U.S. Fish and Wildlife Service

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2007-2008 Acoustic Tracking Studies

May 2011 *By Mark T. Celedonia, Zhuozhuo Li, Scott T. Sanders, Roger A. Tabor, Steve Damm, Daniel W. Lantz and Benjamin E. Price*

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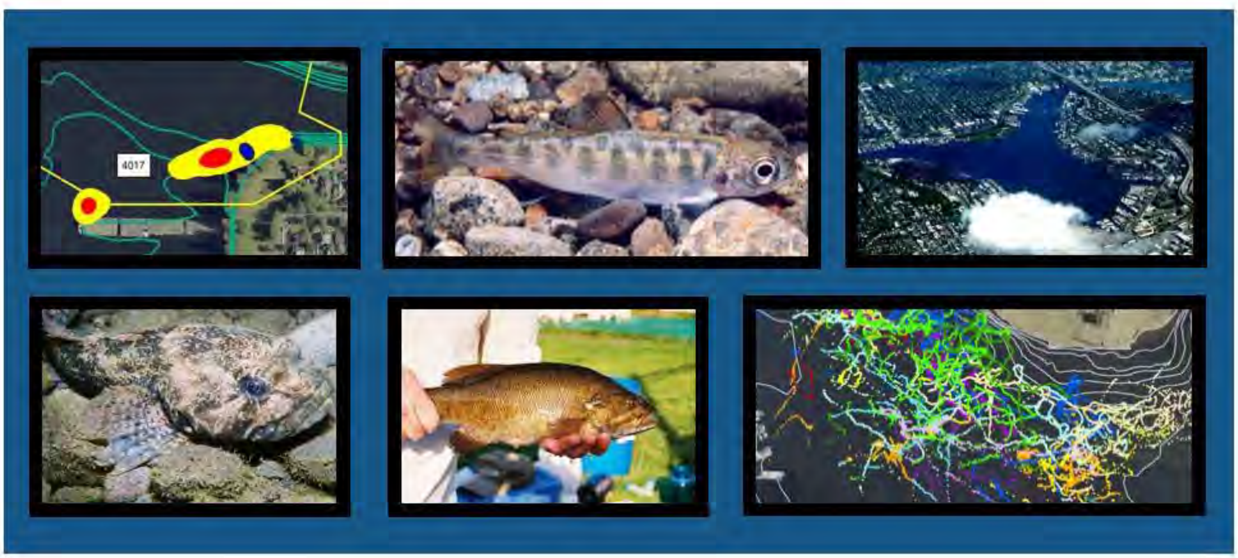

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MOVEMENT AND HABITAT USE OF CHINOOK SALMON SMOLTS IN THE LAKE WASHINGTON SHIP CANAL

2007-2008 ACOUSTIC TRACKING STUDIES

FINAL REPORT TO SEATTLE PUBLIC UTILITIES

by

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EXECUTIVE SUMMARY

This study extended research started in 2004 by Seattle Public Utilities (SPU) and the U.S. Fish and Wildlife Service (USFWS). The purpose of the research was to evaluate movement and habitat use of Chinook salmon *Oncorhynchus tshawytscha* smolts outmigrating through the Lake Washington system. Prior to these studies, little was known about Chinook salmon smolt behavior as they grew larger and moved farther from shore during late-May and June. In 2004-2005, the research focused on rearing areas in southern Lake Washington, and parts of the primary migratory corridor from there to Puget Sound, including the western shore of Lake Washington and the eastern part of the Lake Washington Ship Canal (LWSC). The 2004-2005 studies are summarized in Celedonia et al. (2008b). The present study extended this work by adding investigations in the western parts of the LWSC and at the Ballard Locks. Together, these studies provide a picture of juvenile Chinook salmon outmigration behavior and habitat use during the latter part of the smolt outmigration season.

Objectives of this study were to:

1) evaluate LWSC-wide movement patterns and habitat use (i.e., do fish spend more time in some areas than others);
2) evaluate site-specific behaviors and habitat use patterns at four study sites along the LWSC: University Bridge, Gas Works Park, South Lake Union, and the Ballard Locks;
3) evaluate influence of water clarity, water temperature, and prey abundance and distribution on juvenile Chinook salmon movement patterns, spatial distribution, and habitat use;
4) evaluate influence of water temperature on vertical distribution of fish at the University Bridge and Ballard Locks;
5) evaluate influence of water temperature on exit routes and exiting behavior at the Ballard Locks;
6) evaluate spatial and temporal overlap of Chinook salmon and potential predators; and,
7) evaluate interannual variability in each of the preceding six components.

In order to meet these objectives, a fine-scale acoustic tracking system was used. Hatchery-reared smolts obtained from Washington State's Issaquah Hatchery were used for this study. Each fish was implanted with a tag that emitted a unique code which allowed it to be distinguished from other tags. The system was set up with static hydrophone arrays throughout the LWSC from Portage Bay to the upstream side of the Ballard Locks. Hydrophone arrays were operated during June and July. This methodology was also used in the earlier juvenile Chinook salmon tracking studies (Celedonia et al. 2008b).

Tagged Chinook salmon smolts were released at the eastern end of the LWSC. In general, tagged Chinook salmon:

- moved through Portage Bay in fewer than 24 hours;
- spent one day to two weeks in Lake Union;
- moved through the Fremont Cut in fewer than 24 hours; and,
- spent hours to a week or more in Salmon Bay and near the Ballard Locks.

More than fifty percent of the tagged fish also used south Lake Union, often for more than 24 hours.

In general, tagged Chinook salmon in the LWSC distributed broadly throughout areas with bottom depths ≥ 4 m, although shallower areas were used on occasion. Seasonal and inter-annual shifts in spatial distribution appeared to be related to diel period, water temperature, and water clarity. Overwater structures may have also influenced spatial distribution in some cases. We found little evidence of strong shoreline orientation in the LWSC, although extensive shoreline development throughout the LWSC may have obscured the natural tendencies of the fish. This contrasts with findings in Lake Washington where fish remain relatively close to shore in areas with bottom depths of 1-6 m during the day. Lower abundance of some Chinook salmon predator species in the LWSC may contribute to the shift in horizontal spatial distribution of Chinook salmon here.

Tagged Chinook salmon smolts often used the edges of overwater and in-water structures where water depth was greater than 6 m. This was observed primarily at the University Bridge and South Lake Union sites. In general, Chinook salmon milled throughout a zone that started at the structure edge and extended outward 20 m. These findings were similar to those observed in studies at the State Route (SR) 520 bridge and a nearby overwater condo in Lake Washington (Celedonia et al. 2008a; Celedonia et al. 2009). It is possible juvenile Chinook salmon use structure edges to be near cover. This behavior has important management implications in that use of these areas puts Chinook salmon in close contact with known smallmouth bass *Micropterus dolomieui* habitat. However, the extent to which these behaviors result in increased predation requires further study. Nonetheless, resource managers and policy makers should consider this in the design, modification, and permitting of over- and in-water structures in the LWSC where bottom depths are 6 m and deeper.

At the University Bridge site, fish migration behavior was strongly influenced by the University Bridge. Many tagged fish responded by milling along the eastern edge of the bridge and in nearby areas prior to passing beneath the bridge. Similar behaviors were observed at the SR 520 bridge (Celedonia et al. 2008a; Celedonia et al. 2009). Few if any fish responded to the presence of the I-5 bridge, presumably because it is much higher than the University Bridge and has no in-water structure. The milling behaviors at the University Bridge put fish in prolonged contact with edges of in-water structures that were frequented by smallmouth bass (Tabor et al. 2010). This may increase predation on Chinook salmon smolts. In one cases, data showed predation upon a tagged Chinook salmon in this area.

At night, tagged Chinook salmon frequented areas with artificial lighting and spent prolonged periods in these areas. Similar observations were made along the SR 520 bridge (Celedonia et al. 2009). Relatively dim light levels (1.6-2.0 lx) attracted tagged Chinook salmon. Other studies suggest that predation rates by piscivorous fishes may be higher in lighted areas even if predators on the whole do not select for these areas. Any potentially negative consequences to Chinook salmon might be minimized by reducing the intensity of light reaching the water surface.

We found little evidence to suggest that fish move vertically into deeper water as temperatures warm. Instead, fish vertical distribution was generally consistent throughout each year at both sites where it was studied. Fish at the University Bridge were generally surface oriented and primarily used the upper 6 m of water, even when surface water temperatures exceeded 20^{o}C. At the Ballard Locks, fish distributed throughout the water column. Some diel and inter-annual variation in vertical distribution was evident at each site. These findings suggest that factors other than water temperature drive vertical position selection of Chinook salmon in the LWSC.

At the Ballard Locks, the proportion of Chinook salmon smolts exiting through the smolt flumes declined as water temperature increased during the season. We observed direct and convincing evidence in both 2007 and 2008 that fewer smolts use the smolt flumes at higher temperatures. The proportion of fish exiting through the smolts flumes declined from 52-89% at temperatures less than 18^{o}C, to 0-17% at temperatures greater than 20^{o}C. In addition, at higher temperatures (> 18^{o}C): fewer fish entered the forebay where the smolt flumes are located; fish spent more time on and near the site; more fish used deeper, cooler exit routes (i.e., small and large locks); and fewer fish were observed exiting into Puget Sound. These observations suggest that many smolts avoid the forebay and smolt flume entrance when water temperature exceeds 18^{o}C during the latter part of the outmigration season. The result is that fish linger in the vicinity of the Ballard Locks for longer periods of time, potentially increasing residualism. Fish also switch to other exit routes, namely the small and large locks which can injure fish. Thus, the Ballard Locks, as currently configured, appears to present a substantial barrier to successful, rapid, and minimally harmful Chinook salmon passage during the latter part of the outmigration season.

Changes in locks operations appeared to influence behavior and passage of Chinook salmon. Locks operations differed substantially between 2007 and 2008. Relative to 2007, in 2008 the number of small lockages decreased, the number of large lockages increased, and the number of open smolt flumes increased. These changes may have contributed to increased use of the smolt flumes in 2008. This may have come at a cost, however, as the overall percentage of smolts exiting into Puget Sound through all pathways decreased in 2008. Interestingly, exit through the large lock chamber appeared unchanged. It thus appears possible that, when the small lock chamber is effectively shut off as a possible exit pathway, more fish choose to delay longer and/or not exit rather than use the smolt flumes or the large locks. If true, this suggests that there may be an individual behavioral component to choice of exit pathway.

Chinook use of the area near the small lock chamber declined in 2008. Thus, small lockages appear to attract fish to this area. This has important implications for design and placement of additional passage devices. For example, exit pathways placed near the small lock chamber may be less effective if the number of small lockages is minimized. A more comprehensive understanding of how locks operations influences Chinook salmon behavior is advisable prior to design and placement of additional passage mechanisms.

Researchers have speculated that predation and residualism may increase in the LWSC as water temperatures warm later in the outmigration season. We observed evidence that both of these factors may play a role. Several indicators suggested that predation increased at higher temperatures, although these observations were largely indirect and not consistent from year to year. Evidence for residualism was clouded by the relatively short tag battery life. The extent of predation and residualism that occurs in the LWSC at higher temperatures should receive further study.

The following list summarizes management implications and recommendations that arise from this study. Note that the focus is on late-season survival and fitness of Chinook salmon moving through the LWSC:

- Predation risk from other fishes appears to be highest in areas east of Salmon Bay. Restoration efforts designed to minimize predator habitat and overlap with Chinook salmon habitat should be focused here.
- Habitat protection and restoration efforts should focus on areas with bottom depths ≥ 2-4 m.
- The entirety of Lake Union, including the extreme southern end, should be considered Chinook salmon holding/rearing habitat.
- Efforts should be made to minimize the amount of over- and in-water structures, especially in areas east of Salmon Bay. Primary importance should be placed on areas with bottom depths ≥ 6 m. Areas with bottom depths of 2-6 m are also important, but maybe less so.
- Managers should consider removing, redesigning, and replacing the piling-and-wing wall structures at the University Bridge. These structures were hotspots for both smallmouth bass and Chinook salmon activity. If such structures are necessary, they should be redesigned and replaced with functionally similar structures that contain fewer if any in-water components, and/or in-water components that extend into the water column as little as possible (e.g., in-water components should be as high in the water column as possible). Similar measures should be taken at the Fremont and Ballard Bridges pending further study into Chinook salmon and smallmouth bass use at these specific locations.
- Additional research should seek to understand why smolts reside in Lake Union for extended periods. Is there an inhibition to enter the Fremont Cut? Are conditions in the lake favorable and triggering a volitional rearing behavior? Answers to these questions will help direct further restoration efforts.
- Additional research should seek to better explain the difference in fish vertical distribution between the University Bridge area and the Ballard Locks. Use of deeper, cooler water by fish, such as that observed at the Ballard Locks, may put less stress on the fish and may be more conducive to long-term survival than the strong surface orientation observed at the University Bridge (and conceivably throughout the rest of the LWSC). Managers could then consider whether those conditions can and should be encouraged throughout the rest of the LWSC.
- Water depth in the LWSC generally, and in the Montlake and Fremont Cuts specifically, has been implicated as a potential problem for Chinook movement. That is, the shallower depth in these areas may lead to a thermal barrier inhibiting Chinook passage later in outmigration season. Evidence from this study and from Lake Washington (Celedonia et al. 2008a; Celedonia et al. 2008b; Celedonia et al. 2009)

does not support this hypothesis. This may change, however, as global climate change increases water temperatures.

