kaczynski (1975) found that juvenile chum salmon with mean FL ~38 mm fed primarily on gammarid amphipods, cladocerans, and terrestrial and marine insects in the nearshore waters of Port Susan.

Pink salmon typically feed during the day, with peaks of activity occurring at dawn and dusk (Godin 1981). Juvenile pink and chum salmon grow rapidly during their occupation of the estuary. Daily growth rates range from 2.2-8.6% of body weight for chum salmon (Healey 1979; Salo et al. 1980; Bax and Whitmus 1981; Congleton et al. 1981; Irie 1985; Koshiishi 1986), and 3.1-7.1% for pink salmon (LeBrasseur and Parker 1964; Phillips and Barraclough 1978; Mortensen et al. 1991). In order to grow at this rate, the fish must consume large amounts of prey. Juvenile pink and chum salmon are estimated to consume the equivalent of 10-16% of their body weight per day in prey biomass (LeBrasseur 1969; Parsons and LeBrasseur 1970; Godin 1981). Evacuation rates are rapid, with 50% evacuation times of 6.5 h (at 8-12°C) in 0.6 g juvenile chum salmon (Koshiishi 1980).

The significance of estuaries in the lifecycle of Pacific salmon is well documented. In particular, the first few weeks in the estuary is a critical time for juveniles (Manzer and Shepard 1962; Simenstad et al. 1982; Levings et al. 1989), during which there is high mortality (Godfrey 1958; Ricker 1962; Foerster 1968; Parker 1968; Ricker 1976; Peterman 1982; Bax 1983). There is evidence that mortality of small fish is size dependent, and rapid growth and increase in body size may reduce predation pressure on juvenile salmonids during their first few weeks in the estuary (Parker 1971; Healey 1982a; Hargreaves and LeBrasseur 1985; Furnell and Brett 1986). Juvenile pink and chum salmon are especially susceptible to predation and environmental stresses since they enter the estuary at a small size immediately or shortly after emergence. They are generally smaller than juvenile coho and chinook salmon and reside in the sublittoral zone for 4 to 24 weeks before moving out to the neritic zone (Simenstad et al. 1982).

The Everett Harbor and the Port Gardner vicinity are important rearing areas for juvenile salmonids migrating from the Snohomish River (Tyler 1963; Conley 1977; McEntee 1985; Schadt and Weitkamp 1985; Beauchamp 1986; Beauchamp et al. 1987). If these fish were forced out into the neritic zone prematurely, they might be subject to increased predation pressure and decreased food availability.

Like all Pacific salmon migrating from their natal streams to the sea, juvenile pink and chum salmon migrating from the Snohomish River face stress imposed by osmoregulatory challenges. They must acclimate to salinities of 25‰, and these salinities vary from 8-25‰ at the Homeport as a function of tidal stage. However, the osmotic challenge imposed by salinities of 25‰ is apparently brief, since juvenile chum salmon become seawater adapted in 12 h (Iwata and Komatsu 1984; Hasegawa et al. 1987).

Characteristics of sound in water

There are two components to sound propagation through water: particle displacement and sound pressure. Particle displacement is the to-and-fro movement (on the order of nanometers) of water molecules and is a vector quantity, whereas sound pressure is the oscillatory change in pressure above and below hydrostatic pressure and is a scalar quantity acting in all directions.

In a free sound field without physical obstructions to sound transmission, and with an advancing wavefront that is essentially a plane surface, particle velocity (the first derivative of particle displacement) is proportional to sound pressure in the following manner:

$$v = p/\rho c$$

where v = particle velocity,
p = sound pressure,
ρ = the density of the medium, and
c = the propagation velocity.

The product ρc is the acoustic impedance of the medium. However, sound levels are not usually expressed as particle velocity, rather the logarithmic decibel (dB) scale of sound pressure level (SPL) is used because a great range of sound levels are found in nature:

$$\text{sound pressure level (SPL)} = 20\log_{10} p/p_{\text{ref}} \text{ dB}$$

where p = measured sound pressure, and
p_{ref} = reference pressure.

A reference quantity is always associated with the dB in order to place sound levels in a reasonable range. Twenty µPascal (µPa) of sound pressure is the reference (re:) pressure for the dB scale in humans, because 20 µPa is the average minimum sound pressure perceivable by humans. Therefore, 0 dB re: 20 µPa is the human threshold of hearing. The pain threshold in humans is about 120 dB re: 20 µPa. For each 20 dB increase in SPL, regardless of the reference pressure, the increase in actual sound pressure is tenfold. Thus, a 40 dB increase in SPL is 100 times more pressure, 60 dB is 1000 times more and so on.

Sound pressure and particle displacement are essentially the same at substantial distances from the source. However, within a distance of $\lambda/2\pi$ (λ = wavelength), from the sound source the wavefront is spherical rather than a plane surface, and particle velocity is much higher for a given sound pressure—the “near-field effect.” The near-field can be thought of as the region where the greatest amount of bulk movement of water occurs in response to the sound source, which is not as pronounced after $\lambda/2\mu$ distance from the sound source. This near-field effect can extend up to 50 m from the source for low frequencies such as 5 Hz, which is perceivable by many fish.

Sound propagation through water, is a logarithmic function of distance:

$$y = a + m(\log x)$$

where a = the source-sound pressure level (y-intercept),
m = the logarithmic slope, and
x = the distance from the source.

Therefore, the rate of SPL increase close to the source is rapid compared to that far away.

Sound perception in fish

Fish hearing in general is different from that of terrestrial organisms. Most fish hear with a primitive version of the terrestrial inner ear (located in the skull of fish) and with the lateral line that runs the length of each side of the fish and is often extensively routed on the head. The inner ear and lateral line system are collectively called the acoustico-lateralis system. The lateral line system of fish is extremely sensitive to close range pressure changes. For example, by moving past stationary objects, the blind Mexican cave fish (*Anoptichthys jordani*) is capable of identifying the shape of nearby objects, presumably using its lateral line (Campenhausen et al. 1981; Weissert and Campenhausen 1981).

The inner ear of fish does not have a cochlea as in terrestrial vertebrates; rather there are three symmetrically paired structures with associated bony otoliths: the lagena, sacculus, and utriculus. The lagena and sacculus are directly involved with hearing, whereas the utriculus is mainly for three-dimensional orientation (Platt and Popper 1981). The mechanism for hearing is the differential displacement of high-density otoliths relative to the low-density bodies of fish (about the same density as water), resulting in bending of sensory hair cells that line the lagena and sacculus. This mechanical stimuli is then converted to electrical stimuli in the hair cell body and sent to the brain via the auditory nerve (8th cranial) for processing.

Audiograms or minimum audible field thresholds (threshold SPL for various frequencies) of different species of fish are variable (Tavolga and Wodinsky 1963; Chapman and Hawkins 1973; Chapman and Sand 1974; Hawkins and Johnstone 1978; Coombs and Popper 1979; Saidel and Popper 1987). Families of fish with the best hearing such as cyprinids and ictalurids (Ostariophysan fish) possess a physical connection (via a series of bones, the Weberian apparatus) between the swimbladder and the inner ear. Thus, the swimbladder acts as an amplifier and a transformer in that it transforms the sound pressure component of sound into the particle velocity component that the inner ear is sensitive to.

The hearing ability of other fish such as salmonids and flatfish is limited in bandwidth and intensity threshold compared to other teleosts: Atlantic salmon (*Salmo salar*) are functionally deaf above 380 Hz (Hawkins and Johnstone 1978, Fig. 1). These fish lack the physical connection between their swimbladder and inner ear that Ostariophysan fishes possess (Hawkins 1986). Fish with this type of hearing are most sensitive to particle velocity since the otoliths in the lagena and sacculus essentially respond to particle displacement (Hawkins and MacLennan 1976). In fact, the swimbladder probably does little to enhance hearing in most nonostariophysine fish, including salmon (Enger 1981).

Compared to humans, salmonids have poor hearing on the basis of perceivable frequency range and sensitivity to sound pressure (Fig. 1). Human infants are capable of detecting sounds from 20-20,000 Hz, and at SPLs much lower than that of salmonids. For example, a human would require about 40 dBs re: 1 µPa SPL to hear a 160 Hz pure tone, while a salmonid would require about 100 dBs. Therefore, the salmonid requires close to a thousandfold difference in SPL to hear the same 160 Hz tone.

Behavior of fish in response to sound

Literature on fish hearing clearly demonstrates that fish detect and respond to sounds in their environment (see reviews in Hawkins 1986; Fay 1988; Kalmijn 1988; Rogers and Cox 1988). Fish appear to use sound: to locate prey, evidenced by attraction to a sound stimulus (for example, sharks: Wisby et al. 1964; Nelson 1965; various teleosts and elasmobranchs: Richard 1968; Nelson et al. 1969; rainbow trout, *Oncorhynchus mykiss*: Abbott 1970); for social interactions (bicolor damselfish, *Pomacentrus partitus*: Myrberg 1972; Myrberg and Riggio 1985; gudgeon, *Gobio gobio*: Ladich 1988); for encounters with fishing gear (Olsen 1971 and 1976; Nomura 1980; Wardle 1983; Ona and Toresen 1988); for encounters with hydroelectric bypass systems (Anderson 1988a and 1988b), and to signal the presence of danger, evidenced by fish avoiding a sound stimulus (steelhead trout, *O. mykiss*: VanDerwalker 1967; herring, *Clupea harengus* L.: Blaxter et al. 1981a; Schwarz and Greer 1984; Blaxter and Batty 1985a; 1985b; alewife, *Alosa pseudoharengus*: Haymes and Patrick 1986).

A number of researchers have successfully conditioned fish to sound (Moorehouse 1932; Stober 1969; Abbott 1970 and 1973; Hawkins and Johnstone 1978). While salmonids can be attracted to or repelled from sound through classical conditioning (Abbott 1973), they habituate rapidly or do not respond at all when there is no conditioned response, regardless of SPL (Burner and Moore 1962, Moore and Newman 1956). “At no time did a sound frequency or intensity influence the action of the trout enough to be utilized in guiding young salmon into safe passages around dams and diversions” (Burner and Moore 1962). An explanation for this is that salmon have poor hearing, and the nature of the sounds presented to them in experiments has not been biologically relevant.

The response of fish to sounds in their environment is varied. Other species of fish with better hearing capabilities than salmon have been shown to jump out of the water or swim rapidly away from or towards sound stimuli (Moulton 1956; Hashimoto and Maniwa

1966; Konagaya 1980). The classic fright response of salmonids to sound is not as dramatic, where fish typically elicit a “startle” or “start” behavior (Moore and Newman 1956; Burner and Moore 1962; VanDerwalker 1967). Such behaviors involve sudden bursts of swimming that are short in duration and distance travelled (usually <60 cm). Responses of schooling Atlantic herring to a sound stimulus include packing or balling, polarizing, increases in swimming speed, diving, or avoidance (Herring 1968; Olsen 1969). Few studies have shown that sound can attract or repel salmonids over great distances or for long lengths of time (McKinley and Patrick 1986).

The majority of hearing experiments conducted on salmonids have involved larger juveniles or adult fish, exposed to continuous sound stimuli. Fish under these experimental conditions rarely respond to sudden or loud sound stimuli (Moore and Newman 1956; Burner and Moore 1962). However, the few experiments that have used pulsed (pile driving most closely resembles pulsed sound stimuli) rather than continuous sound stimuli on juvenile fish demonstrated more pronounced responses, such as “startle” or general avoidance (McKinley and Patrick 1986).

Few studies have investigated the behavior of fish in response to changes in SPL over time. Olsen (1971) found a positive correlation between the rate of sound pressure increase and the number of Atlantic herring that would avoid this stimulus (see Blaxter et al. 1981a). Schwarz and Greer (1984) obtained similar results on Pacific herring (*C. harengus pallasi*). However, these studies did not quantify rates of sound pressure increase or the fish's response to the sound stimulus.

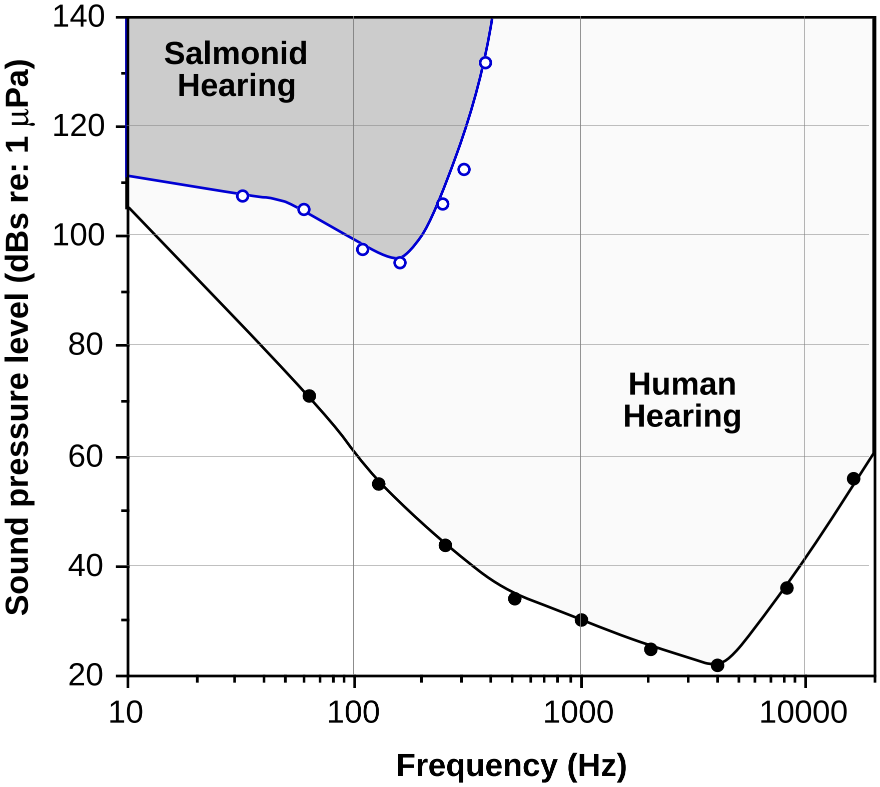

Figure 1. Comparison of Atlantic salmon (30-32 cm TL), *Salmo salar* (Hawkins and Johnstone 1978) and human (Sivian and White 1933 in Fay 1988) sensitivity to sound.

MATERIALS AND METHODS

Study site

Fish behavior observations were made from the shore of the mole and the pile driving rigs (Figs. 2 and 3) at the Everett Homeport, Everett, WA (see Driscoll 1978 for a detailed base information and evaluation study of the Snohomish Estuary). The mole area consisted primarily of rip-rap, with a slope of 30°. Pile drivers placed solid and hollow concrete piles at this site for construction of a 488 m carrier pier and its accompanying 91 m wharf. The DB Pacific rig began at the shoreline and gradually moved offshore working on the carrier pier (Fig. 3). The 60 rig moved back and forth along the shore working on the wharf. See table 1 for a summary of piles, and pile driving equipment.

Table 1. Characteristics of pile driving rigs and piles.

Rig/Dimensions	Pile driver/Hammer wgt	Pile lgth/wgt	Pile type
DB Pacific/76X25 m	Delmag D62-22/6,625 Kg	55 m/26 mt	Hollow
The 60/37X13 m	Delmag D46-32/4,600 Kg	32 m/17 mt	Solid

Pile driving rigs operated for 8-10 hour periods per day on a random daylight schedule (i.e. Monday/Wednesday/Friday pile driving, Tuesday/Thursday non-pile driving, etc., see Fig. 4). Observations were made during daylight hours only. There was no construction activity or observations on weekends.

Procedure

There were two phases to this study: the sound recording and hearing assessment phase and the fish observation phase. The purpose of the first phase was to assess whether or not juvenile salmonids could perceive the sounds of pile driving. Since it was difficult to determine the fish's capability to perceive the sounds of pile driving, the observer phase of the study was initiated in order to measure potential changes in fish distribution and behavior with respect to pile driving.

Sound measurement

Low frequency sound from 20 to 10,000 Hz was measured at the Everett Homeport, with and without pile driving activities at distances of 150 to 1500 m with an ITC model 650-C hydrophone (Fig. 3). Transducer output gain control was modified for low frequencies. Signals were recorded on a portable sound recording unit (Sony Professional Walkman®), analyzed with a Hewlett-Packard 3561 spectrum analyzer, and plotted with a Hewlett-Packard model 7470A two pen plotter.