- Artificial lighting on bridges, docks, and other areas near the water should be directed so that light on the water surface is minimized. Influence of artificial light on predation rate of piscivores should be considered for further study.
- Additional means for fish passage should be considered for the Ballard Locks. Design and placement of additional fish passage should consider influence of locks operations on fish behavior.
- Pending installation of additional fish passage, the locks should be operated to maximize fitness and successful passage of fish into Puget Sound. Additional research may be needed to determine what operational configuration is best. At this time it is uncertain whether increased overall fish passage outweighs the potential damage caused by passing through the small lock chambers. Furthermore, operational configurations different from those in 2007 and 2008 may provide better results.

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INTRODUCTION

In 2004 and 2005, Seattle Public Utilities (SPU) and the U.S. Fish and Wildlife Service (USFWS) conducted acoustic tracking studies of Chinook salmon *Oncorhynchus tshawytscha* smolts and piscivorous fish behavior and habitat use in Lake Washington and the Lake Washington Ship Canal (LWSC) (Celedonia et al. 2008b). The main objectives of those studies were to: 1) evaluate habitat use and movement patterns of juvenile Chinook salmon during their migratory phase in late-May, June, and July; and, 2) determine diel movement and habitat use of predators, including smallmouth bass *Micropterus dolomieui* and prickly sculpin *Cottus asper*, and evaluate spatial and temporal habitat overlap with Chinook salmon smolts. A fine-scale acoustic tracking system was used at four sites in Lake Washington and the LWSC for these purposes. Specific goals of the study were to: 1) document Chinook salmon smolt movement patterns and habitat use at and between the study sites; 2) determine the relationship in space and time between outmigrating juvenile Chinook salmon and piscivorous fishes; and, 3) evaluate the influence of certain features such as overwater structures and aquatic macrophytes on Chinook salmon and predators. Chinook salmon movement and habitat use was predicted to be similar at and between the different sites. For both Chinook salmon and predators it was predicted that habitat selection would be uniform throughout each study site, and that specific areas of each site would neither be selected for or against. Finally, aquatic macrophytes and overwater structures were predicted to not influence movement or habitat use of Chinook salmon or predators. These null hypotheses were rejected in whole or in part as study results showed that Chinook salmon movement and habitat use varied at and between sites, both Chinook salmon and predators selected certain areas of each site, and both aquatic macrophytes and overwater structures appeared to have some influence on movement and habitat use of Chinook salmon and predators.

Based on 2004-2005 results, SPU and USFWS concluded that further study was warranted in order to: 1) evaluate in more detail Chinook salmon movement and habitat use patterns in the LWSC at two spatial scales (site-scale and LWSC-wide); 2) evaluate interannual variability; 3) collect additional ancillary data to help understand observed fish movement and habitat use patterns; 4) increase sample sizes of tagged predators; and, 5) evaluate smolt passage at the Ballard Locks. In order to meet these objectives, the 2007 and 2008 studies focused exclusively in the LWSC. One site from the 2004-2005 studies - Gas Works Park - was included in 2007 and 2008, and three additional study sites in the LWSC were added at the University Bridge and I-5 bridge, in south Lake Union, and at the Ballard Locks. The same fine-scale acoustic tracking system used in 2004-2005 was used in 2007 and 2008. Aquatic macrophyte mapping was also similar. Components added for 2007 and 2008 included water quality sampling, zooplankton sampling, and macrophyte growth monitoring.

In addition to the general study objectives and goals, there were specific study objectives associated with each site. At the University Bridge and I-5 bridge, we wanted to evaluate Chinook salmon's position in the water column relative to water temperature (i.e., do fish move deeper in the water column as water temperatures rise?). We also wanted to evaluate how the presence of the bridges influences movement of Chinook salmon through the area. At Gas Works Park, we wanted to evaluate interannual variability in movement patterns and habitat use. This site also allowed us to evaluate broader scale movement patterns as hydrophones were configured in a manner that allowed us to precisely track fish movements into and out of Lake

Union. The South Lake Union site allowed us to evaluate Chinook salmon use of this part of Lake Union, as well as evaluate habitat use around overwater structures and aquatic macrophytes. Finally, at the Ballard Locks we were interested in evaluating influence of temperature on Chinook salmon choice of outmigration routes and position in the water column.

Acoustic tracking studies in Lake Washington have observed two overarching migrational phases in Chinook salmon smolts (Celedonia et al. 2008a; Celedonia et al. 2008b; Celedonia et al. 2009). One is an active migration phase where fish move quickly and directly through a study site. These fish generally move through the study site in a rapid, direct, and linear fashion with little to no milling and no major movements in directions not toward Puget Sound. The other is a holding phase where fish often spend 1-3 days or more in and near a study site. These fish appear paused in their migration and are often observed milling throughout the site and in localized areas. Individual expression of one migrational phase or the other is largely consistent within release groups, suggesting that fish are responding to common exogenous factors and/or experiencing similar physiological (e.g., smoltification) states. For example, moon apogee can be a strong migrational cue for Lake Washington Chinook salmon (DeVries et al. 2004), although this is not always the case (DeVries et al. 2007; DeVries et al. 2008). We collected additional ancillary data in 2007 and 2008 to help explain migrational phase patterns. Specifically, we collected site-specific water quality and zooplankton data. Also, as part of an allied study in 2008 in Lake Washington at the SR520 bridge (Celedonia et al. 2009), we evaluated gill ATPase as a measure of smoltification in study fish. This data is also applicable to the present study.

Studies in Lake Washington (e.g., Tabor et al. 2006; Celedonia et al. 2008a; Celedonia et al. 2008b; Celedonia et al. 2009) have observed Chinook salmon smolts migrating through and using areas with abundant aquatic macrophytes. Macrophytes may serve as a source of cover and may also allow fish to utilize deeper water areas they would not otherwise use by functioning as a false bottom and shortening the perceived water column depth (Tabor et al. 2006). Conversely, macrophytes growing too near to the water surface may inhibit Chinook salmon use by creating conditions that are too shallow. In 2004-2005, we mapped aquatic macrophyte distribution and density throughout each study site in order to consider this factor in our analysis. However, the mapping surveys were conducted shortly after the tracking portion of the studies concluded, and thus any changes in macrophyte density and vertical growth that occurred during the study period were not captured. Therefore, we implemented a macrophyte growth monitoring survey in order to evaluate how these parameters change during the study period and how such changes may influence Chinook salmon smolt and predator behavioral patterns.

STUDY AREA

The LWSC and Lake Washington comprise the lower portion of the Lake Washington basin, which is approximately 1,570 km^2 and ranges in elevation from 6 to 1,650 m. The eastern 14% (by area) of the basin lies within the Cascade Range, while the western 86% is part of the Puget Sound lowlands. Much of the basin is heavily urbanized with over a million people inhabiting the basin. Much of the City of Seattle is within the basin. The basin has undergone numerous anthropogenic changes over the past 150 years.

The LWSC is a 13.8-km-long artificial waterway that allows navigation between Lake Washington and Puget Sound (Figure 1). The LWSC consists of five sections: Montlake Cut, Portage Bay, Lake Union, Fremont Cut, and Salmon Bay. The largest part of the LWSC is Lake Union which is 235 ha in size and has a mean depth of 9.8 m. The shorelines of Portage Bay, Lake Union, and Salmon Bay are highly developed with numerous marinas, commercial shipyards, house boat communities, and drydocks (Parametrix and Natural Resource Consultants 2000). The shoreline is heavily armored with riprap and concrete bulkhead. The Fremont Cut and Montlake Cut are narrow channels with steep armored banks. The Hiram M. Chittenden Locks, also called the Ballard Locks, is located at the downstream end of the LWSC and controls the water level of the LWSC and Lake Washington. During winter (December to February) the water level is kept low at an elevation of 6.1 m. Starting in late February the water level is slowly raised from 6.1 m in January to 6.6 m by May 1 and 6.7 m by June 1.

Upstream of the LWSC is Lake Washington, a large monomictic lake with a total surface area of 9,495 ha and a mean depth of 33 m. The lake typically stratifies from June through October. Surface water temperatures range from 4-6^{o}C in winter to over 20^{o}C in summer. The lake shoreline is comprised primarily of residential properties (Parametrix and Natural Resource Consultants 2000), and over 78% of upland cover consists of lawn and garden (Toft 2001). Over 70% of the shoreline is retained with bulkhead or riprap, and there are about 22 docks per kilometer of shoreline (Toft 2001). Natural shoreline structures, such as woody debris and emergent vegetation, are rare (Toft 2001). The largest tributary to Lake Washington is the Cedar River which enters the lake at the south end. The other major tributary to Lake Washington is the Sammamish River, whose watershed includes Bear Creek, Lake Sammamish, Issaquah Creek, and several small tributaries.

Compared to other similar-sized basins in the Pacific Northwest, the Lake Washington basin is inhabited by a relatively large number of fish species, including 25 native species (primarily salmonids, cottids *Cottus* spp., and cyprinids) and at least 20 introduced species. Anadromous salmonids in the Lake Washington basin include sockeye salmon *O. nerka*, Chinook salmon, coho salmon *O. kisutch,* and steelhead *O. mykiss*. Sockeye salmon are by far the most abundant anadromous salmonid in the basin with adult returns of sockeye salmon exceeding 350,000 fish in some years (Fresh and Lucchetti 2000).

Historically, the Duwamish River watershed, which included the Cedar River, provided both riverine and estuarine habitat for indigenous anadromous salmonids. Beginning in 1912, drainage patterns of the Cedar River and Lake Washington were extensively altered (Weitkamp and Ruggerone 2000). Most importantly, the Cedar River was diverted into Lake Washington from the Duwamish River watershed, and the outlet of the lake was rerouted through the LWSC. These activities changed fish migration routes and environmental conditions encountered by migrants.

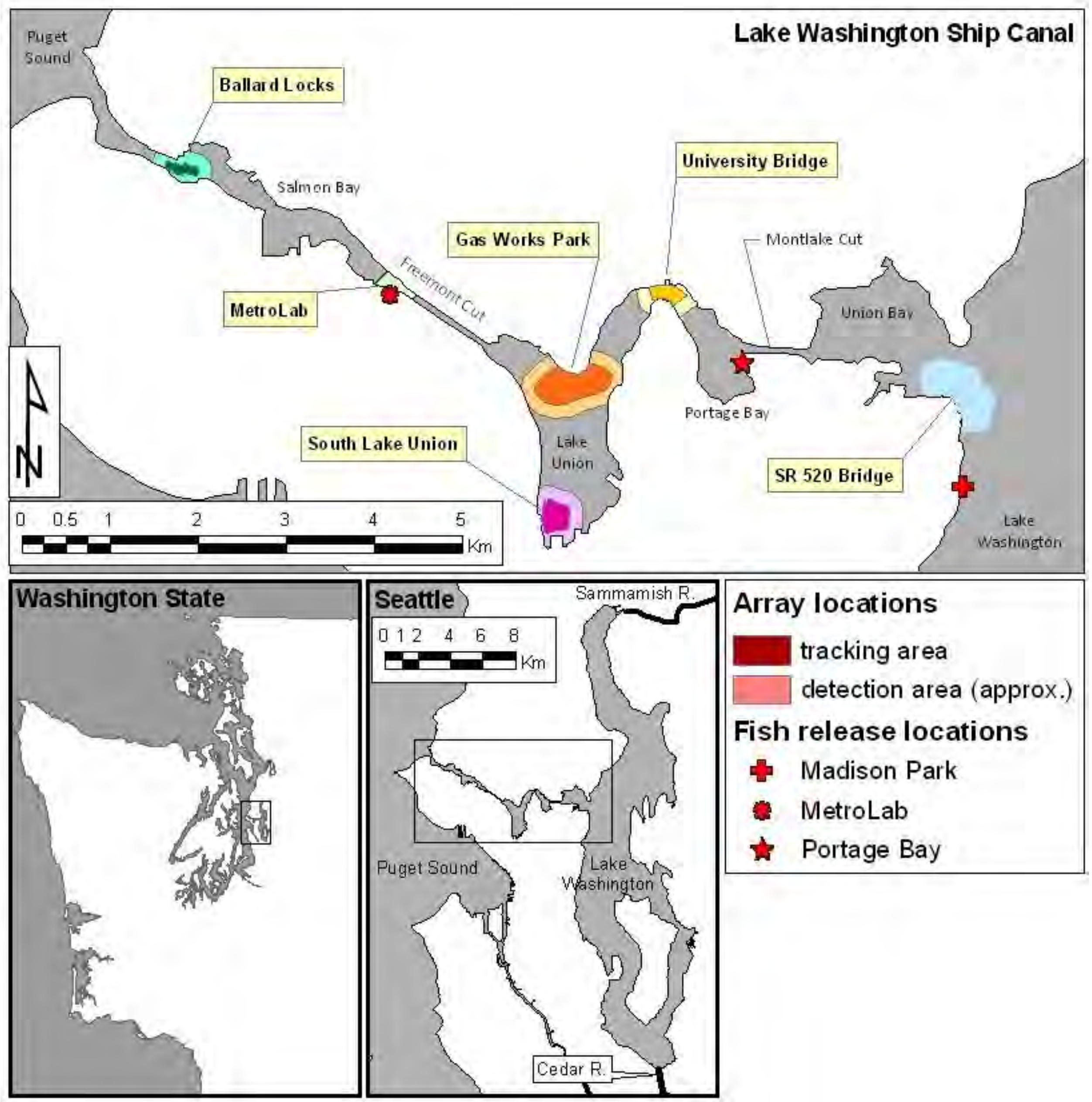

FIGURE 1. Map of the Lake Washington Ship Canal, including study site locations, June-July, 2007-2008. Study sites included: University Bridge, Gas Works Park, South Lake Union, MetroLab (presence/absence only), and Ballard Locks. The SR 520 Bridge site was part of an allied study (Celedonia et al. 2008a). In 2007, SR 520 study fish were released at Madison Park and tracked at the LWSC study sites (present study) in addition to being tracked at SR 520. Tagged Chinook salmon smolts for the present LWSC study were released at Portage Bay in both 2007 and 2008 and at MetroLab in 2008. Tracking area (shown in darker shading) of each site was where triangulated fish tracks were obtained. Approximate detection area (shown in lighter shading) of each site was where tagged fish could be detected but not tracked (i.e., presence/absence was available within the detection area).

The largest run of naturally-produced Chinook salmon in the Lake Washington basin occurs in the Cedar River. Large numbers of adult fish also spawn in Bear Creek. Small numbers of Chinook salmon spawn in several tributaries to Lake Washington and Lake Sammamish. Most hatchery production occurs at the Washington Department of Fish and Wildlife's Issaquah Creek Hatchery. Chinook salmon also spawn below the hatchery and other adults are allowed to migrate upstream of the hatchery if the hatchery production goal of returning adults is met. Additional hatchery production occurs at the University of Washington (UW) Hatchery in Portage Bay.

Adult Chinook salmon enter the Lake Washington system from Puget Sound through the Ballard Locks in July through September. Peak upstream migration past the locks usually occurs in August. Adult Chinook salmon begin entering the spawning streams in September and continue until November. Spawning occurs from October to December with peak spawning activity usually in the first few weeks of October (Burton et al. 2009).

Fry emerge from their redds from January to early-April (Kiyohara and Zimmerman 2009). Juvenile Chinook salmon appear to have two rearing strategies: rear in the river or creek and emigrate to the lake as pre-smolts in May, June, or July, or emigrate as fry between January and mid-May and rear in the south or north end of Lake Washington or in Lake Sammamish for several months. Juvenile Chinook salmon are released from the Issaquah Creek Hatchery in May or early June and large numbers enter Lake Sammamish a few hours after release (B. Footen, Muckleshoot Indian Tribe, personal communication). Juveniles migrate to the ocean in their first year, and thus Lake Washington Chinook salmon are considered "ocean-type" fish. Studies suggest that active migration in Lake Washington and the LWSC occurs primarily during the day and also frequently at dawn (DeVries et al. 2005; Celedonia et al. 2008b; DeVries et al. 2008; M. Celedonia, unpublished data). Fish may pause in their migration and hold for several hours to days in certain locations (Celedonia et al. 2008a; Celedonia et al. 2008b; Celedonia et al. 2009). Holding behaviors are observed during day, night, and crepuscular periods. Smolts migrate past the Ballard Locks from about mid-May to mid-July or later, with peak migration occurring from late May through June (DeVries et al. 2002; DeVries et al. 2003;. DeVries et al. 2005; DeVries et al. 2007; DeVries et al. 2008).

METHODS

Acoustic tracking equipment

Acoustic tracking equipment used in 2007 and 2008 was identical to that used in 2004-2005 (Celedonia et al. 2008b). Construction of hydrophone bottom-mounts is described in Celedonia et al. (2008b). Most hydrophone surface mounts were constructed of 2.54-cm-diameter conduit and attached to wood pilings with screws. Two surface mounts at the Ballard Locks were constructed of heavy-duty aluminum pipe and attached to pier walls with bolts embedded in the concrete. Surface mounted hydrophones were generally about 1.25 m below the water surface. StowAway TidbiT temperature loggers were mounted on all bottom- and surface-mounted hydrophones. Temperature loggers were programmed to record water temperature at 30-min intervals. Once hydrophones were deployed, we performed extensive system testing to ensure sufficient operability and quality of data. Testing included ping-arounds, tag drags, and in some cases release of tagged test fish (coho salmon). The size of the tracking area at each study site was determined using results of tag drags and Chinook salmon and predator data points. Tag drags consisted of moving activated tags throughout a study site. During the tag drag, a GPS unit was used to track the tag path. The GPS track was compared to the acoustic track to verify accuracy of the latter. The resultant acoustic track was also used to verify the boundary of the tracking area.

The area of a site where triangulated fish positions are obtained is termed the tracking area. This is where tag signals are received by at least three or four hydrophones at the same time, and generally includes all areas within the perimeter of the hydrophone array and areas relatively near the perimeter. Outside of the tracking area lies an area where tag signals may be received by only one or two hydrophones. This area combined with the tracking area is called the detection area. The detection area provides useful presence/absence data, particularly at a site like Gas Works Park where the tracking area did not cover the full width of the channel but the detection area did. This enabled us to track movements of all tagged fish into and out from Lake Union.

Hydrophone array configuration and operation

Hydrophone arrays were deployed at five sites in the LWSC in 2007 and 2008: University Bridge, Gas Works Park, South Lake Union, MetroLab, and Ballard Locks (Figure 1). The MetroLab site was located at the western end of the Fremont Cut near the King County Environmental Lab. Two hydrophones were deployed at this site, and were intended to provide presence/absence data only. Hydrophone arrays at the other four sites were intended to provide fine-scale fish tracks. Characteristics of these sites and the hydrophone arrays are described below.

University Bridge

The University Bridge site was located between Portage Bay and Lake Union in a relatively narrow portion of the LWSC. The tracking area was beneath and adjacent to the University Bridge and the I-5 bridge (Figure 2). The University Bridge has two large in-water support structures with piling and wood wing-wall extensions on the sides closest to mid-channel. This bridge is relatively near the water surface, about 10 m above the water. The I-5 bridge has no in-water support structures and is much higher above the water surface, about 50 m above the water. The southern shoreline of the site consists mostly of houseboats and private docks. There is a small park on the southwestern part of the site beneath the I-5 bridge where the shoreline is more open. The northern shoreline contains numerous commercial and industrial overwater structures. Patches of moderately dense to dense aquatic macrophytes – mostly Brazilian elodea *Egeria densa* – grow at depths < 4 m along each shoreline. Gradient was somewhat steep on both sides to depths of about 10 m. The bottom was relatively flat across the middle of the channel.

We deployed 12 hydrophones at this site in both 2007 and 2008 (Figure 2). Hydrophone configuration was nearly identical in both years. The tracking area measured approximately 370 m long and 160 m wide, and totaled 0.062 km^2. The eight hydrophones on the east side of the site (i.e., closest to the University Bridge) were configured to provide accurate vertical, as well as horizontal results. This three-dimensional (3D) tracking area measured 0.013 km^2 in 2007, and 0.007 km^2 in 2008. The two farthest-east hydrophones were not used in 3D tracking in 2008 because these hydrophones provided erroneous results, possibly due to inaccurate position recording at deployment and/or movement after deployment (e.g., by a boat anchor snagging the cable and moving the hydrophone). The four hydrophones on the west side of the site (i.e., closest to the I-5 bridge) were intended to provide accurate horizontal results only.

Gas Works Park

The Gas Works Park site was located on the northern end of Lake Union (Figure 1). The lake bottom here was largely flat at depths of about 11 m (Figure 3). Gradient in the western part of the site was extremely steep, reaching maximum depths within 40 m of shore. Gradient in the eastern part of the site was less severe, reaching maximum depths within 100 m of shore. Substrate throughout much of the site was sand and silt. Some small patches of Eurasian milfoil *Myriophyllum spicatum* were present along the northern shore of the site in water 2-6 m deep. Large debris was present but sparse. The shoreline along this site consisted of three main areas: the eastern part was concrete bulkhead, the central part was riprap, and the western part was largely composed of numerous piers and docks. We deployed 16 hydrophones at this site in both 2007 and 2008 (Figure 3). Hydrophone configuration was similar in both years with some minor differences, and was intended to provide accurate horizontal results only. The tracking area measured approximately 880 m long and 320 m wide, and totaled 0.249 km^2 and 0.268 km^2 in 2007 and 2008, respectively. Differences in tracking area resulted from slightly different hydrophone positions on the western side of the site. On the eastern side of the site, several hydrophone mounts were apparently disturbed after deployment in 2007 which resulted in a reduced tracking area on this side.

South Lake Union

The South Lake Union site was located along the southwestern shoreline of Lake Union near the AGC building, and the Argosy Cruises and Kenmore Air docks (Figure 4). Shoreline here was almost exclusively boat docks and other overwater structures. This site had a unique bathymetric feature in that there was not a simple gradient from the shoreline to the lake bottom. Instead, there was a ridge that ran from the southern to the northern part of the site about 80-200 m from the shoreline (Figure 4). Aquatic macrophytes grew on this ridge in the northern part of the site; otherwise macrophytes were generally not found on site. Beyond the ridge, bathymetry flattened out at maximum depths of 12-13 m. We deployed 10 hydrophones at this site in both 2007 and 2008. Hydrophone configuration was similar in both years with some minor differences, and was intended to provide accurate horizontal results only. The tracking area measured approximately 370 m long and 320 m wide, and totaled 0.109 km^2 and 0.097 km^2 in 2007 and 2008, respectively. The smaller tracking area in 2008 likely resulted from partial obstruction of one hydrophone by debris.

University Bridge

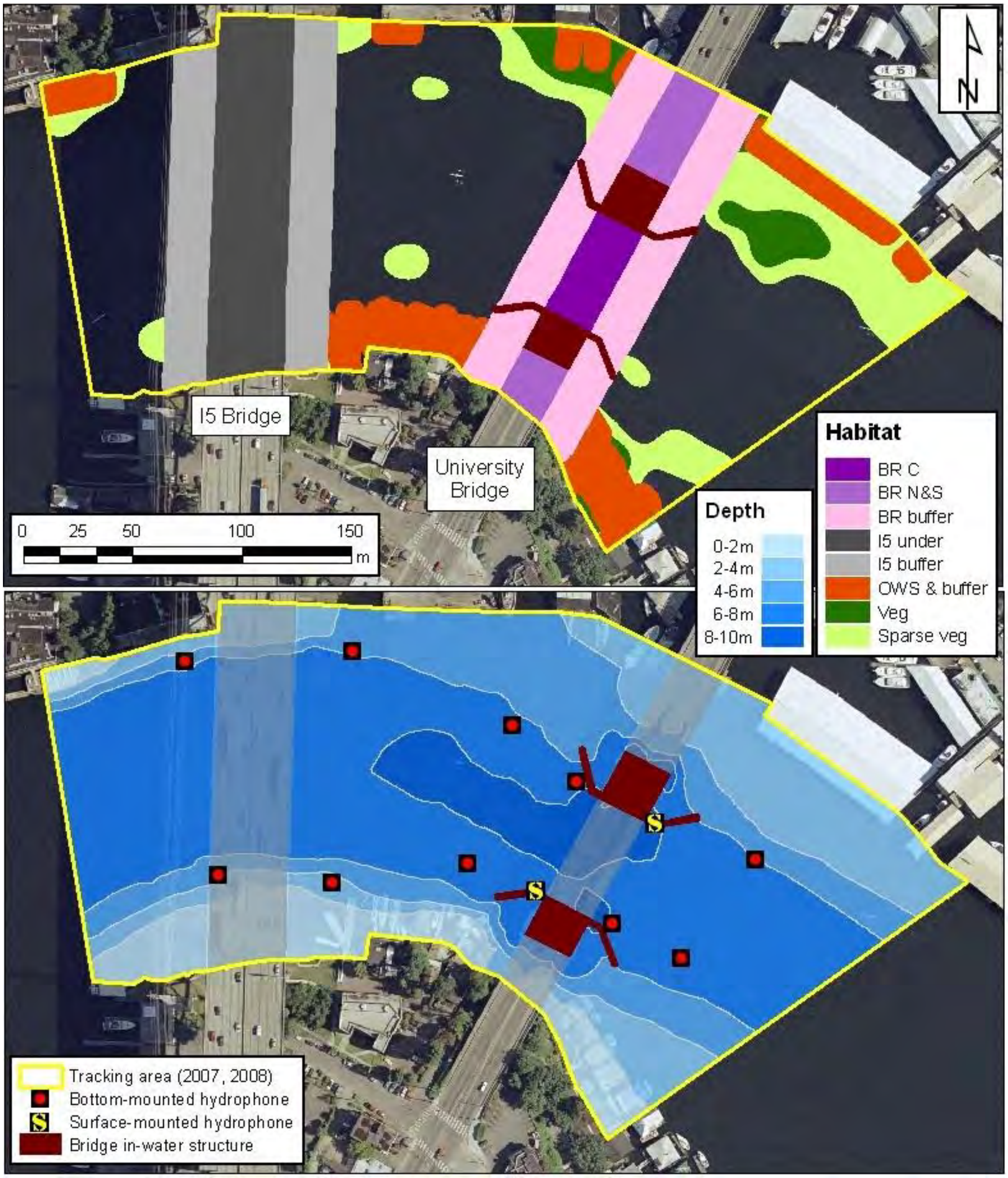

FIGURE 2. Maps of the University Bridge study site, June-July, 2007-2008, showing habitat units (top panel) and hydrophone locations, tracking area, and bathymetry (bottom panel). See Table 2 for habitat unit abbreviations and descriptions. Bridge in-water structure and sparse vegetation are shown for reference only and were not used in habitat selection calculations.