Sound pressure level was calibrated in terms of a logarithmic measure, the decibel, relative to a reference pressure of one μPa [1 μPa $=10^{-6}$ Pa $=10^{-6}$ Nm^{-2} $=10^{-5}$ μbar $=10^{-5}$ dyne/cm^{2}]. SPL is expressed as:

$$\text{SPL} = 20\log_{10} p/p_{ref}$$

where p is the pressure in Pa, and p_{ref} is the reference pressure of 1 μPa. SPL was normalized to a bandwidth of 1 Hz and units expressed as dBs re: 1 μPa. Instrument output was in dBV, and was converted to dBs re: 1 μPa using:

$$\text{SPL in dBs re: } 1\ \mu\text{Pa} = \text{dBV} - \text{gain} + 157 - 10\log_{10}(\text{bandwidth})$$

where gain = a function of the recording equipment settings, in dB,
157 = the hydrophone constant in dBV/μPa, and
bandwidth = a function of the frequency range sampled, in Hz.

The analysis window was 160 ms for analyzing the transients produced by pile driving.

Fish observation

Four observers recorded fish school characteristics. One observer was responsible for both of the rigs. The other three observers stayed along shore. The standardized unit of observation for the mole area was the round. A round consisted of walking slowly around the mole starting either at the elbow of the mole or the mouth of the Snohomish River (Fig. 3). A round typically took 60 min to complete. The relative position of fish schools were categorized into 14 zones each 36 m long with a total of 512 m of shore covered per round.

Observations on the two pile driving rigs were standardized in time by spending one hour on each rig, alternating between the rigs. The locations of fish schools were categorized for each rig (Fig. 5).

Fish presence/absence, distributions about the mole and rigs, school size, distance from shore or rig, water depth, direction of migration, and general behavior were monitored from March 24 to June 15, 1990. Fish behavior was also recorded on a camcorder (JVC model GF-500U). Information on cloud cover, air temperature, wave height, precipitation, wind speed and direction, time of day, salinity, and tidal stage, was also noted. Salinity/temperature profiles were measured at various sites and times with a YSI (model 33) CTD meter.

Presence/absence of fish was characterized by the number of schools spotted per round of the mole or per hour on each rig, with and without pile driving. Presence/absence as a function of salinity was also determined. The mean number of fish schools spotted per round for Julian dates 123, 124, 127, 128, 134, and 135 was calculated. Presence or absence of fish schools as a function of salinity at the skiff dock and main pier (within 3 m of shore) for Julian dates 114, 115, 136, 137, 138, 141, and 142 was determined. The mean number of schools sighted per round of the mole or hour on a rig for each day were determined in order to illustrate changes in school abundance over time.

In order to test for changes in fish school distributions on the mole, raw fish school sightings were normalized by converting into a fraction of the total observed. For example, if 15 schools were observed along the cove side and 5 along the construction side, the fraction of fish schools on the cove side to construction side was 0.75 to 0.25. Julian dates 116, 120, 121, 122, 123, 124, 127, 128, 129, 130, 134, 135, 136, and 137 were used for this analysis.

School size was characterized as 10's, 100's, or 1000's. A comparison was made on the distributions of school size for Julian dates 116, 117, 123, 124, 127, 128, 130, 131, 134, and 135 at the cove and construction side of the site, and, on Julian dates 109, 110, 116, 117, 123, 124, 127, 128, 130, and 131 at the two rigs. Since mean fish school size was bimodal over the study period, school size data for the peak of the outmigration with back-to-back comparisons of pile driving/non-pile driving days was used. Mean school size per day was plotted in order to illustrate changes in school size over time.

Behavior was categorized as: polarized, active milling, and passive milling (Fig. 6). Polarized behavior was characterized by fast (>1 bls) swimming in one direction. Active milling was characterized by slow (<1 bls) swimming in one direction. Passive milling fish exhibited no net movement, and were diffuse. Data from Julian dates 89-143 were used.

Migration direction was categorized as north, east, west, south, or stationary/unknown. North or south movement was rarely noted along shore, and was not used for analysis. Data from Julian dates 89-143 were used.

Water depth, and distance from shore that fish schools were observed at were compared as a function of pile driving.

Stomach content analysis and fish length

Sub-samples were taken from observed salmonid schools for total length, weight, identification, and stomach content analysis, and keyed to species according to Phillips (1977).

A regression was performed on pink and chum salmon TL over time and 95% confidence intervals generated. Fish were sampled with either a dip net from shore, or with the 10 m beach seine at the skiff dock, mole elbow, or main pier. Total length of pink and chum salmon was also compared for pooled data, since neither species exhibited a significant increase in size over time.

Fish targeted for stomach content analysis were sampled from the skiff dock and carrier pier on 5/17/90 with a dip-net (3 m from shore, 0.5-1.5 m water depth), the DB Pacific on 5/18/90 with a purse seine (115 m from shore, 18 m of water) and near Howarth Park at Port Gardner on 5/25/90 with a 33 m beach seine (0-10 m from shore, 0.5-1.5 m water depth). Captured fish were sacrificed by placing directly into 30% formalin, fixed for one week, washed in freshwater for 24 h, and transferred to 30% ethanol. Fish were blotted and weighed, measured, and identified after the washing stage. Stomach fullness, predator and prey weight, prey number and identification, and digestion stage were determined for each fish. Since stomach contents data was only collected once at these four sites, statistics other than means and SD's were not possible. The various prey items were plotted as a function of fraction of abundance by number in the stomachs of pink and chum salmon sampled. In addition, the means of number of: prey types, number of prey per stomach, predator weight, stomach fullness, prey weight, stomach weight, predator TL, predator TL to weight ratio, and stomach weight to predator weight ratio were plotted for qualitative comparisons by site and species of predator (see Appendix 2).

Data analysis

In the experimental design, each round about the mole or each hour on a rig were considered replicates for distributions of fish schools. Chi-square analysis was used for the distributions of fish behavior, direction of movement, school size, and locations about the rigs. Unpaired, two-tailed T-tests were used to compare all other effects. All error bars on figures are 1 standard error (SE).

The data were analyzed with StatView SE+ statistical package on an Apple Macintosh computer to compare measured parameters as a function of pile driving effects. Significant effects of pile driving were examined at 0.05 alpha level.

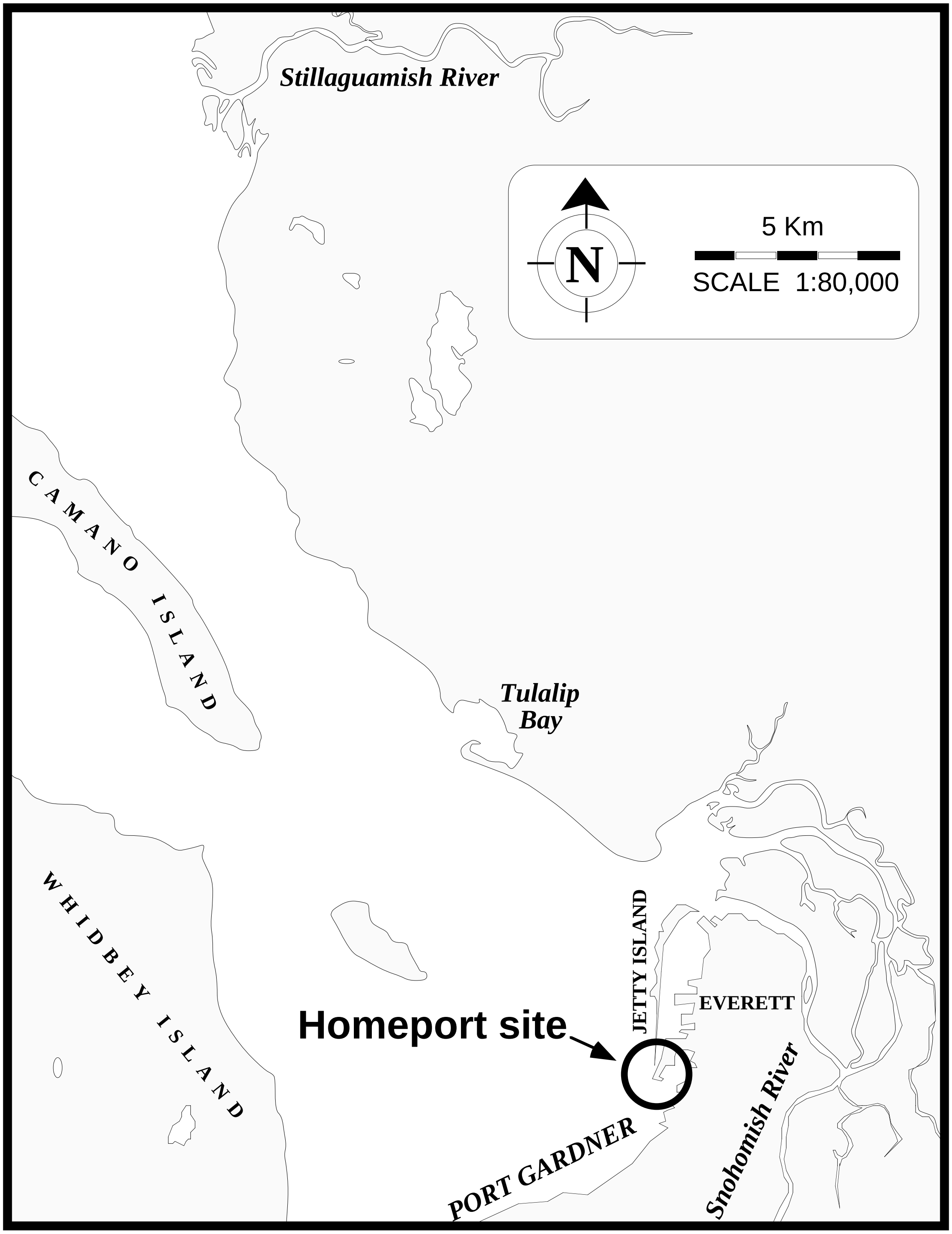

Figure 2. The Everett Homeport site in relation to Tulalip Bay and the Snohomish and Stillaguamish Rivers.

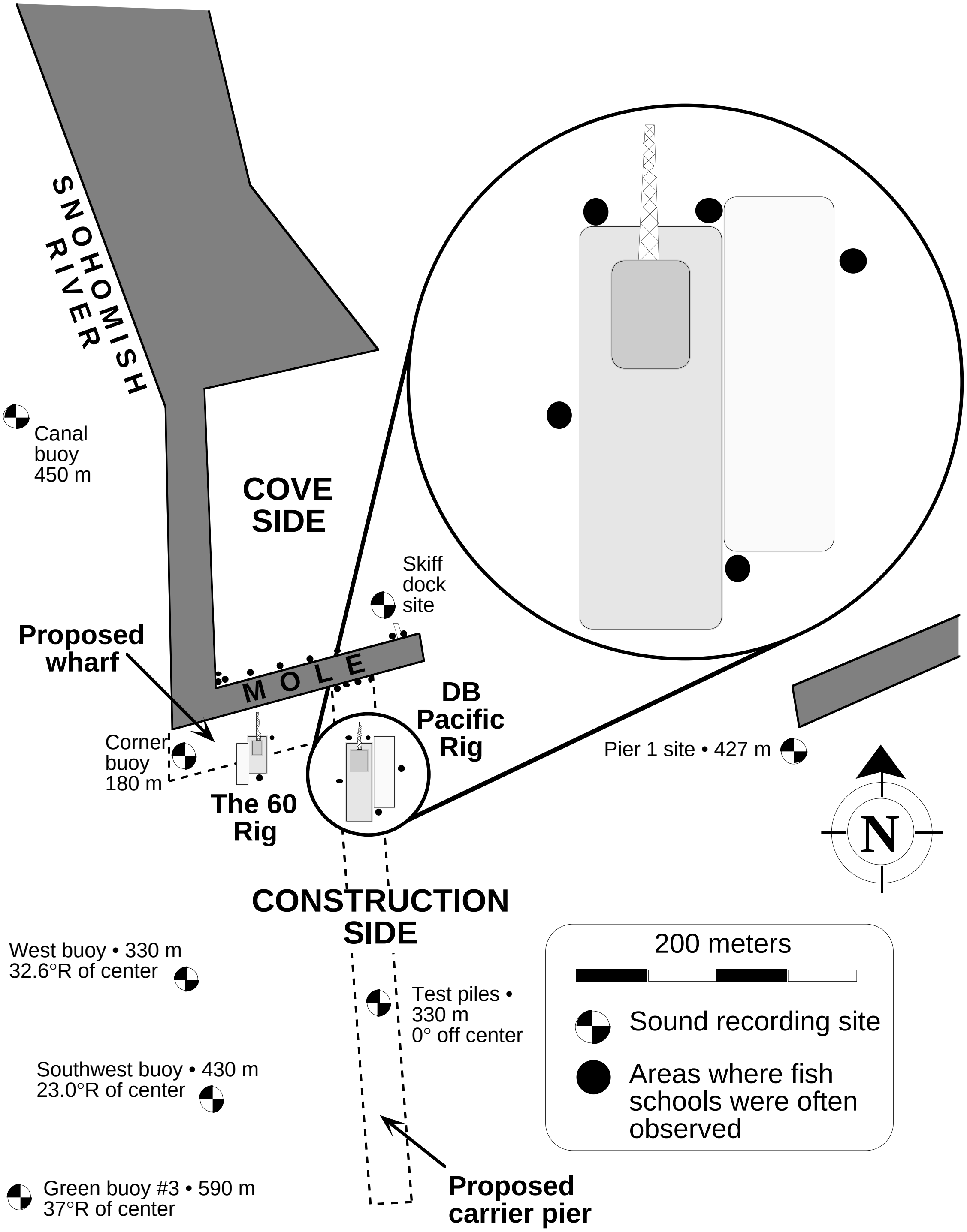

Figure 3. Detail of Everett Homeport site showing sound recording sites and distances, cove and construction side of the mole, and areas where fish schools were often sighted.

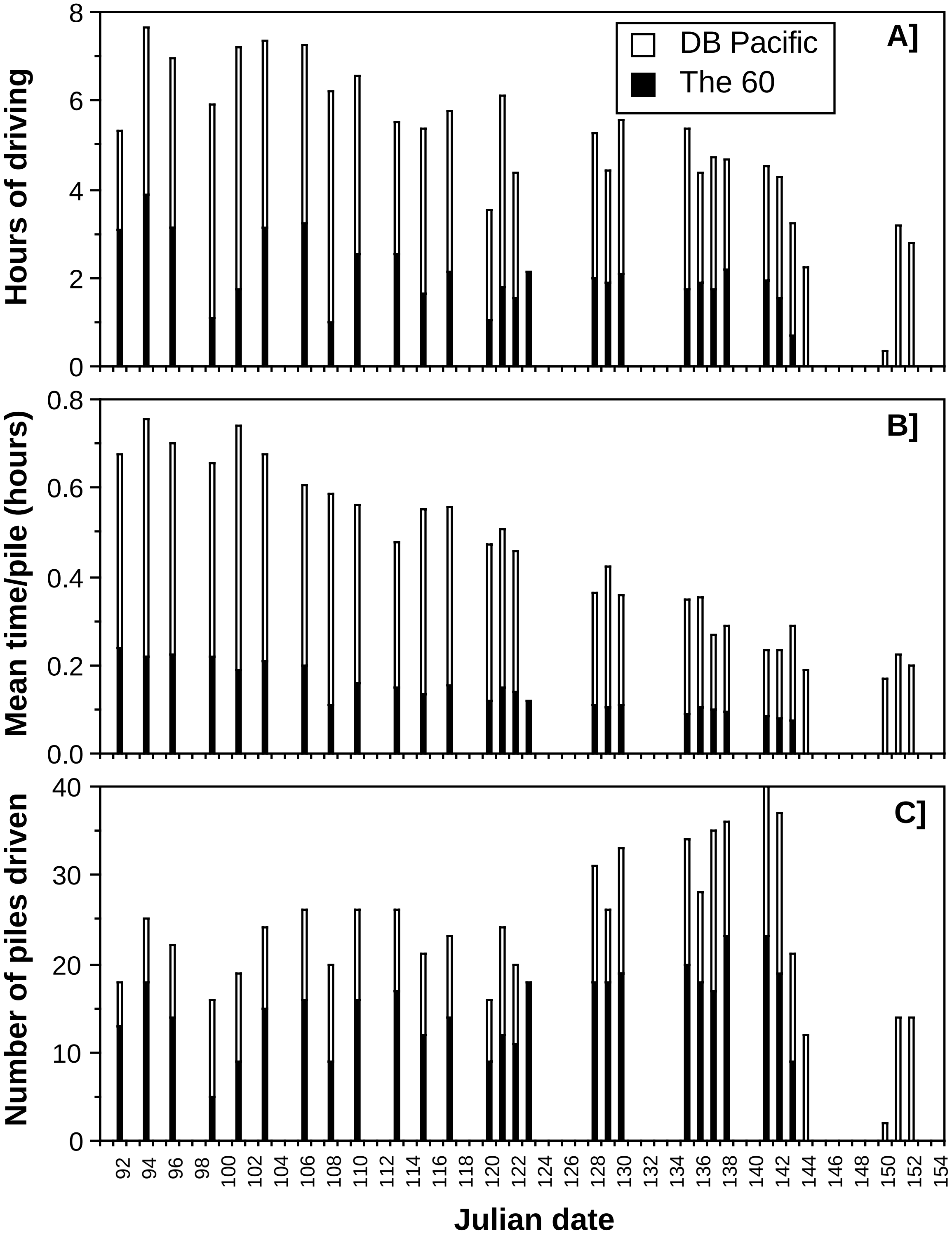

Figure 4. Summary of pile driving at the Everett Homeport, 1990. A] Hours per day that piles were being struck. B] Mean time in hours to drive one pile. C] Total number of piles driven each day.

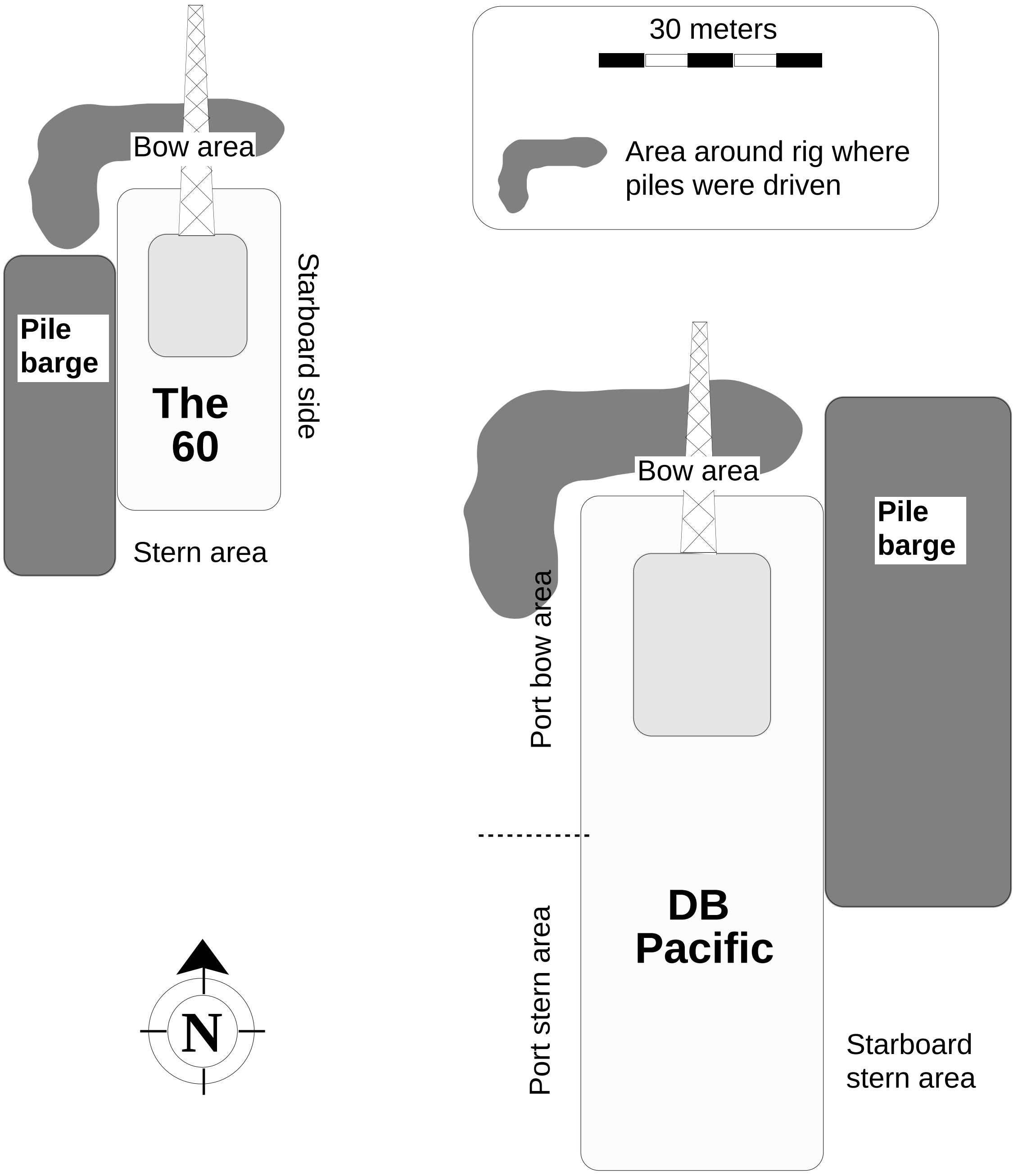

Figure 5. Detail of pile driving rigs (to scale) showing zones where fish schools were spotted, and the area around each rig where pile driving occurred.

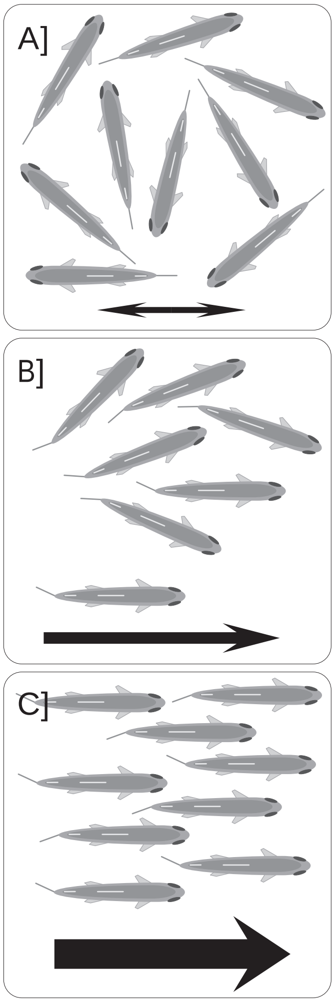

Figure 6. The three fish behaviors. A] Passive milling: no net movement. B] Active milling: slow net movement. C] Polarized: fast net movement.

RESULTS

A total of 343 man-hours were spent observing fish schools at the Everett Homeport from March 30-June 15, 1990: 173 hours along shore, 103 hours on the DB Pacific, and 67 hours on The 60. Seven-hundred and forty schools were sighted along shore, with 50% arriving by May 8, and 90% by May 24 (Fig. 7). Two-hundred and thirty three schools were spotted about the rigs: 145 near the DB Pacific, and 88 for The 60.

Qualitative/general observations

Greater than 95% of fish schools observed were juvenile pink and chum salmon. Observers could easily recognize parr marks on chum salmon, or the green shimmer of pink salmon as the schools milled at or near the surface of the water because schools were rarely >30 cm below the surface. In addition, pink and chum salmon were the only surface oriented species observed in samples from dip nets or beach seines at the site. Most schools sampled with dip nets or beach seines contained both pink and chum salmon in a ratio of approximately 2:1.

Most fish schools were found near the carrier pier or the skiff dock (Fig. 8), and any structure in the water such as piles, docks, and the pile driving rigs, seemed to attract schools of fish. For example, schools could be drawn away from shore by approaching them slowly with a skiff and then drifting away from shore with the school remaining next to the skiff. We rarely observed schools passing under objects such as work skiffs or even logs. They would either stop moving once they encountered the floating object or move around it.

Western grebes (*Aechmorphorus occidentalis*) were prevalent at the site, and their presence corresponded positively with the abundance of juvenile pink and chum salmon at the sight from Julian dates 110-125 (Fig. 9). On numerous occasions, these diving birds were spotted with small fish in their beaks upon surfacing next to a rig. However, this correlation was absent between Julian dates 128-142 when fish schools demonstrated their second peak of abundance.

Overall, <5% of the fish at all sites had empty stomachs. Pink and chum salmon sampled at the skiff dock, main carrier pier, and the DB Pacific were primarily feeding on Calanoida, a more pelagic prey item (>95% by abundance, Fig. 10). In contrast, pink and chum salmon sampled at Port Gardner (see Fig 10), had a more epibenthic and varied diet, primarily feeding on *Tisbe* spp. Juvenile chum salmon were longer than pink salmon, and TL of the two species did not change significantly over time (Fig. 11). Juvenile pink salmon sampled from the skiff dock were significantly smaller than those sampled at the DB Pacific (Fig. 12).

Salinity did not appear to affect the presence/absence of fish sampled at the skiff dock (Fig. 13). However, I was not able to compare presence/absence over the whole site as a function of salinity.

Sources of fish observed

I assumed that all of the juvenile pink salmon sampled in my study were wild stocks as there were no pink salmon hatcheries in the study area. I assumed that the majority of chum salmon observed at the site were wild stocks migrating out of the Snohomish River for the following reasons. There were three hatcheries where chum salmon were released in the vicinity of the Homeport (Fig. 2): the Tulalip Tribal Hatchery release, Tulalip Bay (10 Km from the site); Arlington Hatchery on the Stillaguamish River

(>50 Km from the site); and a WDF facility on the Wallace River, a tributary of the Snohomish.

The Tulalip Tribe volitionally released 5.8 million chum from April 26 to May 3 (mean TL on April 23: 57.1 mm, SE=0.297, 660 fish/Kg, 877 Kg total) into Tulalip Bay. Given the significantly smaller sized chum salmon captured at the Homeport site throughout the study, it seems unlikely that any of these hatchery fish could have been observed at the site, certainly not in the nearshore area. Further, Beauchamp et al. (1987), sampling throughout the Port of Everett and Port Susan area, observed increases in chum salmon abundance and mean TL in response to 2.3 million chum salmon released into Tulalip Bay by the Tulalip Tribe. However, the effect was localized to sites within 1 Km of Tulalip Bay, and increases in chum salmon abundance and mean TL were not observed at more distant (>1 Km) sampling areas. The Arlington hatchery on the Stillaguamish River released 99,832 chum on April 13 (855 fish/Kg, 54.7 mm mean TL, reared 73 days). Since these fish were released more than 50 Km from the Homeport, and the total number released was quite low, I assumed there was no effect. The WDF hatchery on the Wallace River reportedly released “negligible” numbers of chum salmon in 1990.

Pile driving statistics

The DB Pacific and The 60 rig drove piles from March 30-June 15, and March 30-May 23, respectively (Fig. 4). There were 47 days of pile driving and 17 days of non-pile driving during this period. However, the majority of fish school observations were made between Julian dates 120 and 140, a period during which there were 11 pile driving and 4 non-pile driving days. Pile driving rigs struck piles about 50 times per minute, and the average pile took 10 to 15 minutes to drive (Fig. 4). The entire process for driving one pile usually took 30-60 minutes, depending on sediment type and pile length. The amount of time each day spent striking piles was relatively constant throughout the study period (Fig.

4). However, the number of piles driven each day slowly increased over time since the mean time to drive any given pile decreased over time (Fig 4).

The acoustic environment

The results of the acoustic sampling phase of this study are incomplete. Lack of funding and gear malfunction prevented completion of both sampling and analysis stages of the study. Based on the limited data available, SPLs were up to 25 dB above ambient levels, at a range of 593 m from the DB Pacific (Fig. 14).

Fish abundance over time

Although the outmigration appeared unimodal based on the number of schools spotted per round of the mole, an estimate of the total number of fish spotted per day based upon the mean size of fish schools, suggests the outmigration was bimodal (Fig. 15). On both of the construction rigs, there were no peaks in the number of schools sighted or in fish school size. Schools simply were not spotted on the DB Pacific after Julian date 152 (Fig. 16). Observations ceased on The 60 rig on Julian date 143 because the rig had finished its project.

Effects of pile driving on measured variables

Out of the 973 schools observed, one school responded to the initiation of a pile being driven at close (10 m) or long (100-200 m) range. Indications of a response were “starting” or “flashing” at the the onset of pile driving.

There were more schools spotted per round of the mole on non-pile driving days (14.1) compared to pile driving days (11.9), but this difference was not significant (Fig. 17). However, there were significantly more schools spotted on the each of the rigs per hour on non-pile driving days compared to pile driving days (Fig. 18).

The ratio of number of schools on the cove side to number of schools on the construction side of the mole was about 2:1 on pile driving days and 1:1 on non-pile driving days (Fig. 19), and this difference was significant. The distributions of fish schools changed as a function of pile driving on The 60, but not on the DB Pacific rig (Fig. 20).

Fish schools about the mole were usually 2 m from shore in about 1.2 m of water. There were no significant differences in distance from shore or water depth as a function of pile driving.

Pile driving significantly affected the size of fish schools present on the construction side, but not on the cove side (Fig. 21). However, neither of the pile driving rigs showed differences in fish school size distributions with and without pile driving (Fig. 22).

The Chi-squared distributions of the three fish behaviors changed significantly in response to pile driving on the construction side of the mole, but not on the cove side (Fig. 23). Fish behavior was not significantly different between the two rigs, so the data were pooled and there was a significant difference in the distributions of fish behavior as a function of pile driving (Fig. 24). Cloud cover had a significant effect on the distributions of fish behavior on the cove side, but not on the construction side. Tidal stage had no effect on the distributions of shoreline fish behavior. Cloud cover, time of day, and tidal stage did not affect the distributions of fish behavior on either of the two rigs.

There was a significant difference in the distributions of fish school direction of movement as a function of pile driving on the cove side of the mole, but not on the construction side (Fig. 25). There were no significant differences in the distributions of fish school direction of movement on either of the rigs (Fig. 26). Cloud cover significantly altered the distribution of fish school direction of movement on both sides of the construction site, but tidal stage had no effect on the distributions of fish school movement.

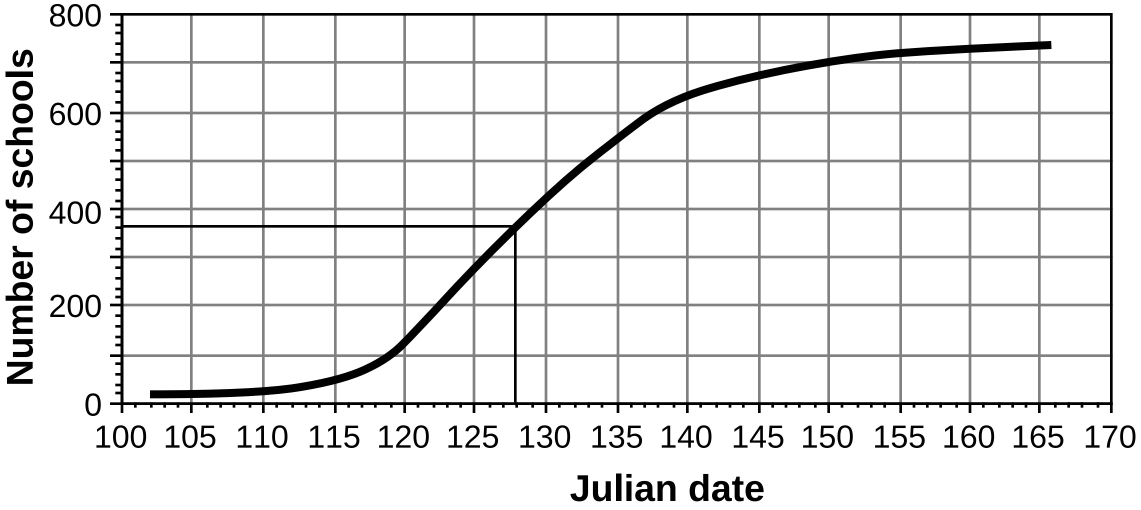

Figure 7. Cumulative number of schools spotted from the shoreline (mole) at the Everett Homeport, 1990. Added lines mark the date at which 50% of the schools had passed.