Gas Works Park

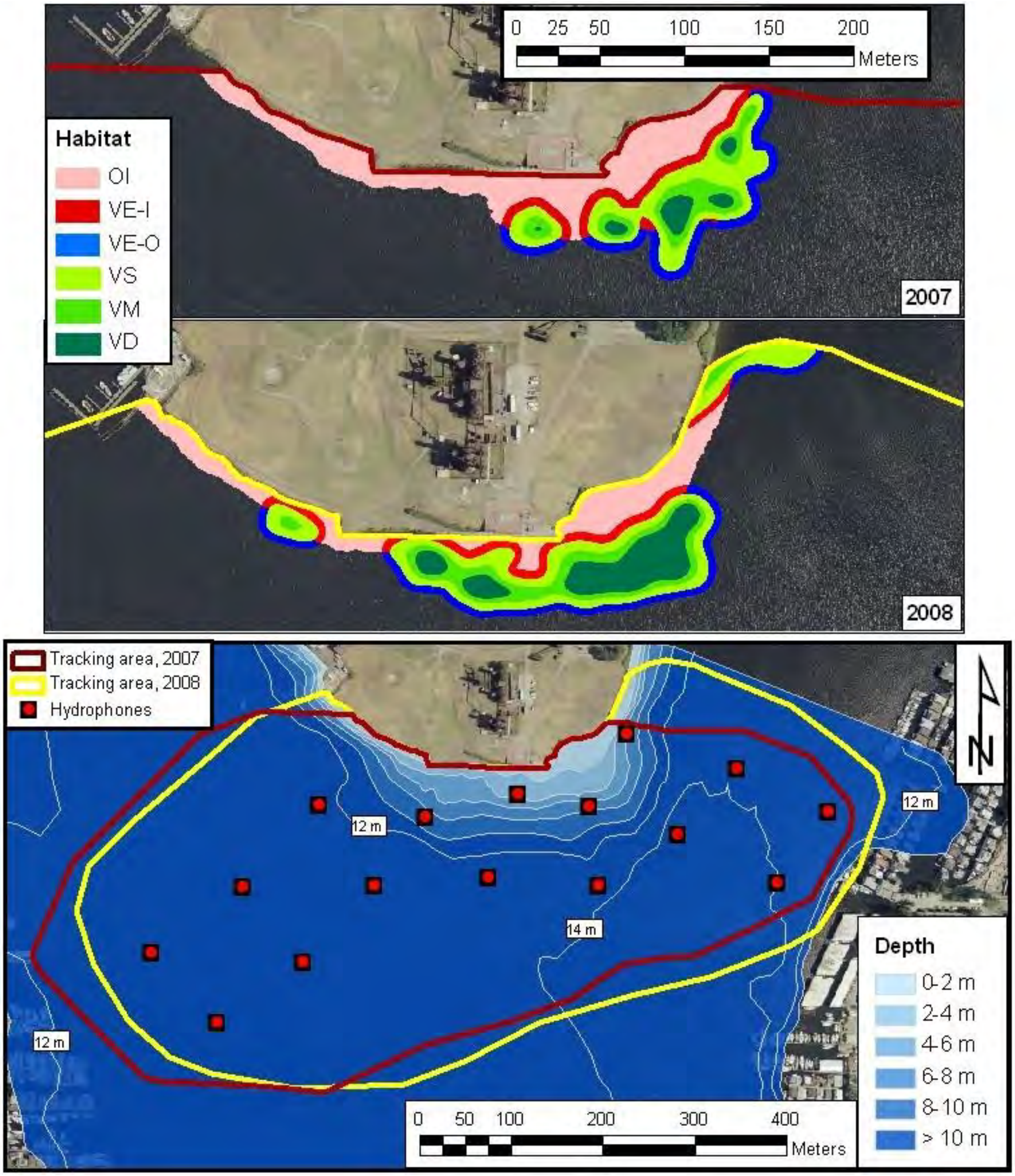

FIGURE 3. Maps of the Gas Works Park study site, June-July, 2007-2008, showing hydrophone locations, tracking areas, and bathymetry (bottom panel), and habitat units (top and middle panels). See Table 2 for habitat unit abbreviations and descriptions. The open water, offshore habitat unit includes all areas of the site not included in one of the other habitat units shown on the map.

South Lake Union

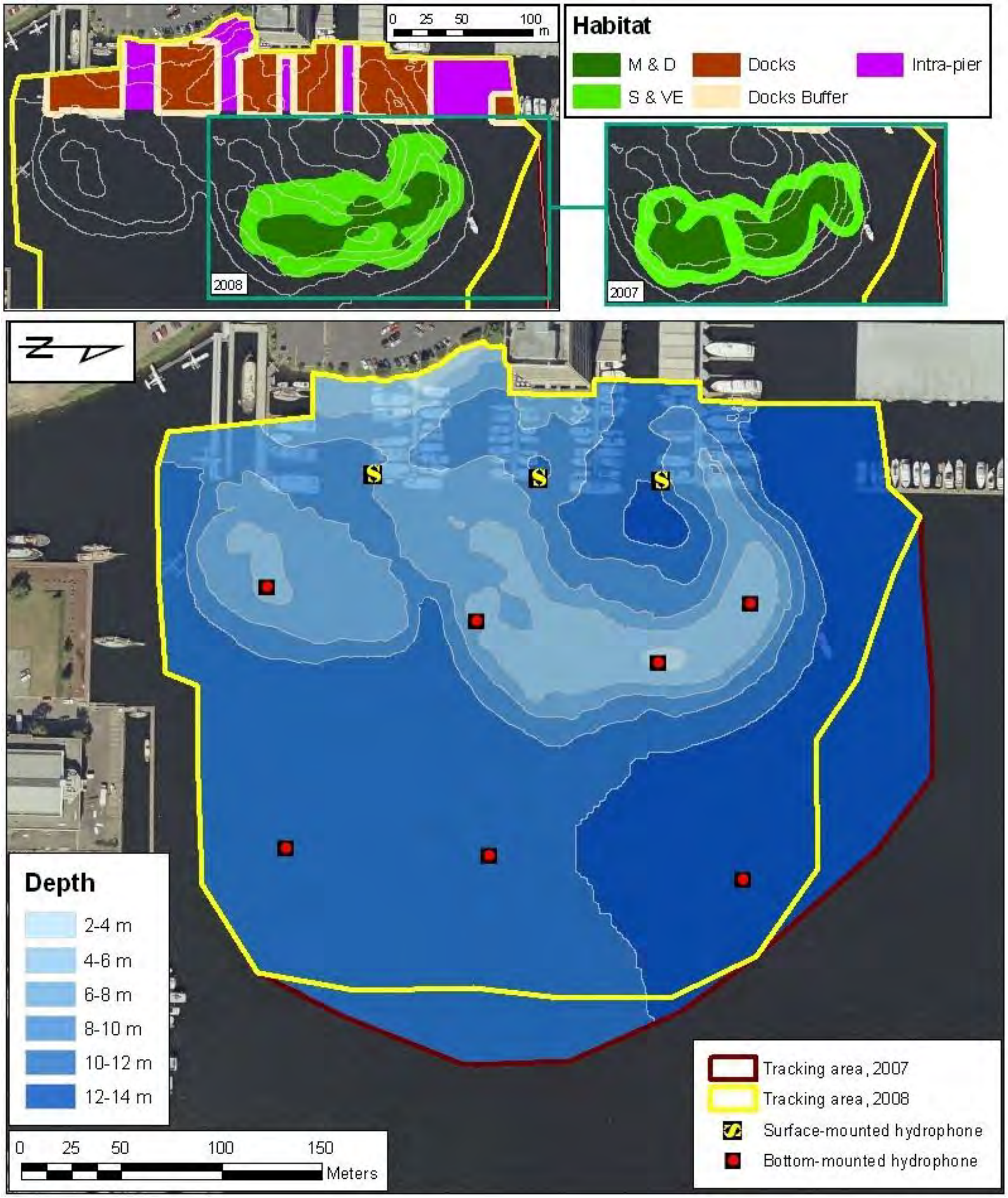

FIGURE 4. Maps of the South Lake Union study site, June-July, 2007-2008, showing hydrophone locations, tracking areas, and bathymetry (bottom panel), and habitat units (top panels). See Table 2 for habitat unit abbreviations and descriptions. The open water unit includes all areas of the site not included in one of the other habitat units shown on the map.

<u>Ballard Locks</u>

The Ballard Locks site encompassed the freshwater side of the locks and included all possible exit pathways for migrating fish (Figure 5). A wooden pier wall supported by pilings extended along the northern portion of the site. The wall extended about 1 m below the surface of the water and was open underneath. At 25 m from the entrance to the large locks, the wood wall ended at a concrete structure that separated the large lock chamber from the shipyard area to the north. A large concrete finger pier separated the large lock from the small lock, and a smaller concrete finger pier separated the small lock from the forebay to the south. A saltwater drain was located on the southeastern tip of the large finger pier. Six spillways were spread along the length of the forebay. Smolt passage flumes were located on second and third spillways from the south. A fish ladder was located in the southwest corner of the site. A private marina extended along the southern shoreline, and a large industrial dock structure was located in the southeastern part of the site. Possible exit pathways for migrating fish included: the smolt flumes, the other spillways (when in operation), the large lock, the small lock, the saltwater drain, and the fish ladder.

Maximum water depth was about 15 m in front of the large locks, about 8-10 m in the area between the entrances to the small and large locks, and about 5 m in the forebay area. We deployed 12 hydrophones at this site in both 2007 and 2008 (Figure 5). Hydrophone configuration was nearly identical in both years. The tracking area measured approximately 330 m long and 160 m wide, and totaled 0.050 km^2. The four eastern-most hydrophones were configured to provide accurate vertical as well as horizontal results at the entrance to the large locks. This three-dimensional (3D) tracking area measured 0.006 km^2. All other hydrophones were intended to provide accurate horizontal results only.

Fish tagging and release

Hatchery-reared smolts obtained from Washington State's Issaquah Hatchery were used for this study. Previous studies indicate that travel times, horizontal spatial distribution, habitat use, and movement patterns were generally equivalent between Issaquah Hatchery and naturally-produced Chinook salmon smolts in Lake Washington and the LWSC (Celedonia et al. 2008b). Also, multi-year PIT tagging studies indicate that movement timing of Issaquah Hatchery juveniles is similar to their naturally-produced counterparts (DeVries et al. 2005; DeVries et al. 2007). Therefore, Issaquah Hatchery Chinook salmon smolts were assumed to provide a reasonable surrogate for naturally-produced fish for the purposes of this study.

Study fish were held and reared at the Issaquah Hatchery until tagging. Juveniles intended for this study were held in a separate tank at the hatchery. In 2007, fish were placed on an accelerated growth regimen to ensure that sufficient numbers of adequately sized fish would be available for tagging when needed. The accelerated growth regimen consisted of rearing the fish in warmer water than what is normally used at the hatchery. Study fish were transported from the Issaquah Hatchery to the King County Environmental Laboratory (MetroLab) the Monday or Tuesday prior to release. Fish were mildly anesthetized in a solution of tricaine methane sulphonate (MS-222) and measured prior to transport to ensure that they were of sufficient size