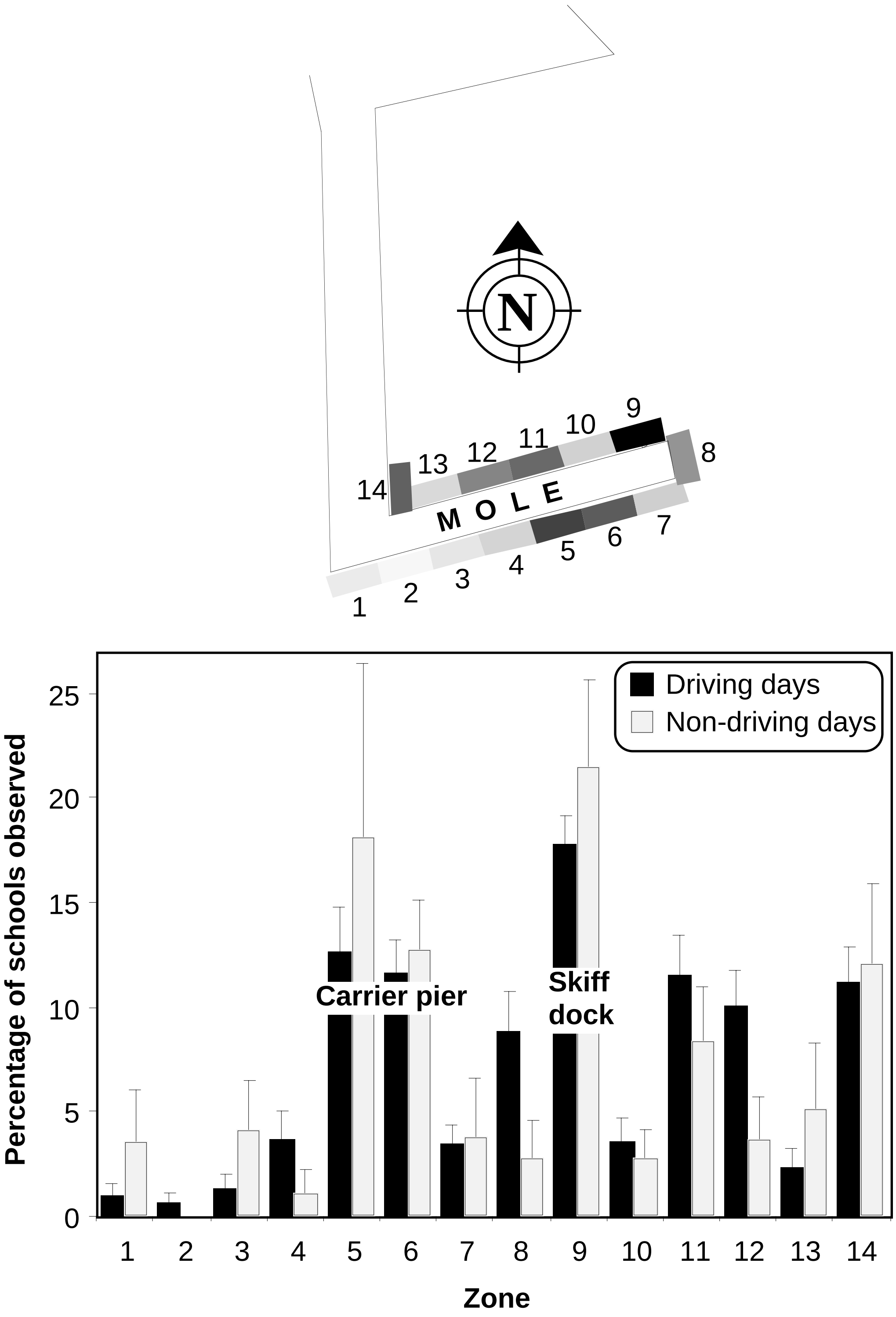

Figure 8. Overall frequency distribution of number of fish school observations for each of the 14 zones along the mole at the Everett Homeport. Intensity of grey-scale on map corresponds to the number of schools sighted.

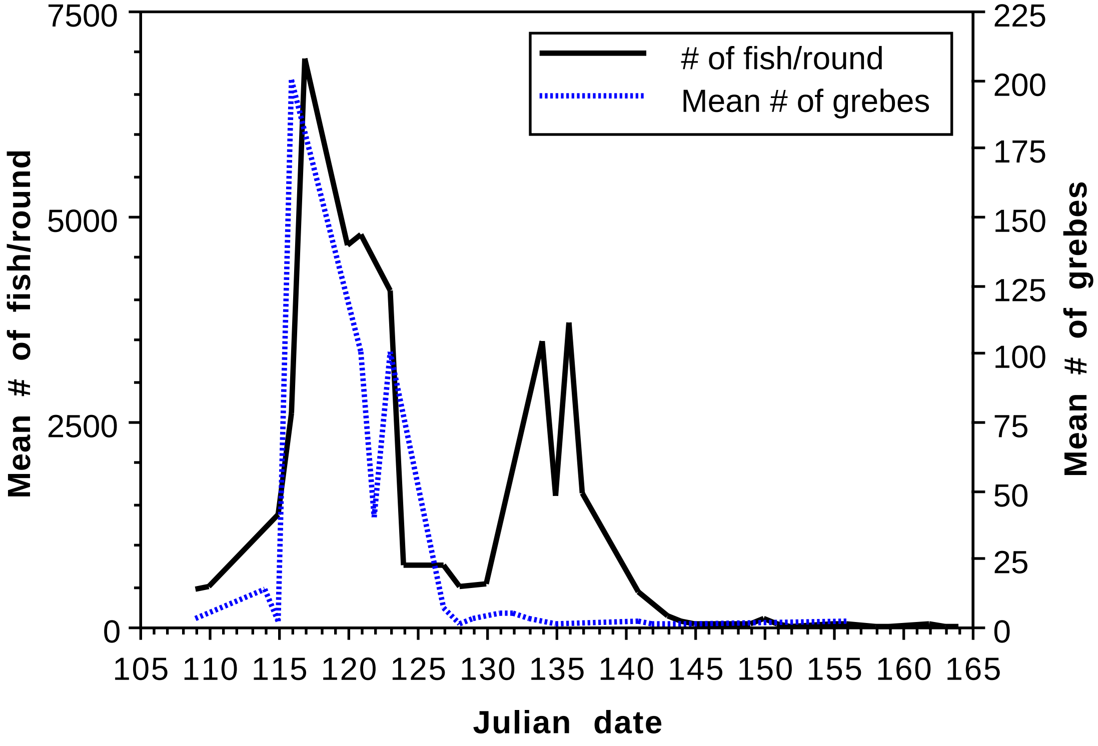

Figure 9. Number of fish spotted per round of the mole and number of grebes spotted near the construction site over time.

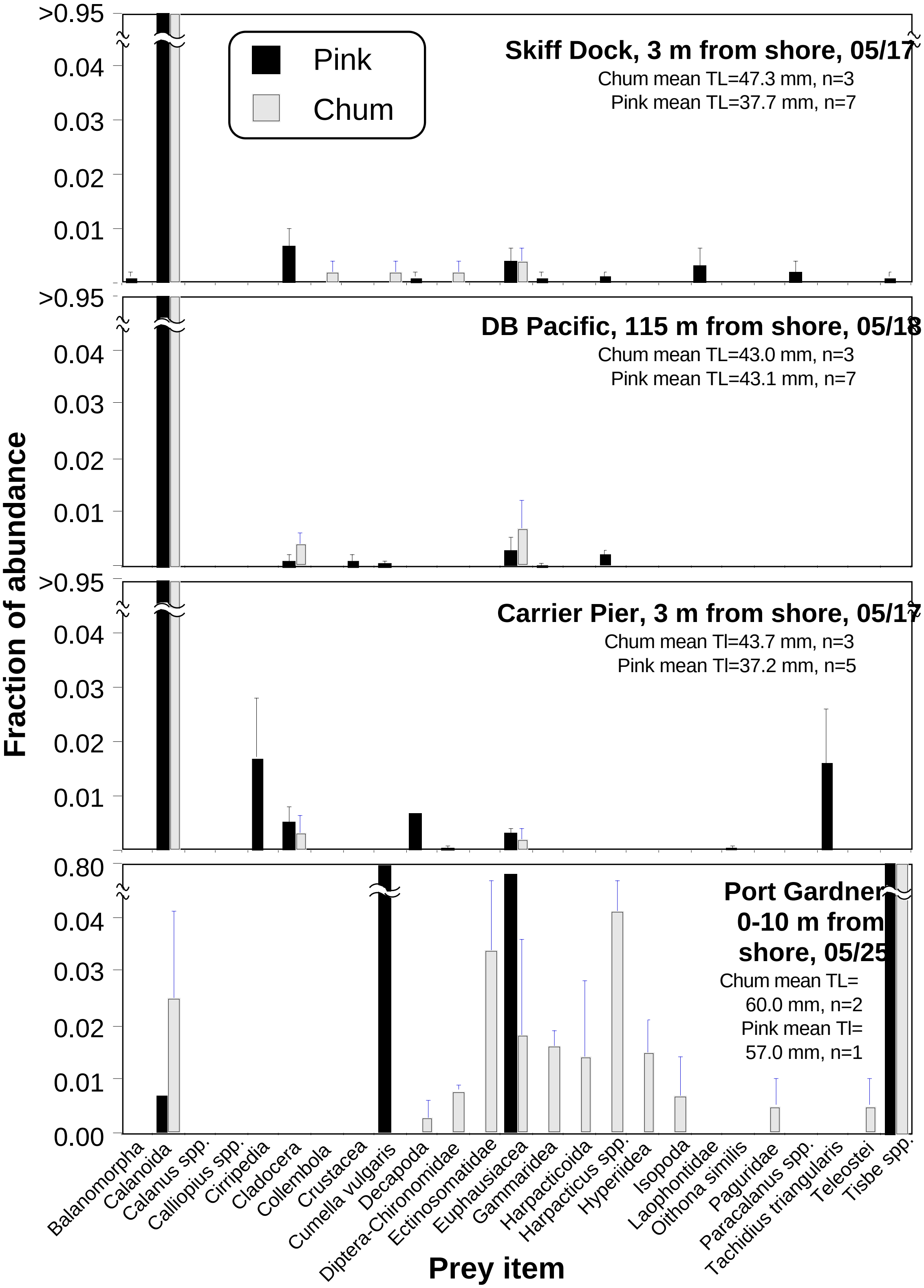

Figure 10. Distribution of prey items from stomachs of juvenile pink and chum salmon captured at the Everett Homeport site, 1990.

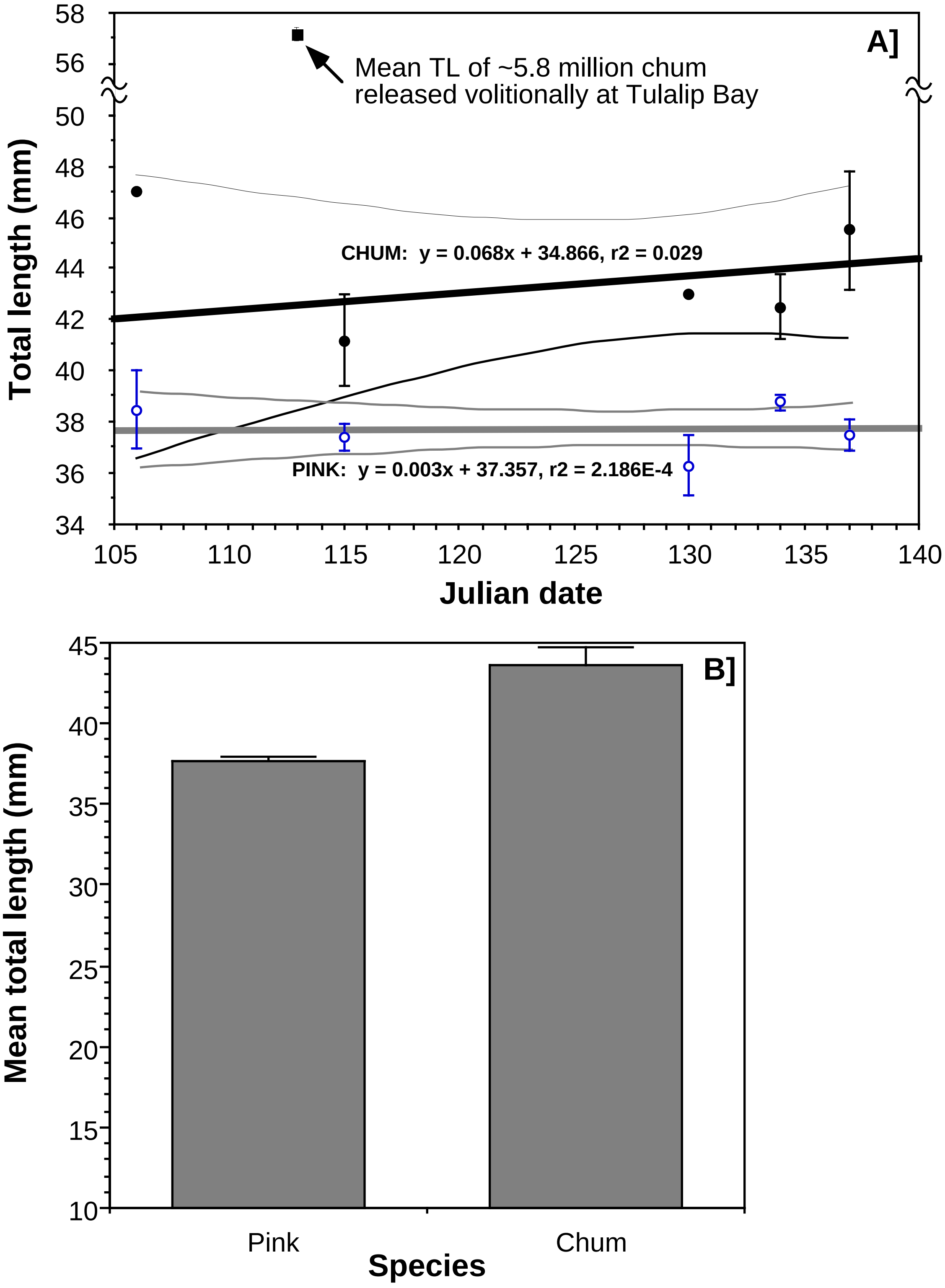

Figure 11. A] Change in total length of juvenile pink and chum salmon over time with 95% confidence intervals. B] Mean total length of pooled pink and chum salmon samples at the Homeport site, 1990 (p=0.0001).

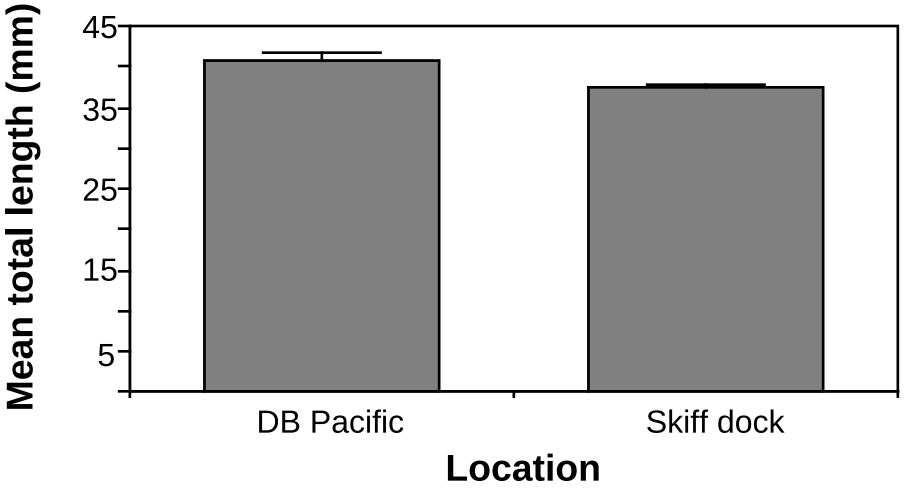

Figure 12. Mean total length of pink salmon sampled at the skiff dock versus the DB Pacific (p=0.002).

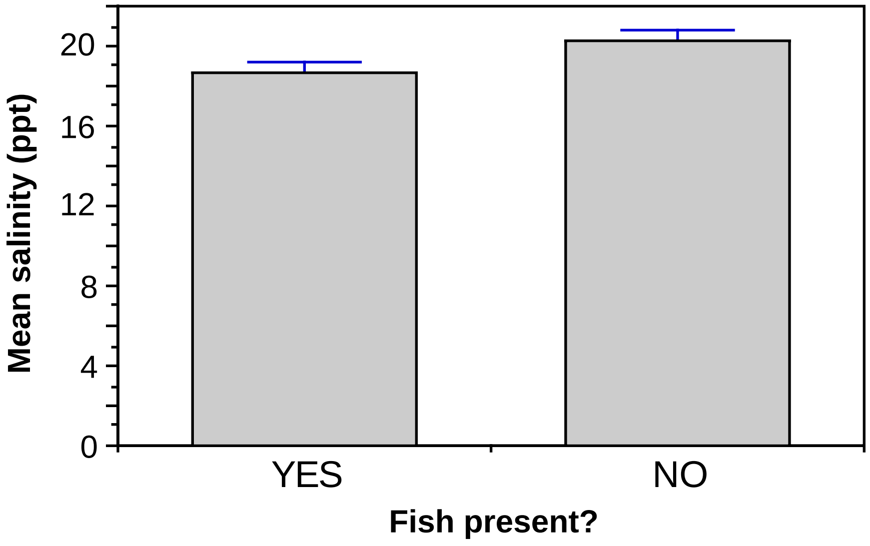

Figure 13. Fish presence at the skiff dock as a function of salinity (p=0.089).

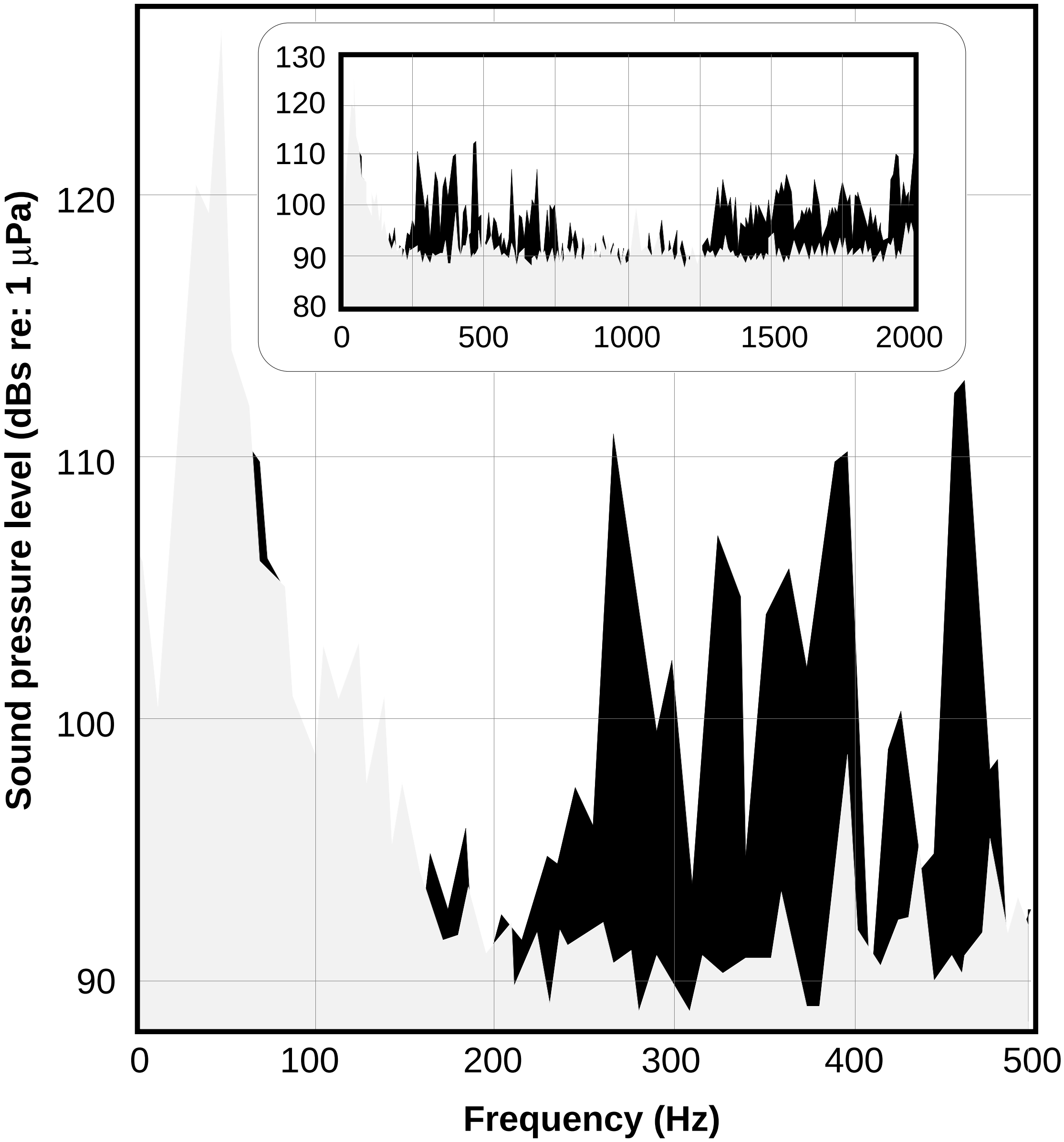

Figure 14. The acoustic environment 593 m from the DB Pacific, hydrophone at 1.5 m water depth. Black is pile driving noise, grey is ambient.

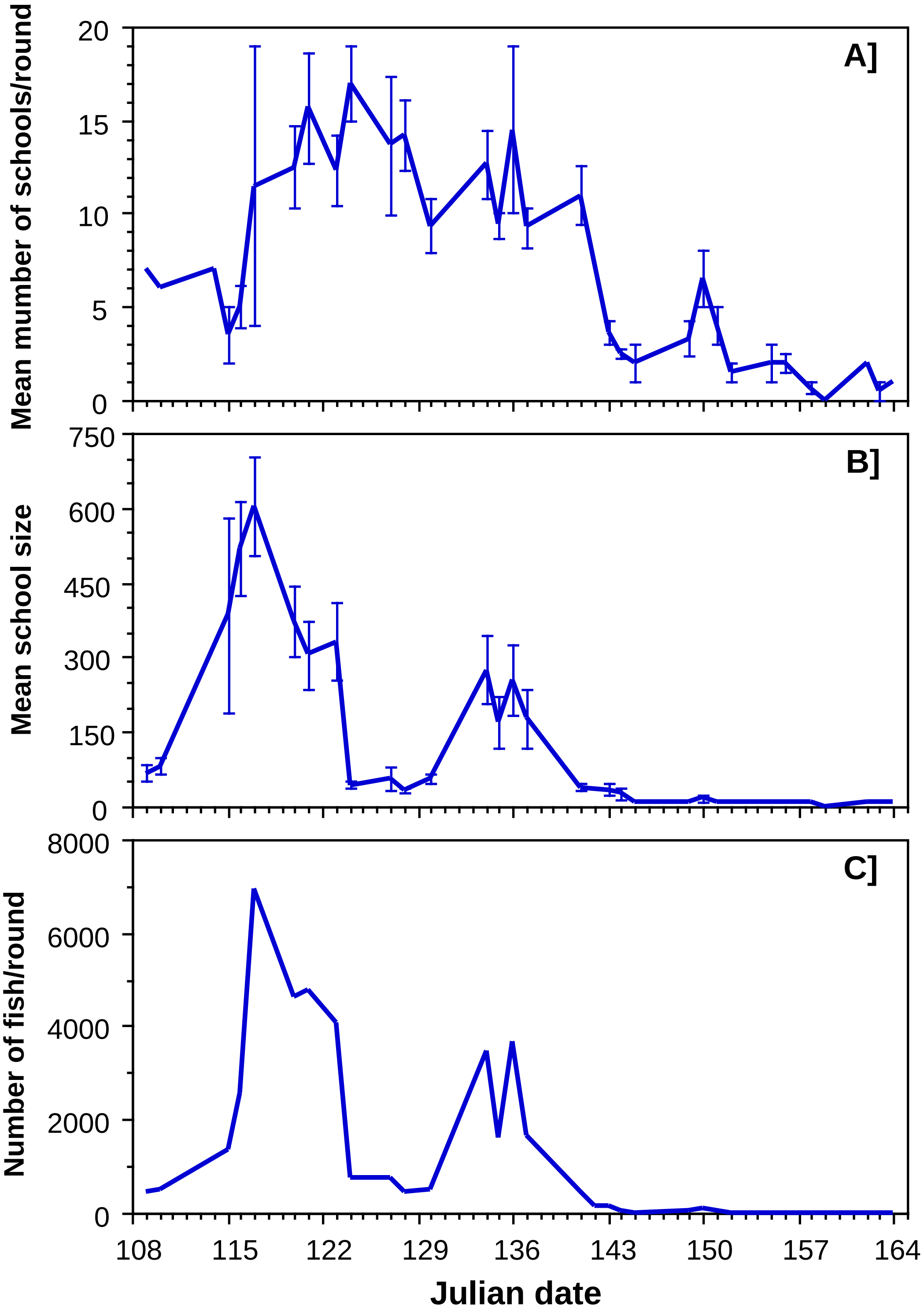

Figure 15. Abundance of juvenile pink and chum salmon over time along the shore at the Everett Homeport, 1990. A] Mean number of schools per round. B] Mean school size per round. C] Estimated number of fish per round.

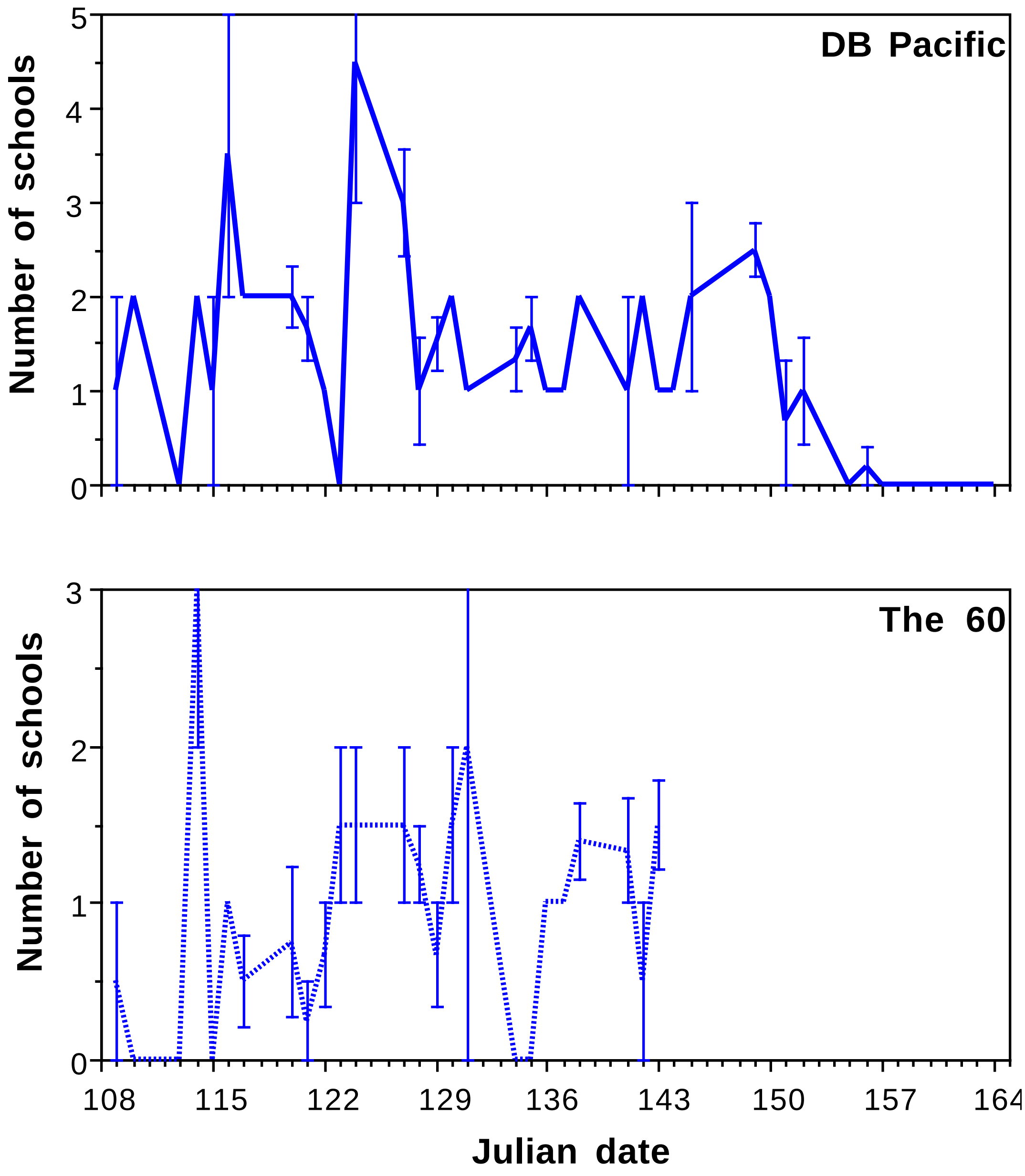

Figure 16. Mean number of schools sighted per hour on the DB Pacific and The 60 rigs over time.

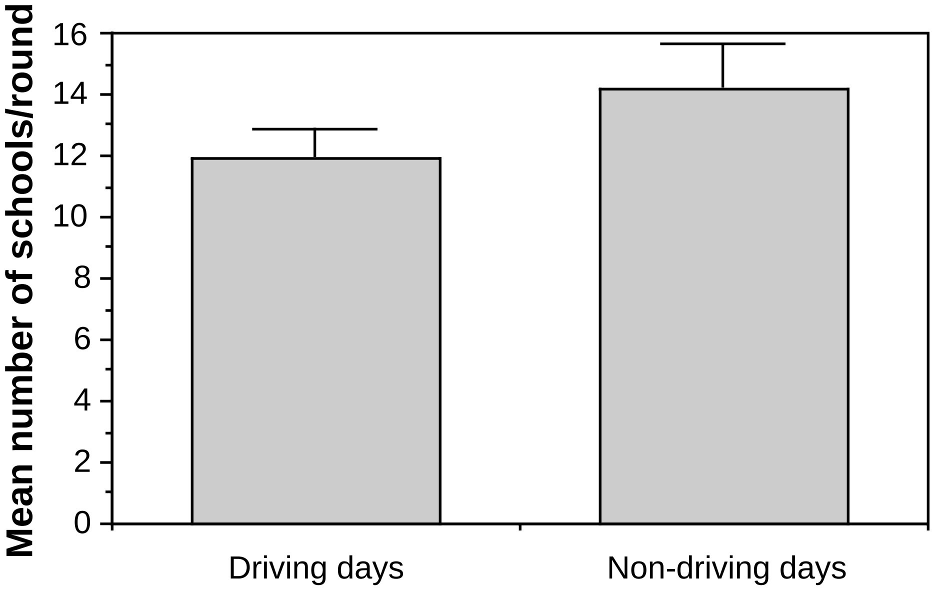

Figure 17. Mean number of schools/round at the Everett Homeport with and without pile driving (p=0.228). Julian dates 123/124, 127/128, and 134/135.

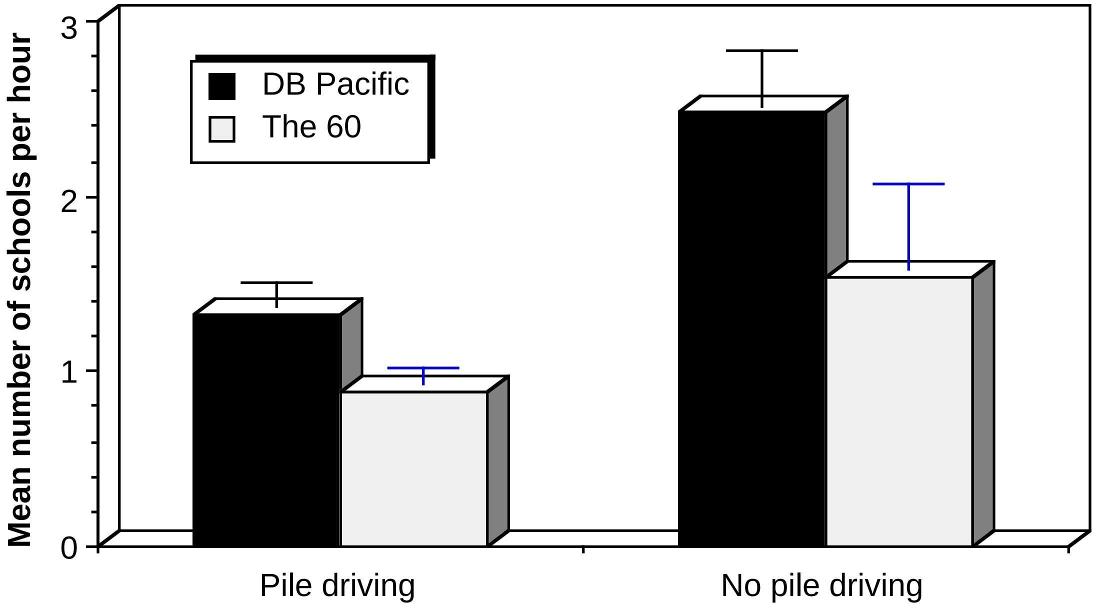

Figure 18. Mean number of schools sighted per hour on both pile driving rigs at the Everett Homeport, 1990. Julian dates 109-143. DB Pacific: p=0.0003, The 60: p=0.041.