Ballard Locks

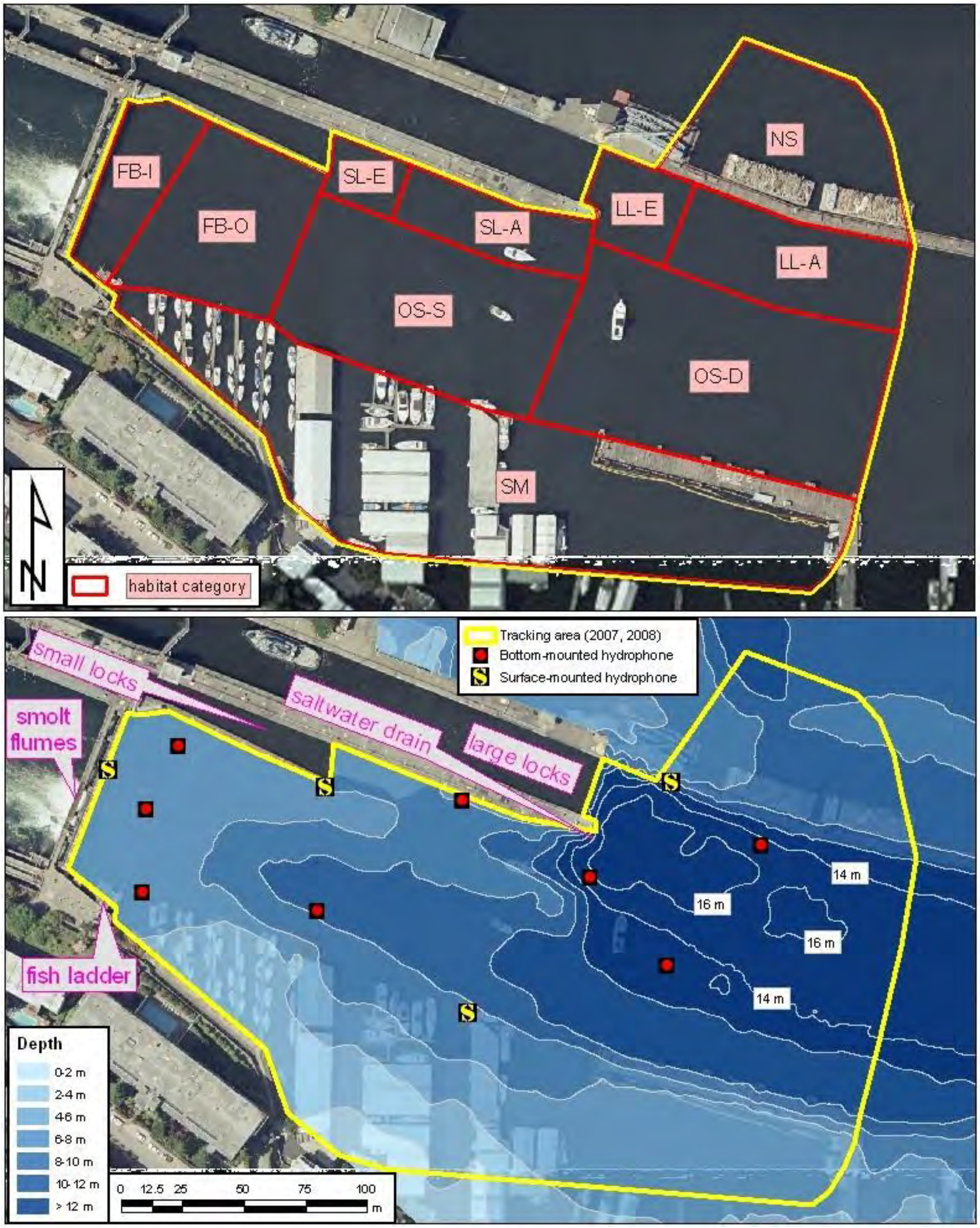

FIGURE 5. Maps of the Ballard Locks study site, June-July, 2007-2008, showing hydrophone locations, tracking area, bathymetry, and possible fish passage routes (bottom panel), and habitat units (top panel). See Table 2 for habitat unit abbreviations and descriptions.

to tag. Fish were acclimated from Issaquah Hatchery water temperature (approximately 13°C) to MetroLab temperature over a period of approximately 0.5 h. Temperatures between the two facilities were generally within 3°C of each other. Fish were allowed to recover from transport for approximately 24 h prior to tagging.

All tags were implanted using a surgical procedure. This procedure is described in Celedonia et al. (2008b). Two sizes of acoustic tags were used. In general, larger smolts (≥ 12.5 g) were implanted with HTI Model 795m MicroAcoustic Tags. These tags weighed 0.75 g in air, and measured 6.8 mm in diameter and 16.5 mm in length. Smaller smolts were implanted with HTI Model 795s MicroAcoustic Tags, which weighed 0.65 g in air and measured 6.7 mm in diameter and 16.4 mm in length. In general, we maintained a tag weight to fish weight ratio of ≤ 6%. Studies on the effects of tagging on fish behavior suggest that this is an appropriate ratio (Adams et al. 1998; Brown et al. 1999; Anglea et al. 2004). Tags were programmed with ping rates of 2.5-3.6 s. Each tag received a unique ping rate which allowed it to be distinguished from all other tags. After implant, fish were placed in a recovery tank where they remained for 24-48 h prior to release. Dead fish or fish behaving abnormally were removed from the sample.

In 2007, implanted tags were programmed the morning of release at the University of Washington Hatchery. Fish were transported from the King County Lab to the University of Washington Hatchery during late-afternoon the day prior to release. An in-situ tag programmer developed by HTI was used to program and switch tags on the morning of release. This device is a large plastic tube with a programming coil in the center. Fish were placed in one end of the tube, and flowing water was used to help guide individual fish into the programming coil. Once the fish was in the coil area, gates were closed at either end to hold the fish in place. The programming coil was connected to a laptop computer which was used to program the tag and switch the tag on. Once this was accomplished, the gate at the downstream end of the coil was opened and the fish was transported via flowing water into a temporary holding tank. Independent acoustic verifiers on the programming coil and in the holding tank verified that tags had been switched on. The entire programming process and transport to the release site was performed without anesthetic. Tag batteries were expected to last 14 days after fish release.

In 2008 we did not use the in-situ tag programmer. Instead, Chinook salmon tags were programmed and switched on at the time of implant. Tag battery life was therefore "lost" during the post-implant/pre-release recovery period. As a result, we expected tag batteries to last approximately 12 days after the fish were released.

In 2007, study fish were released in Portage Bay along the southwest shoreline at West Montlake Park. Fish were released in water 1.5-2.0 m deep and away from overwater structures. In 2008 we released fish at two locations: the same Portage Bay location as in 2007, and in the Fremont Cut off the dock at the King County Environmental Lab. We released fish in the Fremont Cut to bolster the number of fish observed at the Ballard Locks.

In 2007, we performed a similar acoustic tracking study at the SR 520 bridge for the Washington State Department of Transportation (WSDOT) (Celedonia et al. 2008a). For this WSDOT study we released 171 tagged Chinook salmon smolts at Madison Park about 1 km south of the SR 520 bridge. Because we used identical equipment in these two studies, we were able to detect and track these WSDOT fish at all of our tracking arrays in the LWSC. We therefore included WSDOT fish in all of our analyses for 2007. Fish origin, size, tagging procedures, etc. were similar if not identical between the two studies. Specific details can be found in Celedonia et al. (2008a).

Data analysis

Each raw data file was evaluated for the presence of all fish released within 14 days prior to the time period included in the file for 2007 fish, and 12 days prior for 2008 fish. Raw acoustic data was used to determine general site area residence times and site-to-site travel times of tagged fish. The general site area residence time was defined as the time from the first detection at the site to the last detection at the site, regardless of any gaps in between. For example, a fish may be detected on-site, then leave the area and go undetected for some amount of time, then appear on-site again. Fish showing such discontinuities were assumed to remain relatively near the tracking site. The total amount of time a fish is actually tracked on site exclusive of gaps when the fish is not present is termed tracking time.

Data were represented and evaluated with parametric or nonparametric statistics depending on the type of distribution observed (Zar 1999; Sheskin 2000). Minimally-skewed data (e.g., fish lengths and weights) were evaluated with a pooled-variance t-test or single-factor between-subjects analysis of variance (ANOVA). More strongly skewed data (e.g., travel and residence times) were evaluated with a Mann-Whitney U test or Kruskal-Wallis one-way analysis of variance. Unless otherwise noted, statistical significance was established at $\alpha = 0.05$. Multiple and/or complex comparisons were performed using Tukey's HSD (simple comparisons with equal sample sizes) or the Scheffé test (simple comparisons with unequal sample sizes and complex comparisons) for significant ANOVA's, and the Bonferroni-adjusted Mann-Whitney U test for significant Kruskal-Wallis tests (Sheskin 2000). Familywise error rate used for multiple and complex comparisons was $\alpha_{FW} = 0.05$ except for Scheffé tests for which we used $\alpha_{FW} = 0.10$. Sheskin (2000) notes that the larger α_{FW} is appropriate because of the highly conservative nature of this test.

Fish location point data output from the AcousticTag software was imported into ArcMap 9.2 Geographic Information System (GIS) software. Fish tracks were graphically represented and analyzed by overlaying them on an orthophoto of the site with bathymetry and vegetation contours. Each fish track was evaluated for signs of mortality which included one or more of the following: 1) no sign of fish movement in the fish track; 2) no sign of fish movement in the raw hydrophone data; 3) fish movements resembling those of known predators (i.e., smallmouth bass); and, 4) extraordinarily unusual characteristics in the fish track. If a fish showed signs of mortality, it was removed from the data set, and no part of the fish track was used for analysis. An existing orthophoto and bathymetry data were obtained from SPU. Bathymetry was checked against depth measurements that we collected while surveying for aquatic macrophytes. SPU bathymetry data was generally accurate; however some adjustments were necessary at depths $\leq$ 4 m.

Spatial frequency distributions of fish at each site were generated using ArcGIS 9.2 Spatial Analyst. The total number of fish that occurred within a 4 m radius of each tracked fish data point was determined. Graphical representation of results provided an indication of Chinook salmon dispersal throughout the site and highlighted areas of the site that were commonly used by the fish. For analyses involving diel periods, day was defined as the period from one hour after sunrise to one hour before sunset. Night was defined as the period from one hour after sunset to one hour before sunrise. Dawn and dusk were defined as the periods between day and night. Early day was separated from late day at 14:00 hours.

To evaluate the influence of water temperature on fish behavior and habitat use, the study period was divided into three temperature regimes based on predominant surface water temperature at 1-2 m depth: < 18°C, 18-20°C, and > 20°C (Table 1). At the University Bridge, Gas Works Park, and South Lake Union study sites, 17°C was used instead of 18°C in 2007 because too few fish were present at 18-20°C. Exact dates of temperature regimes differed between the Ballard Locks and the other three study sites due to minor variations in temperature (Table 1).

We evaluated population-level habitat selection and selection for total water column depth – also called depth-to-bottom or bottom depth - for each release group of fish. For habitat selection, each site was segregated into discrete habitat units (Table 2). Bottom depth selection was based on depth of the entire water column, not the vertical position of the fish in the water column. For bottom depth selection, the tracking area was segregated into 2 m intervals based on total water column depth (i.e., 0-2 m, 2-4 m, etc.). The total horizontal area of each habitat and bottom depth category contained within the tracking area was considered that category's availability. For each fish, the proportion of points lying within each habitat or bottom depth category was used as a surrogate for the amount of time spent in that habitat or bottom depth. This assumes that the ability to track tagged fish is equal throughout the tracking area, including all habitats and bottom depths. The point data for each fish were separated into appropriate habitat and bottom depth categories using standard tools in ArcMap 9.2.

TABLE 1. Temperature regimes used to evaluate influence of temperature on behavior and habitat selection of tagged Chinook salmon in the Lake Washington Ship Canal, June-July, 2007-2008.

2007		2008	
Temperature regime	Dates	Temperature regime	Dates
University Bridge, Gas Works Park, South Lake Union			
< 18°C	6/1 – 6/20	< 17°C	6/19 – 6/23
18-20°C	6/21 – 7/2	17-20°C	6/24 – 6/30
> 20°C	7/3 – 7/15	> 20°C	7/1 – 7/12
Ballard Locks			
< 18°C	6/2 – 6/22	< 18°C	6/21 – 6/29
18-20°C	6/23 – 7/6	18-20°C	6/30 – 7/13
> 20°C	7/7 – 7/18	> 20°C	7/14 – 7/23

From Manly et al. (2002), the selection ratio for the j[th] fish and the i[th] habitat (or bottom depth category), was calculated as

$$\hat{w}_{ij} = (u_{ij} / u_{+j}) / \pi_i$$

where u_{ij} is the amount of time spent in habitat i by fish j, u_{+j} is the amount of time fish j was tracked across all habitat types, and π_i is the proportion of available habitat of type i relative to all available habitats at the study site. For each release group of fish, a mean population-level selection ratio for each habitat type was calculated as

$$\hat{w}_i^{'} = \sum_{j=1}^{n} \hat{w}_{ij} / n$$

where n is the number of fish tracked across all habitat types.

To determine if there was significant selection among a release group of fish for a particular habitat type, simultaneous Bonferroni 90% confidence intervals were calculated as

$$\hat{w}_i^{'} \pm z_{\alpha(2I)} SE(\hat{w}_i^{'})$$

where I is the number of habitat types, and

$$SE(\hat{w}_i^{'}) = \sqrt{\frac{1}{n(n-1)} \sum_{j=1}^{n} (\hat{w}_{ij} - \hat{w}_i^{'})^2}$$

Selection for a habitat type is demonstrated when the lower confidence interval is > 1, and selection against a habitat type is demonstrated when the upper confidence interval is < 1. Confidence intervals that include 1 indicate proportional distribution across that habitat type. That is, the habitat type is neither selected for nor selected against, but rather is used in proportion to its availability.

The methods used to evaluate habitat and bottom depth selection avoid the problem of pseudoreplication by taking each animal as the experimental unit (Aebischer et al. 1993; Garton et al. 2001; Manly et al. 2002; Rogers and White 2007). Also, by evaluating each animal's proportional habitat and depth use, serial correlation between an individual's data points does not present a problem (Aebischer et al. 1993; Rogers and White 2007). In fact, the high frequency of location sampling achieved with the HTI system provides a concomitantly high level of detail with regard to habitat use. Such detail, according to Aebischer et al. (1993), provides more precise estimates of habitat use, and the associated high degree of serial correlation is rendered a non-issue as long as proportional habitat use of individuals is the basis for analysis.

TABLE 2. Habitat types used to determine habitat selection at four study sites, University Bridge, Gas Works Park, South Lake Union, and Ballard Locks, June-July, 2007-2008. See Figures 2-5 for maps showing habitat units at each site.

			Area (ha)		Area (%)	
Habitat Type	Abbreviation	Description	2007	2008	2007	2008
University Bridge						
U. Bridge, mid-channel	BR C	Area directly under the mid-channel span of the bridge.	0.13	0.13	2.1	2.1
U. Bridge, near shore	BR N&S	Area directly under the sections of the bridge that lie north of the north support structure and south of the south support structure.	0.27	0.27	4.4	4.4
U. Bridge buffer, center	BR buffer-C	Area within 20 m of the edge of the mid-channel bridge span.	0.24	0.24	3.9	3.9
U. Bridge buffer, north and south	BR buffer-N&S	Area within 20 m of the edge of the north and south bridge spans.	0.45	0.45	7.3	7.3
I-5 bridge under	I5 under	Area directly under the I-5 bridge.	0.60	0.60	9.5	9.5
I-5 bridge buffer	I5 buffer	Area within 20 m of the I-5 bridge	0.64	0.64	10.3	10.3
Overwater structures and buffer	OWS & buffer	Area directly under and within 5 m of overwater structures (other than bridges).	0.56	0.56	9.1	9.1
Vegetation	Veg	Area with moderately dense or dense macrophytes and not in a bridge, structure, or buffer habitat unit.	0.17	0.17	2.7	2.7
Open water	OW	Area not included in the other categories.	3.13	3.13	50.7	50.7
Gas Works Park						
Open water, inshore	OI	Inshore (< 4 m depth) unvegetated area, not within 5 m of macrophytes.	0.51	0.43	2.05	1.59
Open water, offshore	OO	Offshore (≥ 4 m depth) unvegetated area, not within 5 m of macrophytes.	23.77	25.23	95.37	94.24
Dense vegetation	VD	Area of dense macrophytes.	0.06	0.26	0.24	0.97
Vegetation edge, inshore	VE-I	Inshore (< 4 m depth) unvegetated area, within 5 m of macrophytes.	0.10	0.15	0.42	0.55
Vegetation edge, offshore	VE-O	Offshore (≥ 4 m depth) unvegetated area, within 5 m of macrophytes.	0.13	0.19	0.54	0.72
Vegetation, moderate	VM	Area of moderate macrophytes.	0.13	0.21	0.51	0.78
Vegetation, sparse	VS	Area of sparse macrophytes.	0.22	0.30	0.87	1.13

TABLE 2. (cont.)

Habitat Type	Abbreviation	Description	Area (ha) 2007	Area (ha) 2008	Area (%) 2007	Area (%) 2008
South Lake Union						
Docks	Docks	Area directly under docks.	1.07	0.40	8.56	4.06
Docks buffer	Docks buffer	Area within 5 m of docks.	0.42	0.80	3.38	8.17
Intra-pier	Intra-pier	Area between docks.	0.26	0.27	2.04	2.76
Moderate and dense vegetation	M & D	Area of moderately dense and dense macrophytes.	0.48	0.33	3.89	3.44
Sparse vegetation and vegetation edge	S & VE	Areas of sparse vegetation and within 5 m of macrophytes.	0.50	0.73	3.96	7.49
Open water	OW	Area not included in the other categories.	9.82	7.22	78.20	74.07
Ballard Locks						
Forebay, Inner	FB-I	Forebay area within 30 m of the spillway.	0.20	0.20	3.98	3.98
Forebay, Outer	FB-O	Area adjacent to the inner forebay.	0.42	0.42	8.26	8.26
Small lock entrance	SL-E	Area immediately outside of the small lock chamber.	0.08	0.08	1.58	1.58
Small lock approach	SL-A	Area leading up to the small lock entrance.	0.20	0.20	3.87	3.87
Large lock entrance	LL-E	Area immediately outside of the large lock chamber.	0.14	0.14	2.75	2.75
Large lock approach	LL-A	Area leading up to the large lock entrance.	0.34	0.34	6.81	6.81
Offshore, Deep	OS-D	Mid-channel area south of the large lock approach and entrance.	0.94	0.94	18.69	18.69
Offshore, Shallow	OS-S	Mid-channel area south of the small lock approach and entrance.	0.67	0.67	13.26	13.26
North shipyard	NS	Area north of the large lock approach and entrance.	0.51	0.51	10.14	10.14
South marina	SM	Southern part of the tracking area containing numerous boat docks and overwater structures.	1.55	1.55	30.65	30.65

Fish vertical position selection within the water column was evaluated at parts of two sites: University Bridge and Ballard Locks. Vertical position selection could not be evaluated in other areas of these sites, at Gas Works Park, or at South Lake Union because proper hydrophone geometry was unattainable in these other areas. Similar methods as those used for habitat selection were used to evaluate vertical position selection. Fish vertical positions were grouped into depth strata at 3 m intervals (i.e., 0-3 m, 3-6 m, etc.). Fish vertical position selection was compared between the three temperature regimes at each site.

Relative use of the various available exit pathways into Puget Sound were evaluated at the Ballard Locks. The last point locations for each fish were identified in ArcGIS. When these occurred in close proximity to an exit pathway, we assumed that the fish exited via that pathway. Fish with last point locations not near an exit were assigned a designation of "did not exit." These fish may have residualized or they may have exited after their tag batteries expired, at which point they would have been unobservable to the tracking gear. Particular emphasis was placed on the smolt flumes and the forebay area in our exit pathway and behavioral analyses. One management goal for Chinook salmon at the Ballard Locks is to maximize use of the smolt flumes. In this light, the forebay area is important in that fish must enter and traverse the forebay in order to use the smolt flumes. If fish are unwilling or unable to enter the forebay, they cannot exit through the smolt flumes. Thus, evaluating use of the forebay in relation to exiting behavior is critical for understanding the roles that both the smolt flumes and the forebay play in attracting or deterring fish from exiting.

Water quality and aquatic macrophytes

Water quality was periodically sampled at each study site during the study period. Sample point locations were selected to represent the variety of habitat types throughout the study area (e.g., shallow water and deep water, vegetated areas and unvegetated areas, nearshore and offshore). In 2007, 6-11 points were sampled at each site, and 2-4 points were sampled at each site in 2008. We sampled fewer points in 2008 because 2007 sampling suggested relative uniformity across each site. The following water quality parameters were sampled at each point: Secchi depth, temperature, dissolved oxygen, conductivity, and salinity. The latter four parameters were sampled at 1 m depth and then 2-m depth intervals thereafter to within 1 m of the substrate. Water quality was sampled once each week during the study period, commencing the week of the first release of tagged Chinook salmon, and concluding the week after the last release. All sampling was performed between 08:00 and 17:00. In 2007, sampling was conducted using a Hach Hydrolab MiniSonde 4a, and in 2008 a YSI 85 Instrument was used. All instruments were calibrated prior to sampling.

Macrophyte growth and water column depth to the top of macrophytes were monitored at the University Bridge and South Lake Union sites in 2008. At each site, two transects were established to represent distinct areas of each site where macrophytes were known to grow based on 2007 macrophyte mapping. Three sample points were established along each transect. A GPS unit was used to navigate a boat to each pre-established point. At each point, an underwater camera was lowered from the boat and the following data were collected: presence/absence of macrophytes; density of macrophytes; species of macrophyte(s) present; water column depth to top of macrophytes; and total water column depth. Macrophyte density was categorized according to ocular coverage within the viewing area of the camera: > 95% cover was categorized as "very high density"; 75-95% as "dense"; 25-75% as "moderate"; and 1-25% as sparse. Areas with < 1% cover were considered unvegetated. Monitoring was performed on the same days as water quality and zooplankton sampling.

In addition to monitoring macrophyte growth, we also conducted extensive macrophyte mapping surveys in both 2007 and 2008 at the University Bridge, Gas Works Park, and South Lake Union sites. We used a point-intercept method to survey macrophytes. Transects were established at approximate 20-m intervals perpendicular to shore, and survey points were established at approximate 15-m intervals along each transect. Survey methods were as described for macrophyte growth monitoring. Transects were surveyed to a depth of 10-11 m, which was the maximum depth macrophytes were expected. When presence/absence of macrophytes differed between two sequential points (e.g., present at one point, but not at the next), we attempted to locate a more precise location for the edge. The following numbers of points were surveyed: University Bridge, $n_{2007} = 117$, $n_{2008} = 175$; Gas Works Park, $n_{2007} = 170$, $n_{2008} = 188$; South Lake Union, $n_{2007} = 176$, $n_{2008} = 189$. We used the Spatial Analyst Spline tool in ArcGIS 9.2 to generate macrophyte density contours based on survey point data. For splining, we used n = 5 points and regularized with a weight value of 0.1.

Zooplankton sampling

Zooplankton was sampled at the Gas Works Park site in 2008 at two points to obtain an index of prey availability. One sample point was located near shore (70 m from shore), and the other off shore (230 m from shore). Zooplankton was collected with a 50-cm-diameter by 2-m high net with 500-µm mesh. We used a large-mesh net to eliminate small zooplankton that typically is not consumed by juvenile Chinook salmon (Craddock et al. 1976; Rondorf et al. 1990). At each sample point, we took one vertical sample of the upper 5 m. At the offshore point, we collected an additional sample of the upper 10 m. After lowering the net to the desired depth, it was slowly raised by hand to the surface. No estimate of net efficiency was made; however, we assumed the net efficiency was quite high because of the large mesh size and large net size. Each sample was placed in a sample jar and preserved with 10% formalin. Zooplankton samples were collected on the same dates as water quality sampling. Sampling was performed between 10:30 and 15:30.

In the lab, each sample was rinsed with tap water for a few minutes to remove as much formalin as possible. Samples were then examined under a dissecting microscope; all material that was not zooplankton including algae, insects, other plant material, etc. was removed. Visual examination of the samples under the dissecting microscope indicated more than 99% (by number) of the zooplankton was *Daphnia* spp. Samples were placed in a weighing tray and dried in a desiccation oven for 24 h at 110^{o}C. Afterwards, samples were removed and weighed to the nearest 0.0001 g. The number of dried grams of zooplankton per liter of water sampled was calculated for each sample.

RESULTS

Water quality, macrophyte growth, and zooplankton abundance

Surface water in the LWSC warmed earlier in 2007 than in 2008 (Figures 6 and 7) Temperatures in 2007 were generally stable during the earlier part of the study period, and then gradually increased from late June to the end of the study period. In contrast, temperatures in 2008 showed steady warming throughout the study period. Greater thermal stratification was evident at the University Bridge site in 2008 than in 2007. For example, in 2008 temperature at 4 m depth was usually 0.9-3.5°C (mean 2.2°C) cooler than at 2 m depth, but in 2007 4 m depth was only 0.2-1.4°C (mean 0.6°C) cooler than 2 m depth. Water clarity in the LWSC was considerably higher in 2008 than in 2007 (Figure 8). Secchi depth varied between 2-5 m in 2007 and 4-7 m in 2008. Dissolved oxygen concentrations at Gas Works Park declined to relatively low levels at about 10 m depth in 2007, and at 12 m depth in 2008 (Figure 9). At the University Bridge site, dissolved oxygen at 9 m depth was occasionally low in 2007, but was similar to other depths in 2008. At the Ballard Locks, dissolved oxygen was uniform throughout the water column down to the deepest depths sampled (12 m). Salinity was detected at 8-10 m depth at Gas Works Park in 2007 and at 12-14 m in 2008 (Figure 10). Salinity was often < 0.50‰, but reached 1.40‰ at 13 m depth in early July 2007. Salinity was usually not detected at the University Bridge site, except in early July 2007 when 0.10‰ was detected at 8-10 m. Low levels of salinity were detected at South Lake Union. In 2007, 0.03-0.17‰ was detected at 10-12 m. No salinity was detected at South Lake Union in 2008, except for 0.10‰ at 12 m on one sample date (July 16). Salinity was detected much higher in the water column at the Ballard Locks. Low levels of salinity (0.02-0.10‰) were detected as high as 2-4 m depth (Figure 10). Maximum salinity levels of 9.20-12.10‰ were recorded at depths of 14-15 m.

Macrophyte growth monitoring points at the University Bridge were insufficient to adequately document macrophyte growth. This was because most points were inadvertently located either just outside the macrophyte beds or in areas that only saw sparse growth. No points were located in areas that yielded moderately dense or dense macrophytes. At the South Lake Union site, one monitoring transect was located in an area where macrophytes did not grow, and the other was located in the only macrophyte bed found on site. Survey results in the macrophyte bed were inconsistent, showing a general decline in growth and erratic patterns in density. These results were likely spurious and were probably cause by the narrowness of the macrophyte bed, patchy distribution of higher density zones, and variations of up to ± 10 m from intended survey points due to difficulty of navigating in this area. Despite this failure to accurately monitor macrophyte growth, the survey data provided useful information on general characteristics of the macrophyte bed during the study period. Macrophyte height ranged from 0.2-1.1 m during the study period, and the upper extent of the macrophyte bed was 3.4-5.5 m below the surface of the water.