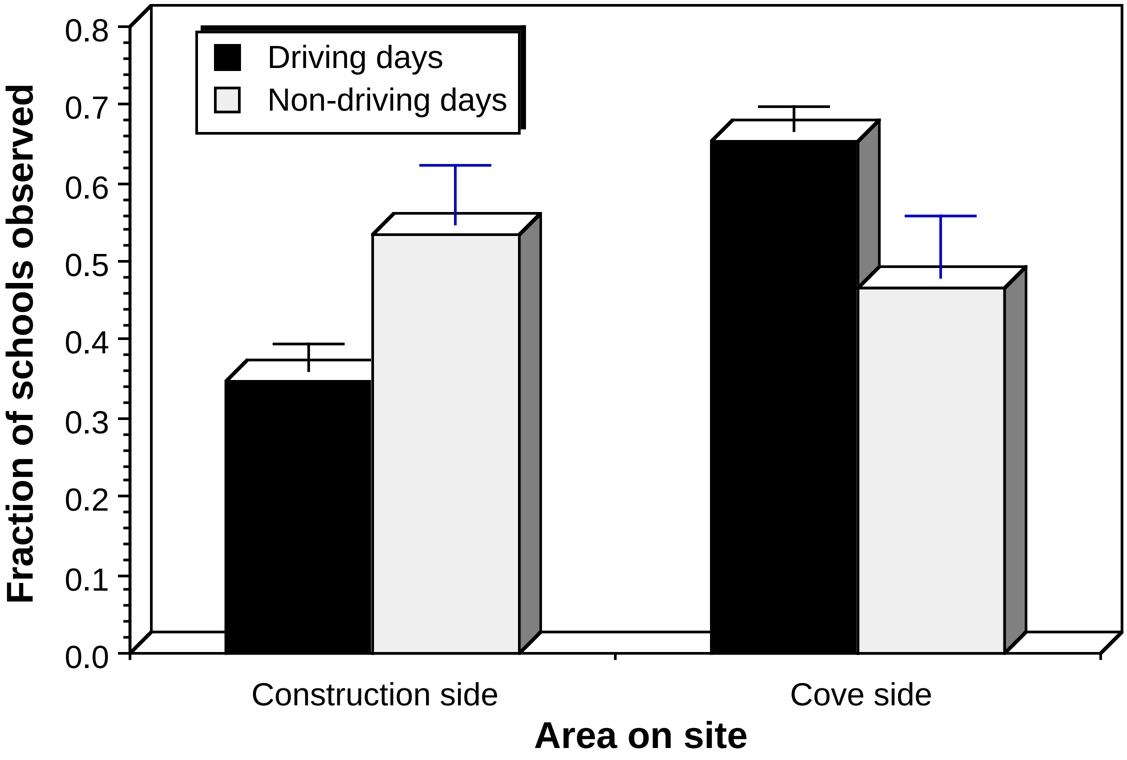

Figure 19. Distribution of fish schools on each side of the mole for Julian dates 116, 120-130, and 134-137 (p=0.015).

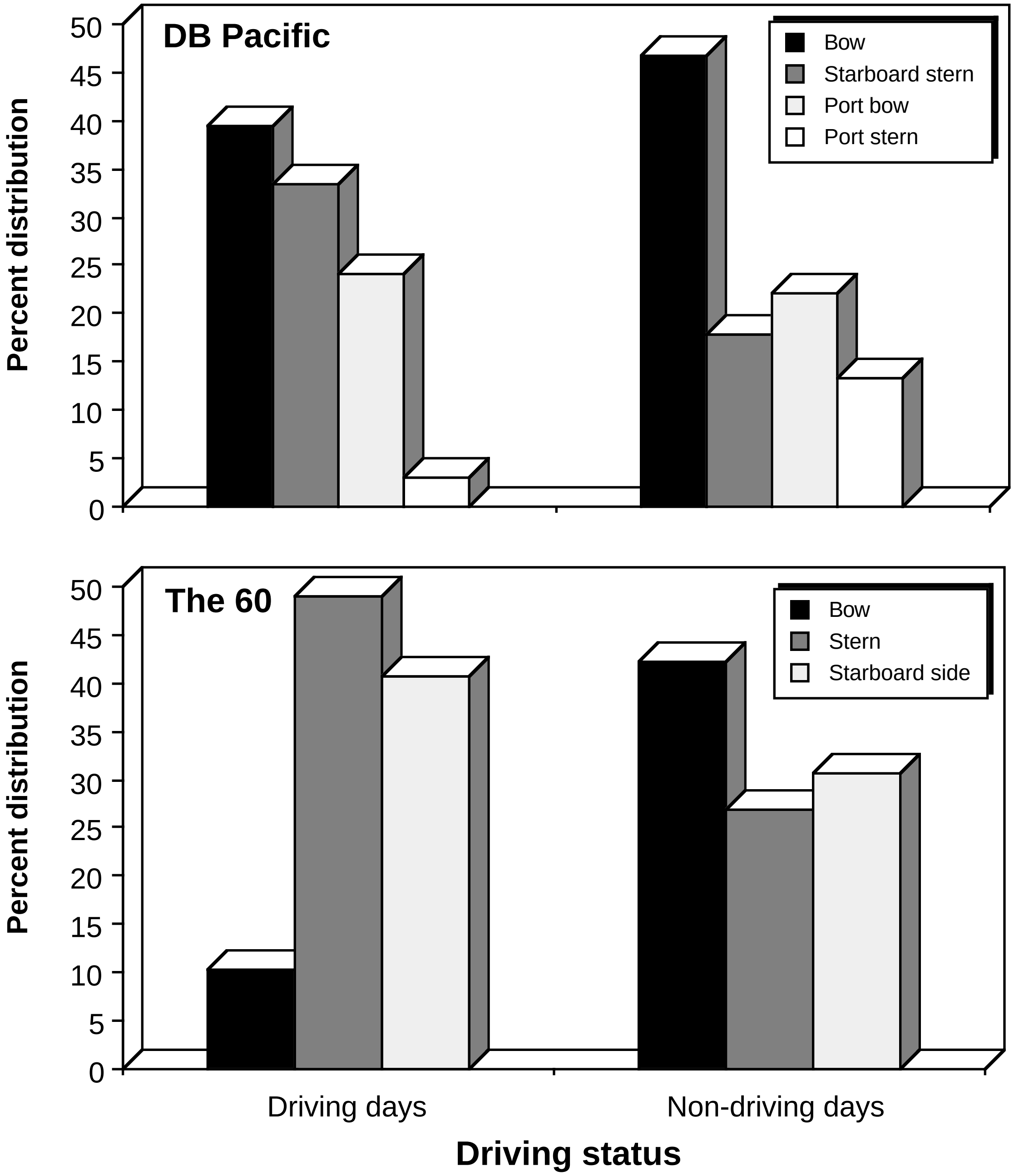

Figure 20. Distributions of fish schools about the DB Pacific and The 60 rigs. No rainy days, one observer only. DB Pacific: total Chi-square=6.717, p=0.081. The 60: total Chi-square=10.665, p=0.005.

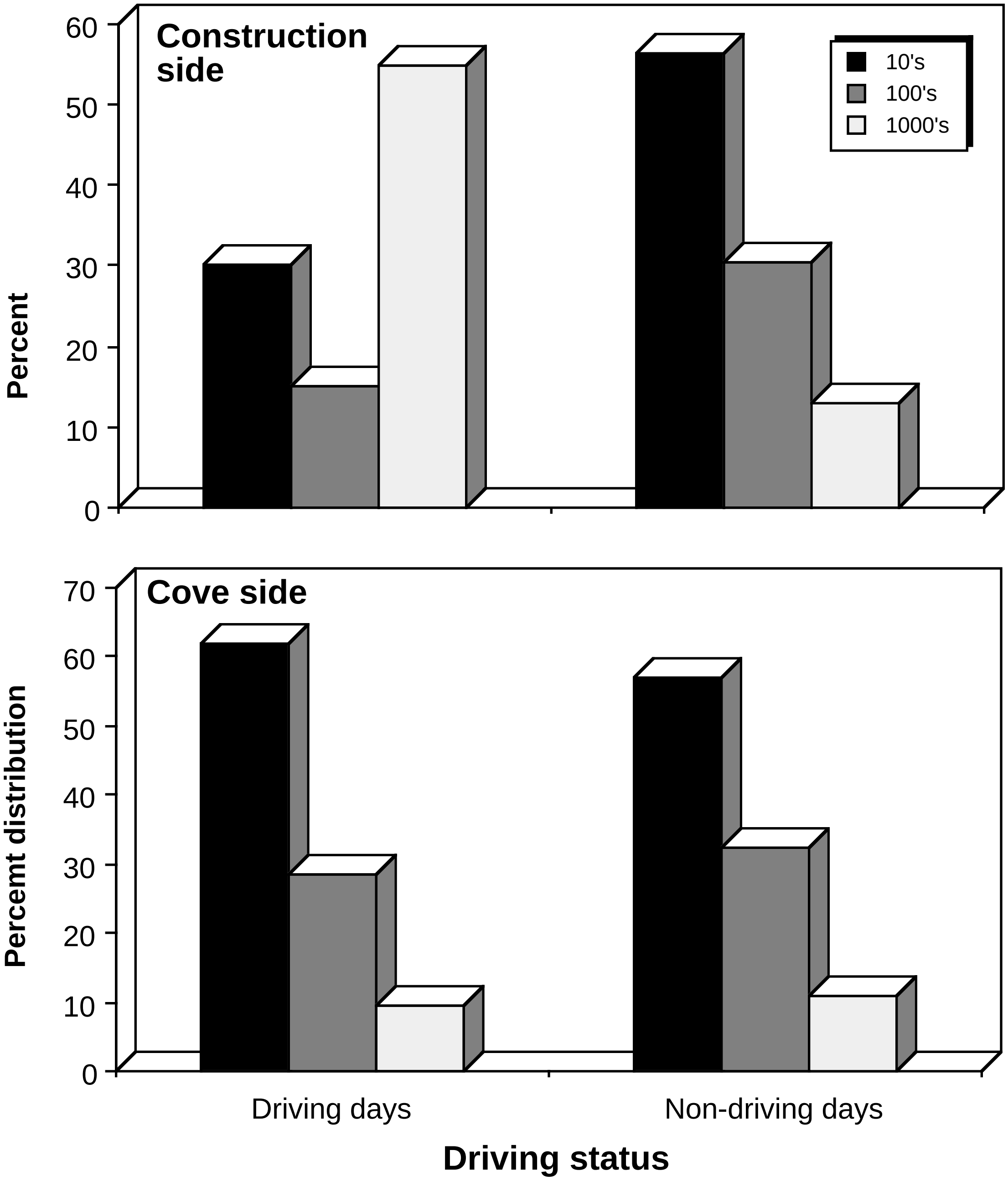

Figure 21. Distribution of fish school sizes with and without pile driving for each side of the mole. Julian dates 116, 117, 124, 127, 128, 131, and 134, no rainy days. Construction side: total Chi-square=12.838, p=0.002. Cove side: total Chi-square=0.162, p=0.922.

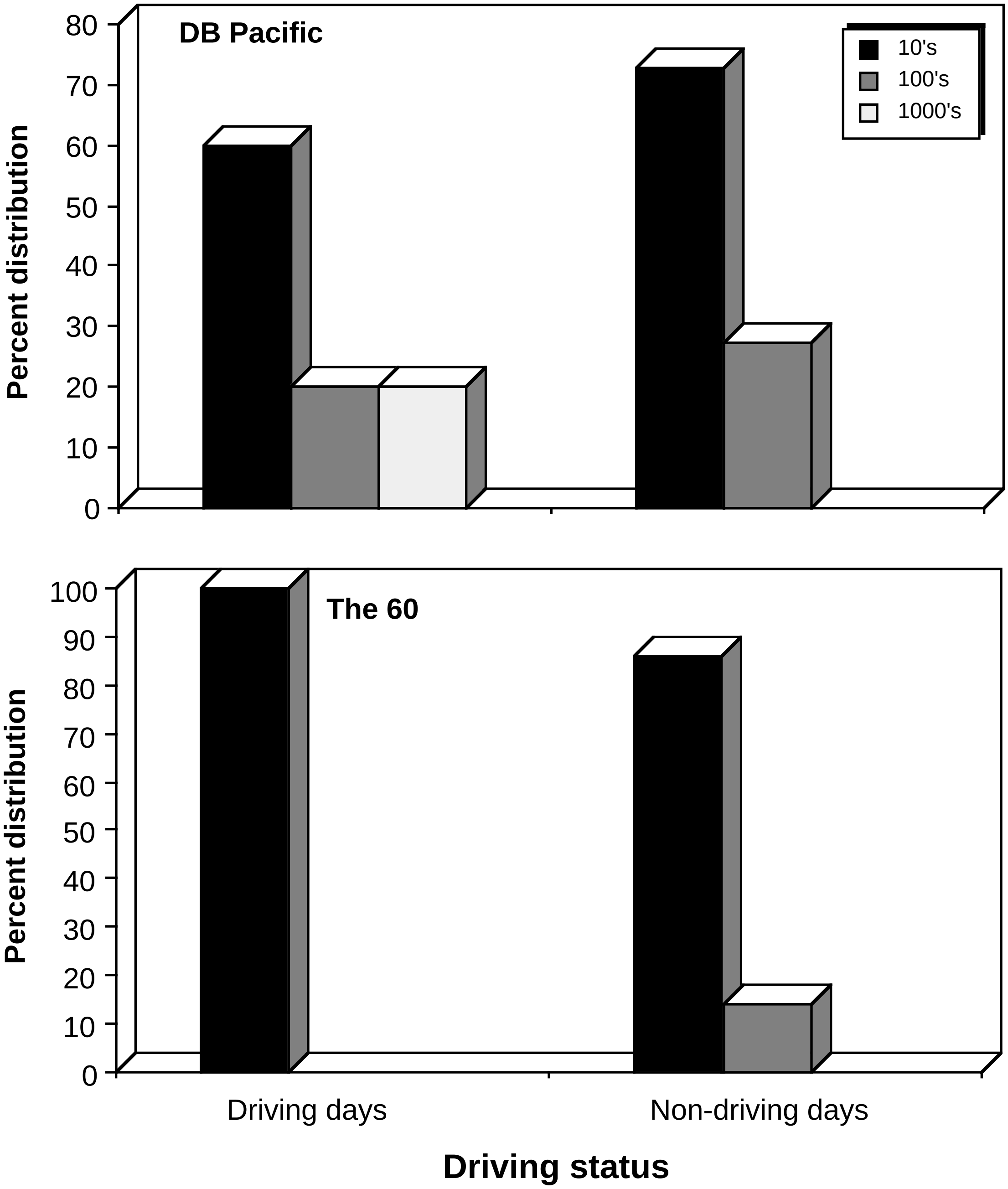

Figure 22. Distribution of fish school size around the DB Pacific and The 60 rigs with and without pile driving. Julian date 109/110, 116/117, 123/124, 127/128, 130/131, one observer, no rainy days. DB Pacific: total Chi-square=4.707, p=0.095. The 60: total Chi-square=2.154, p=0.142.