Zooplankton mass at Gas Works Park was generally greater offshore than nearshore (Figure 11). Mass in the upper 5 m of the water column ranged from 51-102 mg/m^3 at the nearshore location, and 64-190 mg/m^3 offshore. The magnitude of difference between the nearshore and offshore locations was usually ≤ 1.6, except on July 16 when the offshore location had 3.3 times

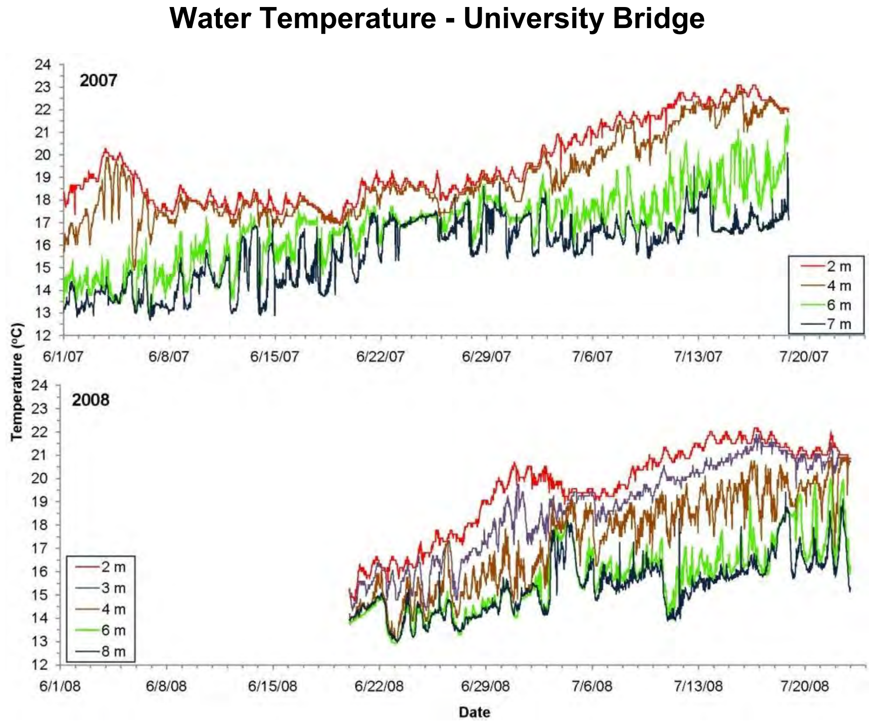

FIGURE 6. Water temperature at different depths at the University Bridge study site, June-July, 2007-2008.

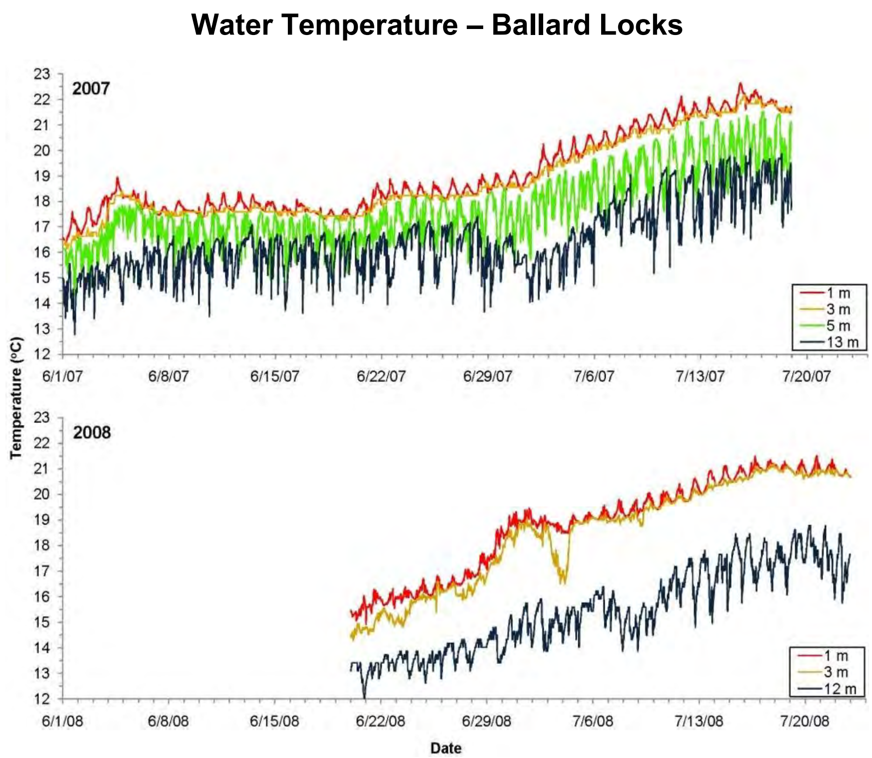

FIGURE 7. Water temperature at different depths at the Ballard Locks study site, June-July, 2007-2008.

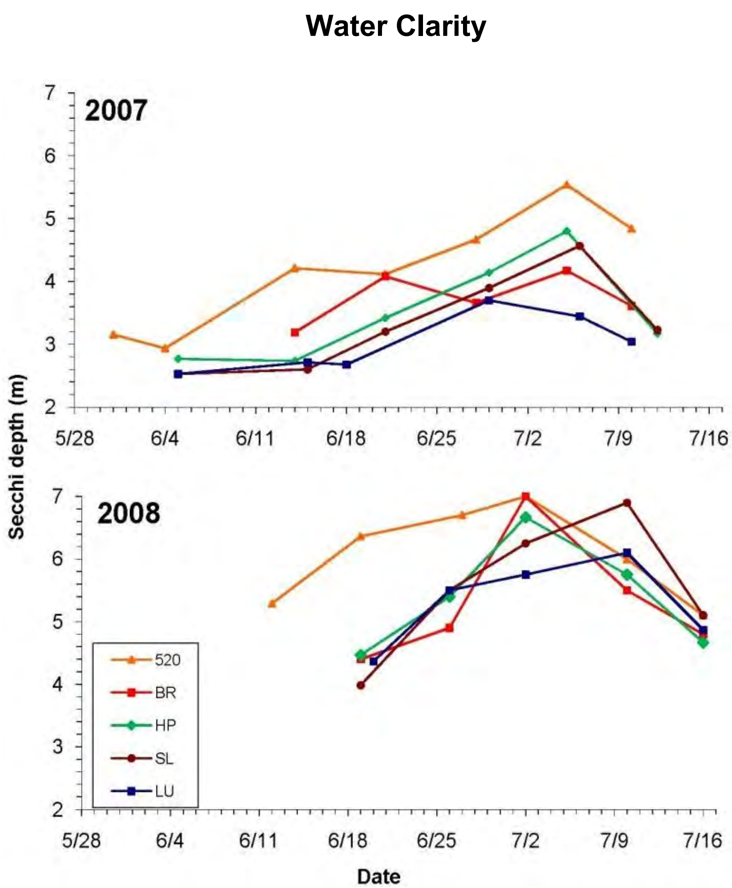

FIGURE 8. Secchi depths (m) at LWSC study sites, June-July, 2007-2008. Secchi depths in Lake Washington at the SR 520 bridge are provided for comparison.

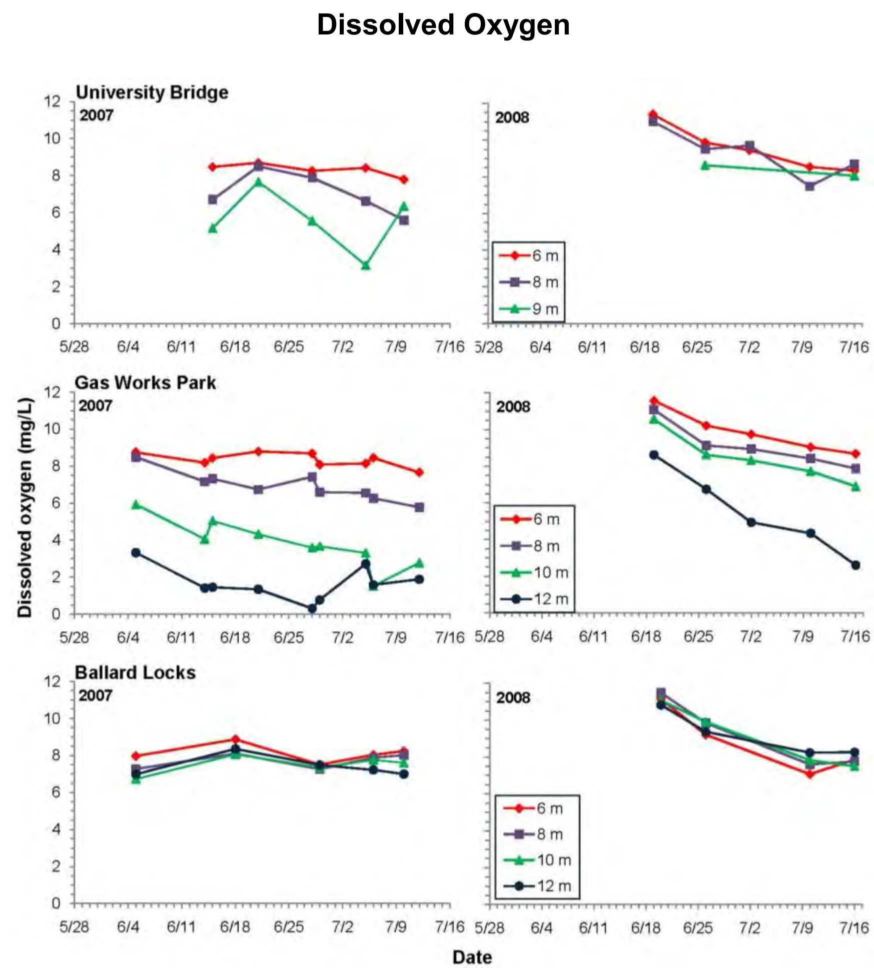

FIGURE 9. Dissolved oxygen concentrations (mg/L) at different depths at the University Bridge, Gas Works Park, and Ballard Locks study sites, June-July, 2007-2008.

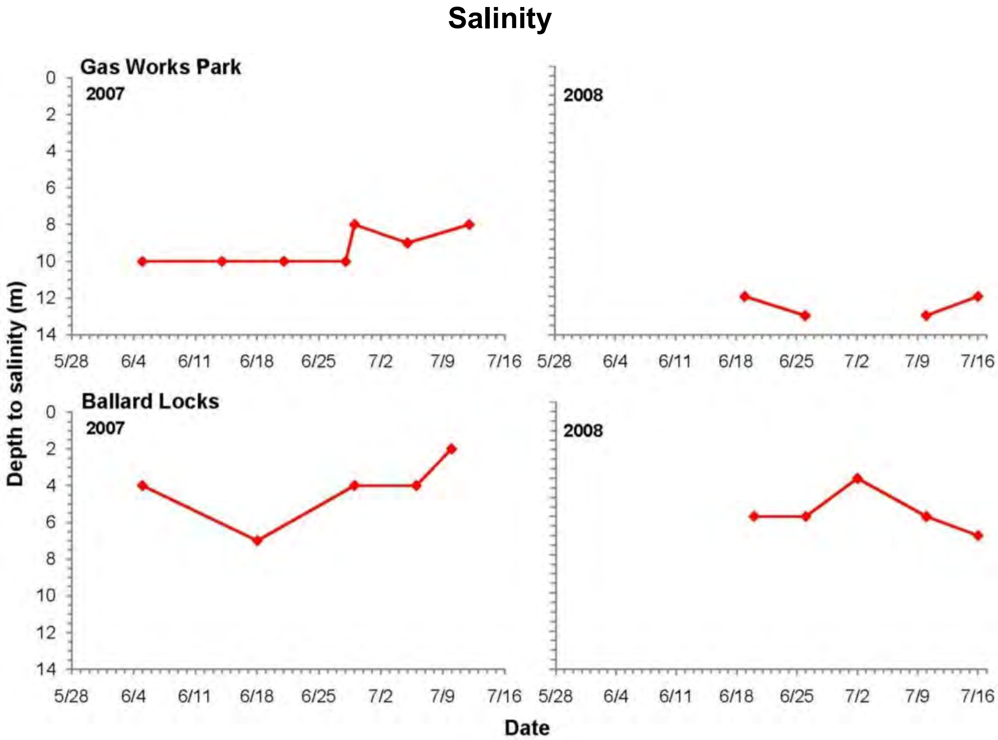

FIGURE 10. Depth (m) to detectable salinity (minimum 0.01‰) at the Gas Works Park and Ballard Locks study sites, June-July, 2007-2008.

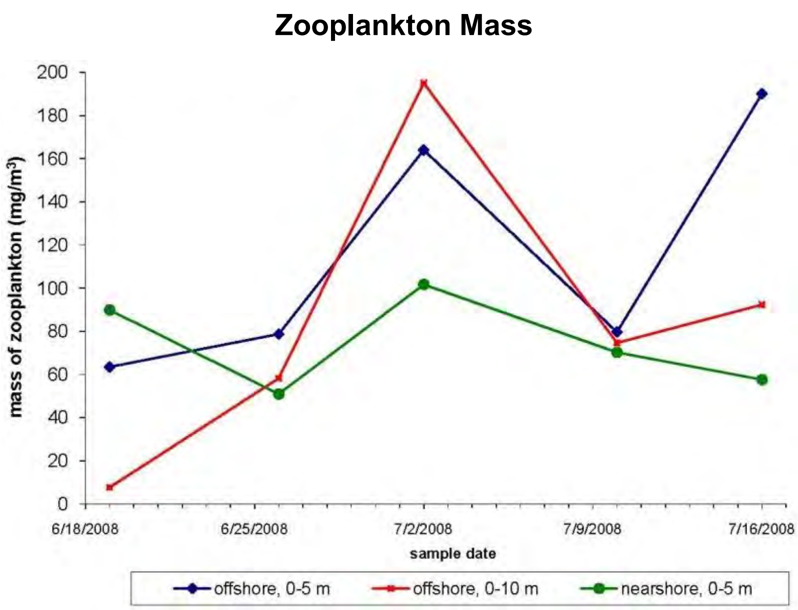

FIGURE 11. Zooplankton dry mass (mg/m^3) at two sampling locations and two depth strata at the Gas Works Park study site, June-July, 2008. One sampling location was 70 m from the north shore (nearshore), and the other was 230 m from the north shore (offshore). Zooplankton was sampled in the upper 5 m of water (0-5 m) at both locations, and in the upper 10 m of water (0-10 m) at the offshore location.

the mass of the nearshore location. Zooplankton appeared evenly distributed through 0-10 m depth on the middle three sample dates (June 26, July 2, and July 10), but appeared concentrated in the upper 5 m on June 19 and July 16. Informal subsampling of zooplankton samples confirmed that Daphnia species made up the overwhelming majority of specimens.