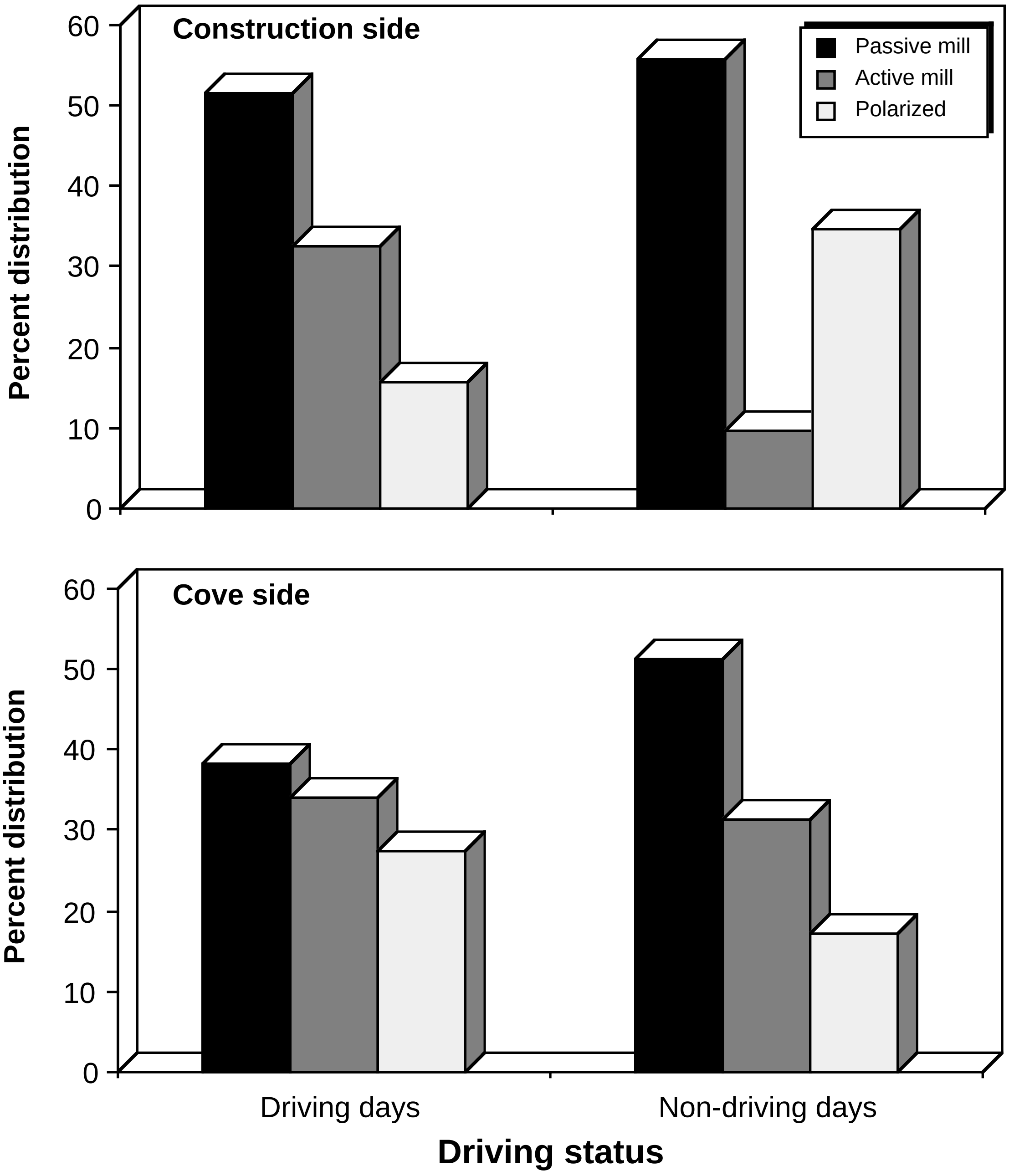

Figure 23. Distributions of fish behavior with and without pile driving on the construction side and cove side of the mole. Julian dates 89-143, no rainy days Construction side: total Chi-square=12.442, p=0.002. Cove side: total Chi-square=4.025, p=0.134.

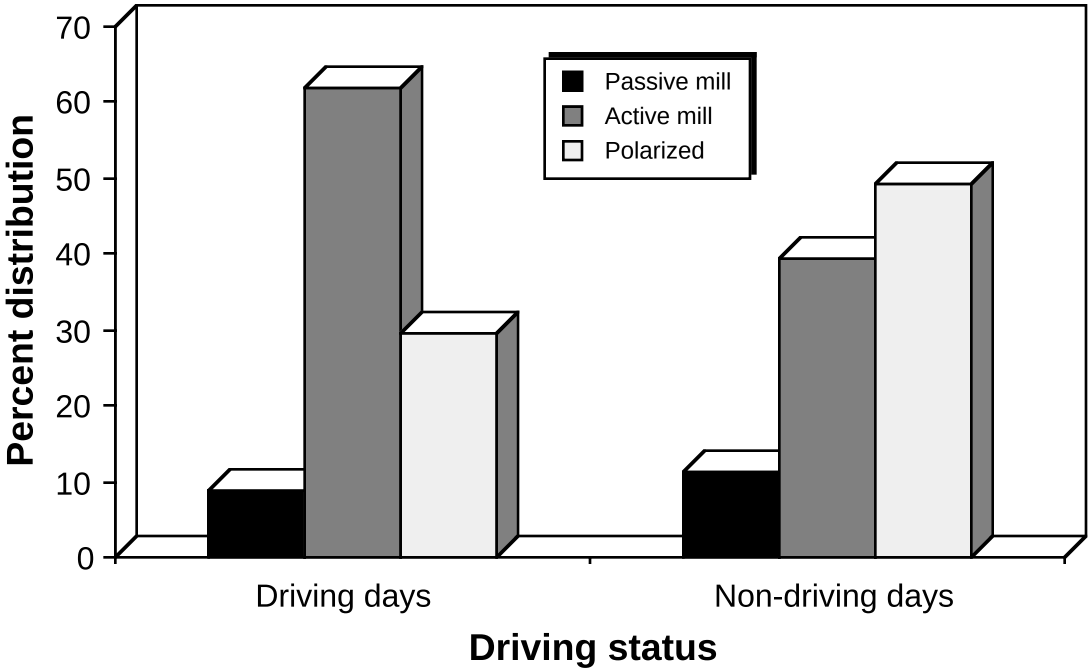

Figure 24. Distributions of fish behavior with and without pile driving on both pile driving rigs. No rainy days, one observer. Total Chi-square=9.009, p=0.011.

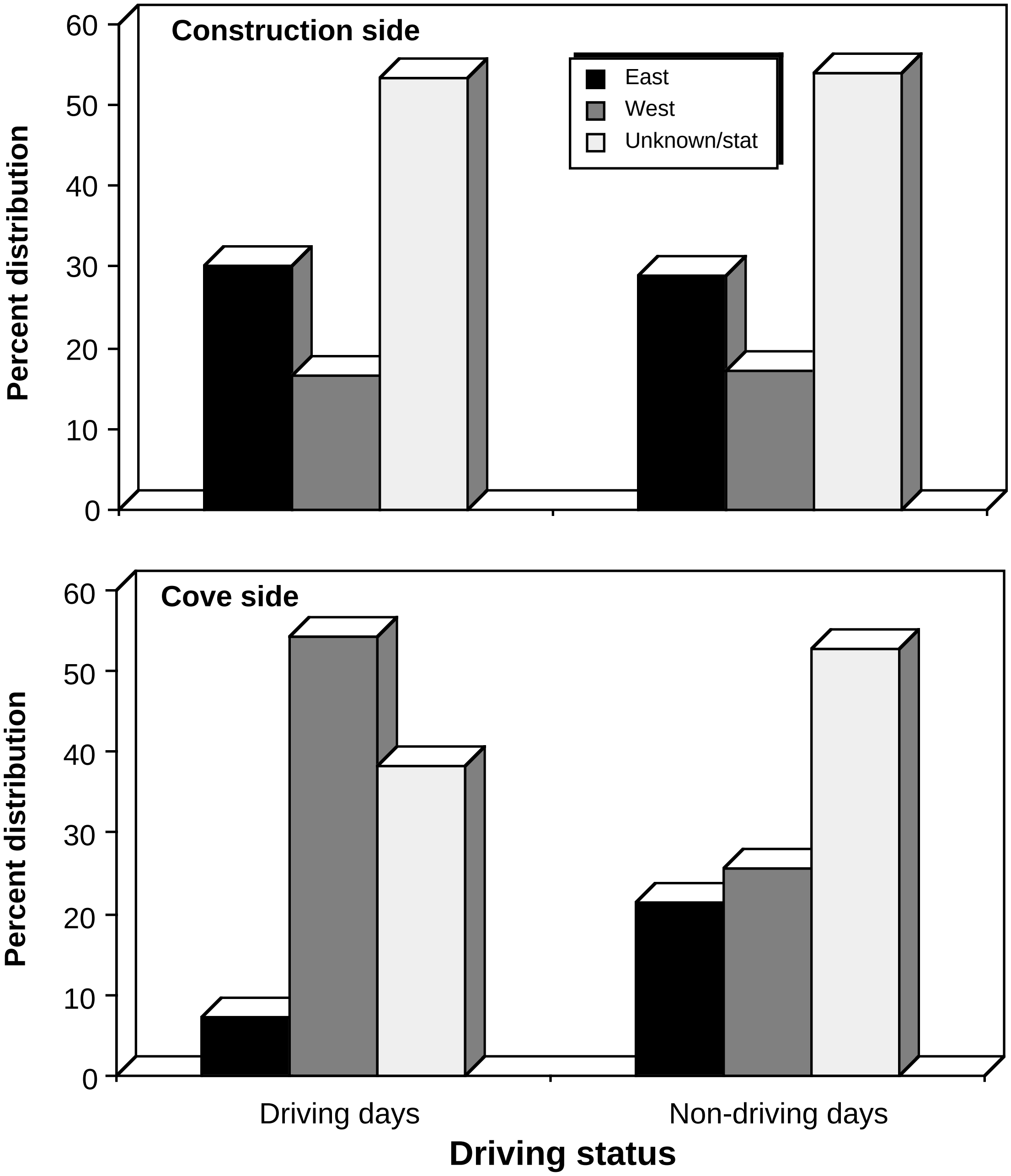

Figure 25. Distributions of fish school movement on each side of the mole with and without pile driving. Julian date 89-143, no rainy days. Construction side: total Chi-square=0.024, p=0.988. Cove side: total Chi-square=18.53, p=0.0001.

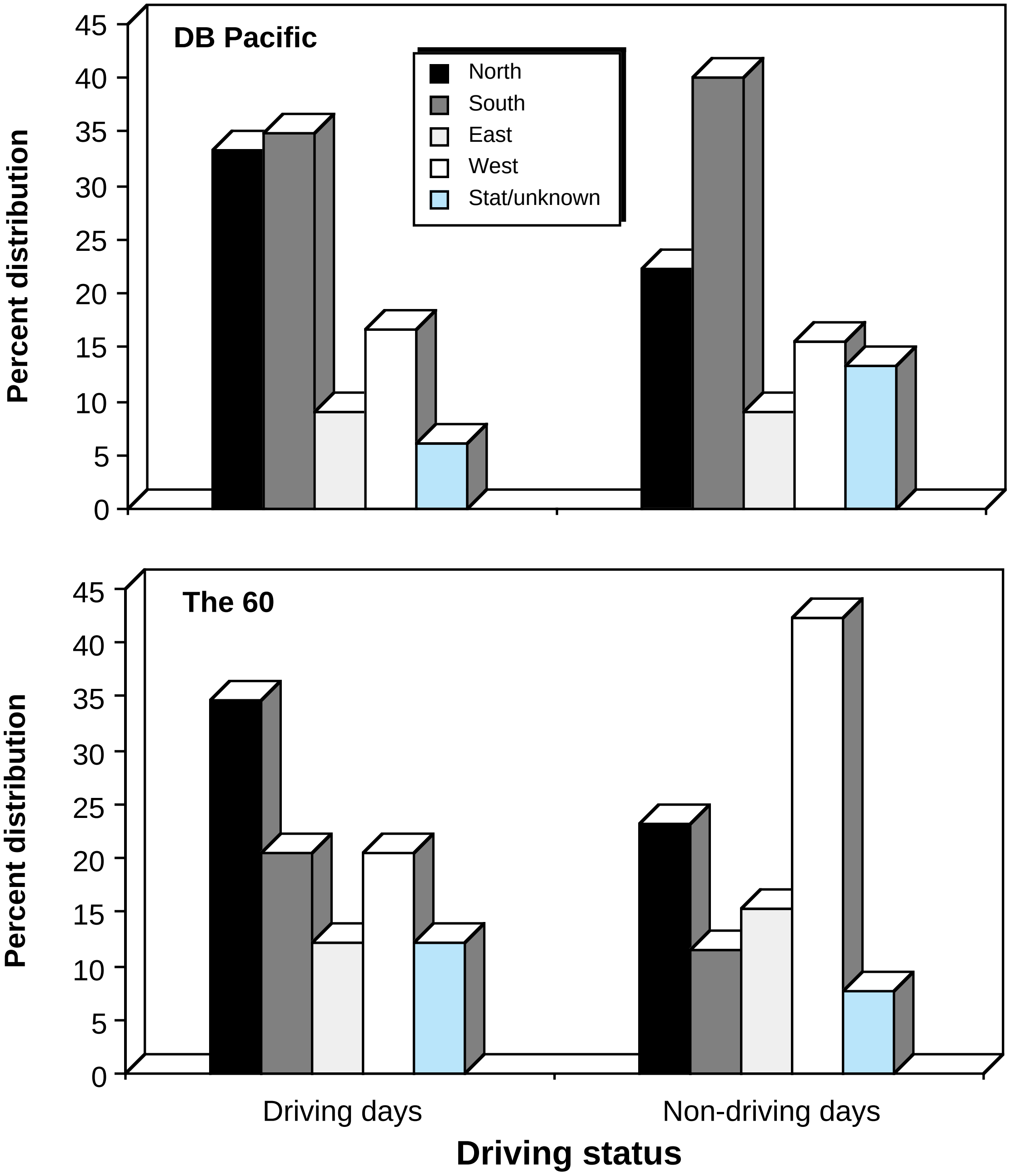

Figure 26. Distributions of fish school movement on the DB Pacific and The 60 rigs with and without pile driving. One observer, no rainy days. DB Pacific: total Chi-square=4.884, p=0.299. The 60: total Chi-square=2.931, p=0.569.

DISCUSSION

The first few weeks in the estuary is a critical time for juvenile Pacific salmon (Manzer and Shepard 1962; Simenstad et al. 1982; Levings et al. 1989), during which there is high mortality (Godfrey 1958; Ricker 1962; Foerster 1968; Parker 1968; Ricker 1976; Peterman 1982; Bax 1983). Fish are particularly subject to stress during this period. In this discussion, I will address the potential impacts of pile driving sounds on fish at the Everett Homeport, and the general ecological information garnered from this study. Then, I will address my results concerning changes in fish behavior and ecology in response to pile driving noise, and the limitations of this study.

The acoustic environment and fish ecology

Chronic exposure to moderate sound levels can alter fish ecology. Fry of *Cyprinodon variegatus* and *Fundulus similis* exposed to a SPL 20 dB above control noise levels exhibited diminished growth (Banner and Hyatt 1973). Meier and Horseman (1977), were able to influence fat stores, growth rates, and reproductive indices in *Tilapia aurea*, by operating a buzzer wrapped in plastic in aquaria with the fish. Contrary to the results of Banner and Hyatt (1973), sound appeared to improve growth rates and fat stores. The reason for this apparent difference might be that Meier and Horesman used short (20 minutes/day) stimuli in a Pavlovian classical conditioning context, whereby fish learned to associate the sound with being fed. Sound levels at the Homeport site certainly were at least 20 dB above ambient, but these were transient as opposed to continuous sounds. The question of whether or not pile driving diminishes growth in juvenile pink and chum salmon cannot be answered in the scope of this study.

Pile driving sounds may temporarily or permanently damage the hearing of juvenile salmon. Popper and Clarke (1976) found that goldfish (*Carassius auratus*) demonstrated up to a 30 dB decrease in hearing sensitivity when exposed to 149 dB re: 1 μPa for 4 hours, but that hearing returned to normal after 24 hours. Enger (1981) used a SPL of 180 dB re: 1 μPa to destroy bundles of cilia on the saccular maculae of codfish as evidenced by scanning electron microscopy. This treatment was presumed to cause permanernt hearing loss. Cox et al. (1987) also were able to destroy cilia on the saccular and lagenar maculae of goldfish with high SPLs. While the SPL at pile driving sites does not appear to be at intensities capable of this damage, experiments regarding the minimum SPL that damages fish hearing have not been conducted for salmon. Therefore, it is conceivable that salmon in close proximity (<10 m) to a pile being driven will experience temporary or permanent hearing loss.

Juvenile pink and chum salmon almost certainly cannot perceive the sounds of pile driving on the cove side of the mole because the mole acts as an acoustic muffle. Based on the audiogram generated by Hawkins and Johnstone (1978), the sounds of pile driving on the construction side of the mole appear to be within the perceivable frequency range of salmonid species (Figs. 1 and 14). The question remains as to whether or not the intensity is sufficient for audition. There are a number of limitations on comparing the audiogram produced by Hawkins and Johnstone (1978) to that of juvenile Pacific salmon.

First, the audiogram was derived from Atlantic salmon ranging in length from 32 to 36 cm TL, and about 500-700 g. Pink and chum salmon at the Everett Homeport were typically 38 and 44 mm TL, and about 0.5 to 1.0 g. Since salmonids appear to rely entirely on their inner ear and lateral line for hearing, and are most sensitive to particle velocity rather than sound pressure (they do not appear to have a transducer such as a Weberian apparatus for converting sound pressure into particle displacement), it seems reasonable to assume that a fish with larger otoliths (and a greater moment of inertia) might have a different audiogram than a fish with smaller otoliths. However, there are no studies on salmonids to document this.

Since the sounds produced by pile driving are “transient” in nature, analysis of the SPL requires sampling over a set time interval or integration time. The duration of this integration time changes the power spectra of the signal being analyzed. The longer the interval, the lower the overall SPL will become for the same signal. Ideally, the integration time should correspond to the minimum integration time required for the target species to perceive sound of a given source. This critical interval will vary with source frequency and intensity, and with fish species. Since the critical interval for juvenile Pacific salmon is not known, it becomes difficult to say for certain whether or not they will be able to hear the sounds of pile driving. Fay and Coombs (1983) found that the interval at which sound pressure had to be increased in order for the fish to continue perception of a given frequency (400 Hz pure tone) occurred somewhere between 320 and 710 ms for goldfish. The analysis window integration time for my study was 160 ms. If the critical interval of juvenile pink and chum salmon is greater than this, the levels presented will appear high. If the interval is less than this, the levels presented will appear low.

In order to assess whether or not pile driving sounds are audible to juvenile pink and chum salmon, I have synthesized the following criteria from the literature. First, the SPL must be at least that of the minimum audible field of salmon in Figure 1 for the frequencies of interest. Analysis of the sound field 593 m from the DB Pacific at the Homeport showed significant acoustic energy between 200 and 400 Hz. Second, ambient noise should be at least 24 dB less than the minimum audible field of the fish; otherwise masking will occur, and the fish will not hear the sound stimulus (Hawkins and Johnstone 1978). Ambient levels at the Homeport site were 80 to 90 dB re: 1 μPa, and this is 10-30 dB below the minimum audible field of Atlantic salmon. Third, Olsen (1969 and 1976) found that the stimulus SPL had to be 20-30 dB higher than ambient noise levels in order to induce a behavioral response in Atlantic herring. Sound levels between 200 and 400 Hz at the Homeport were at least 20 dB above ambient, 593 m from the source. Finally, broad-band, pulsed sound rather than continuous, pure tone sounds are more effective at altering fish behavior (see Hering 1968 in Olsen 1971; Olsen 1971; Blaxter et al. 1981b; Schwarz and Greer 1984). The sounds produced by pile driving are pulsed and broad-band.

Another impact that pile driving sounds might have on juvenile pink and chum salmon is auditory masking. Masking occurs when adjacent frequencies to the stimulus frequency are present. Therefore, it is conceivable that pile driving noise masks the sounds of approaching predators making them more difficult to detect by juvenile salmonids. Another possibility is that juvenile salmon may habituate to the sounds of pile driving and “ignore” the sound of an approaching predator. Qualitatively, fish schools on the construction side of the site were less apt to startle when approached by observers compared to schools on the acoustically isolated cove side of the site, indicating habituation to the sound may have occurred.

In summary, it is conceivable that the sounds produced by a pile driving rig are audible to juvenile Pacific salmon from more than 300 m from the source. In trying to assess the impacts of any stimulus on an organism, one must consider the biological relevance of that stimulus. Juvenile pink and chum salmon may clearly hear the sounds of pile driving from great distances. However, the perceived relevance of that signal to the fish cannot be answered without further research concerning salmonid audition.

General fish ecology

The following discussion does not provide particular insight into the effects of pile driving on the ecology of juvenile pink and chum salmon. However, it does present pertinent information regarding salmonid ecology at the mouth of the Snohomish River.

The precise correlation of western grebes with the first peak of the outmigration suggests that these diving birds were feeding on outmigrating juvenile salmon. Whether or not this predation contributed significantly to pink and chum salmon mortality is not known. Wood (1987a and 1987b), found that predation on juvenile salmonids by the common merganser (*Mergus merganser*) had a significant impact on juvenile coho salmon in their natal streams, but did not have a significant impact on fish in tidal waters.

The observation that TL of pink and chum salmon did not increase over time is consistent with previous research in the Port of Everett and other nearshore estuarine areas. Beauchamp (1986) and Beauchamp et al. (1987) found that pink and chum salmon TL did not increase significantly in freshwater sampling areas near the mouth of the Snohomish until late May. McEntee et al. (1985), did not observe an increase in fork length (FL) for juvenile pink and chum salmon sampled with a beach seine at the Homeport site, but did see an increase for purse seine sampled fish. Sturdevant et al. (1991) also found that juvenile pink salmon did not exhibit an increase in FL through April and early May in Prince William Sound, Alaska. Therefore, it seems logical to assume that the fish observed at the Homeport were probably transient, moving rapidly through the area. The possibility that the fish were holding-up and not growing is conceivable. However, this becomes unlikely when the rate of feeding is considered.

The co-occurrence of pink and chum salmon in fish schools has been documented in the literature (Irie et al. 1981), and the Everett Homeport was no exception. Virtually all dip-net and beach seine sets produced pink and chum salmon together.

The dietary composition of fish sampled at the Homeport site is different from accepted norms. However, these were fish sampled from steeply sloping rip-rap shores, hardly an optimal environment for epibenthic organisms to flourish. Irie (1987), found that juvenile chum salmon (47 mm mean FL) primarily fed on small calanoida or harpacticoida in small harbors around eastern Hokkaido, Japan, an environment similar to that of the

Homeport site. Stomach content studies conducted in the Everett Harbor area prior to Homeport construction activities (Schadt and Weitkamp 1985), indicate that juvenile pink and chum salmon primarily fed on epibenthic organisms such as gammarid amphipods and harpacticoid copepods, but there were significant quantities of pelagic species, such as calanoid and cyclopoid copepods in the diet. Fish sampled by purse seine sets in the same area primarily had insects, euphausids, and calanoid and cyclopoid copepods, a more pelagic diet (Schadt and Weitkamp 1985). Therefore, it is not surprizing to find that the fish in my study fed almost entirely on pelagic prey items like calanoida.

Does pile driving affect fish distribution and behavior?

Outmigrating salmonids experience a variety of sensory stimuli when they encounter a pile driving site. However, certain stimuli may have greater significance than others. The primary concern behind the regulations restricting pile driving is that the sounds generated by pile driving underwater will disturb the fish. Visual disturbances are certainly another potential disturbance to consider. The differences observed in fish behavior and presence/absence may have been a result of the skiff and worker activity surrounding the rigs on pile driving days. However, this explanation does not apply to shoreline data since miscellaneous construction activity along shore was constant throughout this study, regardless of pile driving status. Therefore, I assumed that sound and visual disturbances were the primary stimuli present at pile driving projects, and salmonids are certainly capable of detecting these stimuli.

Assuming juvenile pink and chum salmon found the sounds of pile driving aversive, fish schools in this study would be expected to ball-up, dive, polarize or swim away in response to the sounds of pile driving. Of these responses, polarized behavior was observed at the Homeport. However, differences in the behavior of fish in this study were evident over time. For example, fish schools would rarely polarize when a given pile driver started driving. Some schools were simply polarized, but the incidence of polarized behavior was higher on non-pile driving days compared to pile driving days on both rigs and the shoreline observations. The data changed as a function of pile driving during the day, but not if there was pile driving at the moment a school was observed.

The prevalence of fish schools at or near the surface where salinities were the lowest is consistent with other studies (Tyler 1963; Iwata 1980; Iwata et al. 1982; Iwata and Komatsu 1984; Irie 1985). Fish schools rarely would dive deeper than 1 m in the water column in response to disturbances such as a rock being thrown at them or a gull shadow passing over. Hoar (1951), noted diving and scattering behavior in pink and chum salmon fry in response to a hand wave. However, these fish were in freshwater. It is generally assumed that juvenile pink and chum salmon reside near the surface in the freshwater lense (10-14‰ salinity) at the mouth of a river because of osmotic stress (Iwata et al. 1982). As a result, they are apparently reluctant to dive into the water column in response to any aversive stimulus and “chose” to escape laterally instead.

A major concern of WDF was that fish would be driven offshore into the neritic zone in response to pile driving. Had this been the case, I would have expected fish schools to be less abundant on pile driving days, if not absent entirely. This did not occur along shore. However, fewer schools were observed around pile driving rigs on pile driving days compared to non-pile driving days. This difference could have been due to either pile driving or the associated activities (such as work skiffs) of pile driving. Fish schools that were observed along shore did not change their distance from shore, suggesting they were not being driven to deeper water. Since I relied on human observation for quantifying fish abundance, there is a possibility that fish schools were driven offshore, undetected by observers. I would estimnate that schools >10 m from shore would not be visible to observers. Active hydroacoustics and purse seining would help answer that question.

Other studies have used humans for observation of fish schools, but met with limited success for various reasons. Schreiner et al. (1977), visually surveyed over 13 Km of shoreline by boat. Since schools are easily startled by boat movement, observation was difficult. In addition, observations were only possible on clear, sunny days, and the shear magnitude of shoreline to be observed was too much. Allen (1974), was also constrained by the same limitations. For my study, a short length of shore (488 m) was surveyed not from a boat, rather, observers walked slowly along shore in order to avoid startling the fish schools. Observation averaged 5-6 h each day, 5 days a week. In addition, fish schools were easily observed on overcast days.

Tidal stage did not appear to play a significant role in the abundance or behavior of fish in this study. Migration from the Snohomish River was believed to be strongly correlated with tidal stage, but not with time of day according to Tyler (1963). However, Tyler was referring to fish in the river channel. The mole area at the Homeport did not have swift currents that could sweep fish away.

The ultimate question of pile driving effects on fish distribution and behavior is difficult to answer in the context of this study. Given that fish alter their distributions about the site and change their behavior in response to pile driving, what is the effect on their overall fitness? In this case, that question cannot be answered with any degree of certainty. We must assess the risk imposed to these fish, which can be a subjective process. If the fish were prematurely driven to the neritic zone soon after emergence, their fitness would probably be decreased. If the sounds of pile driving at the site stress the fish, they may have reduced growth rates or perhaps increased mortality. These “if's” cannot be clarified in the context of this study. One thing is certain though, the habitats of juvenile salmon have already been radically modified in many areas, and additional stress could have synergistic effects.

Study limitations

This study was designed to test the feasibility of various methods to assess the impact of pile driving on juvenile salmonid distribution and behavior. There are no other studies to date that have examined this issue. While in some instances it is difficult to separate all of the factors contributing to fish behavior and ecology at the Homeport, I have tried to restrict the variability introduced by tidal stage, different observers, weather, and fish behavior.

Another limitation of this study is the skewness of pile driving to non-pile driving days. Had there been an equal sample size, many of the variables such as tidal stage, time of day, cloud cover, and observer subjectivity would have been normalized. For example, most non-pile driving days had >50% cloud cover, hence, it was difficult to separate the effects of cloud cover and pile driving on fish behavior and/or observer perception of fish behavior. Nevertheless, there were many instances where fish behavior was affected by pile driving and/or its associated activities, when tidal stage, observer, weather, and time of day were accounted for.

The Everett Homeport is one site, studied for one season. The results of this study cannot necessarily be extrapolated to other sites where pile driving is occurring. For example, the juvenile pink and chum salmon considered for this study were newly emerged and apparently moving rapidly along shore. Juvenile pink and chum salmon at other sites that are not in close proximity to a river might move slowly through the area and be subject to perturbance from pile driving because of increased exposure time.

The majority of data collected for this study was based on human observation, which, has its limitations and biases. On windy or rainy days it was particularly difficult to observe fish schools. Each of the four observers had slightly different opinions concerning the size and behavior of any given school. Fish schools most certainly could have been deeper in the water column, or further from shore on pile driving days and this would not have been apparent to observers. The possibility that schools were deeper and hence not visible is not likely since Iwata et al. (1982) never saw chum salmon fry below the freshwater lense based on 5 years of underwater observations. In addition, other species of fish were observed deeper in the water column by observers in my study. Fish schools may also have avoided the site entirely on pile driving days and headed to deeper water of Port Gardner or the gently sloping beaches of Jetty Island.

SUMMARY AND RECOMMENDATIONS

The impact of pile driving noise on the distributions and behavior of juvenile pink and chum salmon at the Everett Homeport site was not apparently as extreme as hypothesized in the worst case scenario by WDF. The prevalence of fish schools did not change significantly with and without pile driving, and schools were often observed about the pile driving rigs themselves. The effects of pile driving appear subtle according to my investigation. There may be changes in general behavior and school size, and fish appear to be driven towards the acoustically isolated cove side of the site during pile driving. Fish were feeding well the day they were sampled about the rigs and along shore. Ultimately, it is difficult to ascertain the impact of pile driving noise on juvenile salmonid fitness. In order to answer this question, and consequently make any changes in the regulations imposed by WDF, further research would be necessary.

The hypothesis for subsequent research on the effects of pile driving on the ecology of juvenile pink and chum salmon would be as follows. First, juvenile salmon perceive the sounds of pile driving from at least 1000 m. Second, the sounds of pile driving stress fish within a given range and this stress increases mortality and/or decreases growth. Third, fish are driven away from any given construction site either away from or along shore.

In order to answer the first part of the hypothesis, the range at which salmon perceive pile driving sounds could be characterized. This could be accomplished under laboratory conditions using classically conditioned fish.

For the second part of the hypothesis, juvenile salmonids could be exposed to pile driving sounds representative of any given sight for 8-10 h a day. Plasma cortisol levels would be monitored since increased plasma cortisol levels is considered to be a primary response of vertebrates, including Pacific salmon, to stress (see reviews by Schreck 1981, 1982; Thomas et al. 1986). Body weight, TL, and otolith increments would also be measured since low levels of sound have been shown to inhibit growth in larval fish (Banner and Hyatt 1973), and otolith increments are an extremely accurate measure of juvenile salmonid growth (Volk et al. 1984).

The use of active hydroacoustics to track fish at construction sites in conjunction with human observers and beach and purse seines would yield extensive information of juvenile salmonid distributions about pile driving construction sites. A low cost, portable hydroacoustic device was developed in conjunction with this study, capable of identifying location, direction of movement, and size of fish schools. These units would be installed at various locations at any site. In addition, for species confirmation and size, underwater cameras would be signaled to take a photograph of schools detected by the equipment. Beach seining in conjunction with purse seining would yield similar information as hydroacoustics, but would not be subject to sampling error induced by high turbidity or waterborne debris, for example.

Finally, mark and recapture experiments using fluorescent dye would yield information concerning individual residence time and migration rates at any site. This would facilitate calculating exposure times for all species of interest to correlate with laboratory experiments on growth effects and stress.

The combination of all these experiments would result in a better understanding of the impact pile driving noise has on the fitness of juvenile salmonids exposed to the sounds of pile driving. My study alone cannot demonstrate convincingly whether or not pile driving has a detrimental effect on the fitness of juvenile pink and chum salmon.

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APPENDIX A: Glossary.

dB: Decibel. The unit of sound measurement defined as 20 times the log of the product of the sound pressure being measured times the inverse of the reference pressure.

SPL: Sound pressure level.

TL: Total length of a fish, defined by the distance from the tip of the snout to the trailing edge of the caudal fin.

FL: Fork length of a fish, defined by the distance from the tip of the snout to the fork of the caudal fin.

WDF: Washington Department of Fisheries

Acoustico-lateralis system: The lateral line system and inner ear of fishes.

Cochlea: A small, spiral shaped, bony tube found within each of the paired inner ears of terestrial vertebrates where the sensory hair cells are located.

Emergence: The time in a Pacific salmon's life history when juveniles emerge from the gravel after yolk sac absorption.

Epibenthic invertebrates: Invertebrates that inhabit the surface of submerged substrates in an estuary.

Habituation: A type of learning in organsims whereby repeated exposure to a given stimulus yields decreased behavioral response over time.

Nauplii: Lifestage in many groups of larval *Crustacea*, characterized by 3 pairs of appendages and a single median eye.

Nearshore zone: Oceanographic term describing the area between the shore and the surf zone.

Neritic zone: Oceanographic term describing the zone extending from low tide level to a depth of about 183 m.

Particle displacement: The component of sound that is the to-and-fro movement (on the order of nanometers) of water molecules, and is a vector quantity.

Pelagic invertebrates: Invertebrates that are free-swimming and inhabit open waters of the estuary.

Sound pressure: The component of sound that is the oscillatory change in pressure above and below hydrostatic pressure, and is a scalar quantity acting in all directions.

Startle response: A reflex response of organisms to a stimulus in which the organism darts suddenly and for short duration in order to escape the stimuli.

Sublittoral zone: Oceanographic term describing the zone extending from low tide level to a depth of about 21 m.

APPENDIX B: Summary graphs of stomach content analysis.