Tagged fish release

In 2007, three groups of tagged Chinook salmon smolts were released at Portage Bay during June and July (Table 3). Also, three groups were released at Madison Park in June as part of a separate tracking study at the SR 520 bridge. In 2008, three groups each were released at the Portage Bay and MetroLab release sites during June and July. All 2007 release groups and 2008 Portage Bay release groups were evaluated at all study sites. The 2008 MetroLab releases were analyzed at the Ballard Locks site only. Fish size was generally comparable between release groups within the same year (Figure 12). Lengths and weights were significantly different between the two years (ANOVA, length: $p < 0.001$; weight: $p < 0.001$). On average 2007 fish were larger than 2008 fish, although the magnitude of difference was small.

TABLE 3. Numbers, lengths, and weights of tagged Chinook salmon released in Lake Washington and the LWSC, June-July, 2007-2008.

Release date	Release site	No. fish released	Mean FL [SD] (mm)	Mean wt. [SD] (g)
June 1, 2007	Madison Park[a]	36	105.7 [3.1]	13.3 [1.0]
June 14, 2007	Madison Park[a]	59	106.0 [2.7]	12.9 [0 .9]
June 15, 2007	Portage Bay	56	105.4 [2.9]	12.2 [1.1]
June 28, 2007	Madison Park[a]	64	108.5 [4.9]	14.3 [2.2]
June 29, 2007	Portage Bay	60	107.6 [3.8]	13.6 [1.6]
July 6, 2007	Portage Bay	54	108.0 [4.7]	14.5 [2.3]
June 19, 2008	Portage Bay	34	105.9 [6.1]	11.5 [0.9]
June 20, 2008	MetroLab	21	101.5 [1.6]	11.9 [0.6]
June 27, 2008	Portage Bay	35	104.3 [2.1]	11.6 [0.6]
June 27, 2008	MetroLab	13	105.8 [3.7]	11.7 [0.8]
July 11, 2008	Portage Bay	38	104.4 [3.4]	12.0 [0.6]
July 11, 2008	MetroLab	24	109.4 [3.1]	12.8 [0.9]

[a] Madison Park fish were released as part of a separate tracking study. These fish were tracked at our LWSC study sites and were included in our analyses.

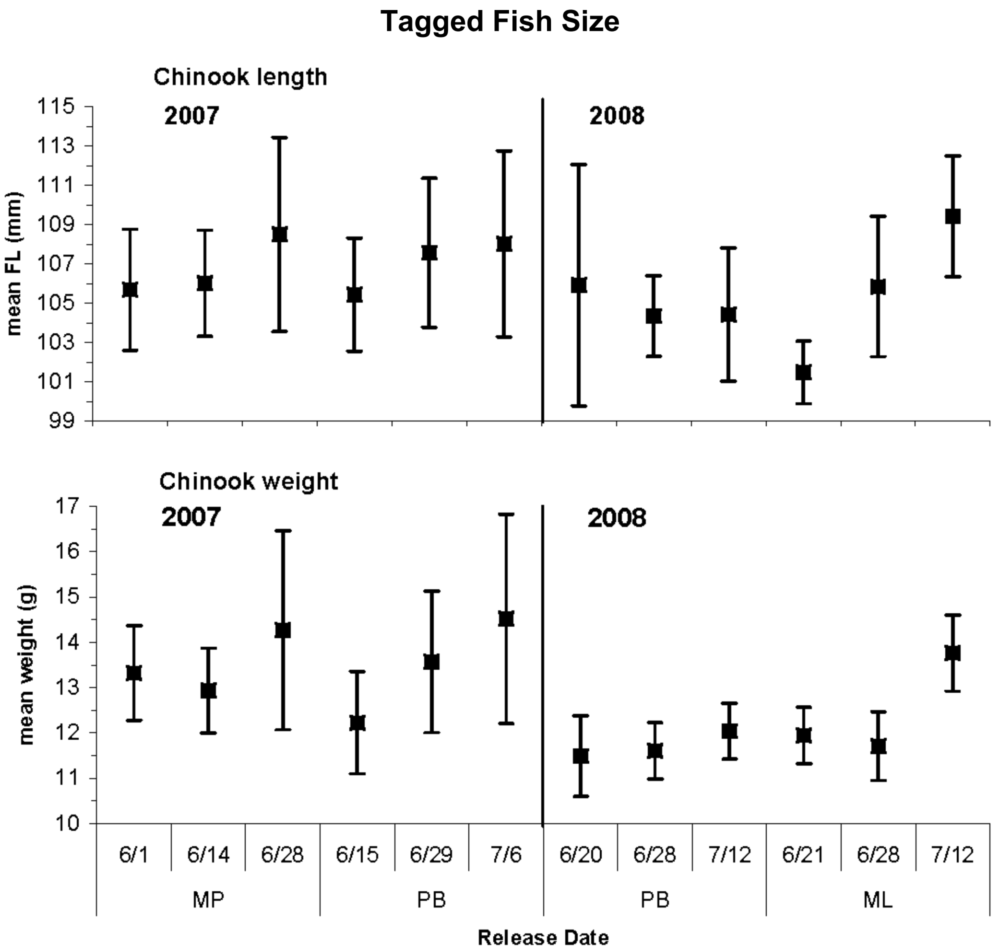

FIGURE 12. Mean size (fork length [FL] and weight) of tagged Chinook salmon smolts released during June-July, 2007-2008. Error bars are one standard deviation. Release site abbreviations are: MP = Madison Park; PB = Portage Bay; ML = MetroLab.

Post-release behavior of tagged fish

Most fish released at Portage Bay traveled to the University Bridge site within a few hours of release (Figure 13). Median travel time for all groups was 0.9–4.9 h except for one release group – June 19, 2008 – which had a median travel time of 16.1 h. Three groups showed relatively little variability (June 15 and July 6, 2007, and July 11, 2008). The other three groups showed considerably more variability and were skewed toward longer times.

Schooling of tagged fish from the Portage Bay release site to the University Bridge site and beyond was common. Tagged fish schooling was most prominent in three release groups: June 15 and July 6, 2007, and July 11, 2008. Four distinct tagged fish schools were observed among the July 6, 2007 release group, and two distinct schools were observed among the June 15, 2007 and July 11, 2008 groups. Most schools consisted of 4–7 fish, with some exceptions. One of the

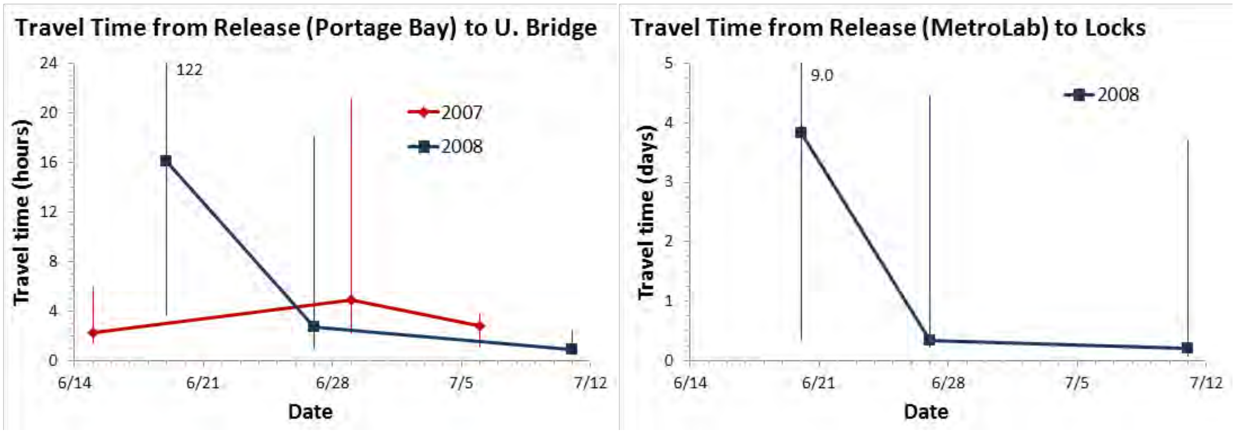

FIGURE 13. Travel time of tagged Chinook salmon from release to first study site, June–July, 2007–2008. Travel time from Portage Bay release site to the University Bridge study site is shown on the left, and from MetroLab release site to the Ballard Locks study site is shown on the right. Markers represent medians, error bars represent 10^{th} and 90^{th} percentiles. See Figure 1 for release and study site locations, and Appendices A and B for data and results of statistical analyses.

two schools observed in the July 11, 2008 release group contained 26 fish. All fish from this release group except one were observed in either this school or the other. On July 6, 2007, one school of 11 tagged fish entered the site. These fish reversed direction and moved off-site where they broke into two schools of 7 and 4 fish, evident when they re-entered the site. Schools showed varying degrees of dissolution while moving through the University Bridge site, between the University Bridge and Gas Works Park sites, and at the Gas Works Park site. That is, some schools moved through the University Bridge site intact, while other schools appeared to break down while on or near the site. Likewise, some schools were completely dissolved by the time fish reached Gas Works Park, while other schools remained at least partially intact. Schools broke down while at or near Gas Works Park. For example, 17 fish from the July 11, 2008 group entered the Gas Works Park site schooled, but only 6 remained schooled upon exit. All other schools appeared to dissolve while in Lake Union.

Tagged fish released at the MetroLab release site on June 20, 2008 showed substantial variability in travel time times to the Ballard Locks, with some fish reaching the Locks in as little as 8 hours and others taking up to 9 days (Figure 13). Median travel time for this group was 3.8 days, and was substantially longer than the 5.1 and 7.8–hour medians observed in the latter two release groups. This temporal trend was similar to that observed for fish released at Portage Bay in 2008. For both release sites, the earliest release group took considerably longer to reach the first study site than the latter two release groups, although the magnitude of difference was much smaller for the Portage Bay release site. No schooling was observed in MetroLab–released fish entering the Ballard Locks site.

Tagged fish presence at study sites

In general, 79-95% of tagged fish released at Portage Bay and the MetroLab were detected at the first downstream site (i.e., University Bridge for Portage Bay releases, and Ballard Locks for MetroLab releases) (Table 4). There was one notable exception: only 38% of tagged fish released at MetroLab on June 20, 2008 were detected at the Ballard Locks. The fate of the remaining 62% was uncertain: these fish did not remain near the release site, nor did they move into Lake Union (raw acoustic data files from the Gas Works Park site showed none of these fish

TABLE 4. Numbers of tagged Chinook salmon smolts detected at each study site and the proportion of fish that were detected from the previous site, June-July, 2007-2008. Study site abbreviations are: U. Br. = University Bridge; GWP = Gas Works Park; SL = South Lake Union; ML = MetroLab; LU = Ballard Locks. SL (shaded) is outside the direct migrational path to Puget Sound.

Release site	Release date	No. fish released[a]	U. Br. (prop. of tagged)[a]	GWP (prop. of U. Br.)	SL (prop. of GWP)	ML (prop. of GWP)	LU (prop. of ML)
2007							
MP	all releases	-	83	81 (0.98)	53 (0.65)	44[b] (0.54)	44 (1.00)
	6/1	-	30	30 (1.00)	11 (0.37)	27[b] (0.90)	27 (1.00)
	6/14	-	28	26 (0.93)	24 (0.92)	9[b] (0.35)	9 (1.00)
	6/28	-	25	25 (1.00)	18 (0.72)	8[b] (0.32)	8 (1.00)
PB	all releases	170	156 (0.92)	125 (0.80)	92 (0.74)	26[b] (0.21)	25 (0.96)
	6/15	56	53 (0.95)	50 (0.94)	38 (0.76)	8 (0.16)	7 (0.88)
	6/29	60	54 (0.90)	41 (0.76)	33 (0.80)	12[b] (0.29)	12 (1.00)
	7/6	54	49 (0.91)	34 (0.69)	21 (0.62)	6 (0.18)	6 (1.00)
2008							
PB	all releases	107	86 (0.80)	82 (0.95)	44 (0.54)	36 (0.44)	26 (0.72)
	6/19	34	27 (0.79)	27 (1.00)	14 (0.52)	13 (0.48)	8 (0.62)
	6/27	35	29 (0.83)	27 (0.93)	16 (0.59)	10 (0.37)	7 (0.70)
	7/11	38	30 (0.79)	28 (0.93)	14 (0.50)	13 (0.46)	11 (0.85)
ML	all releases	58	-	-	-	-	41 (0.71)
	6/20	21	-	-	-	-	8 (0.38)
	6/27	13	-	-	-	-	11 (0.85)
	7/11	24	-	-	-	-	22 (0.92)

a Movement of fish from the Madison Park release site to the University Bridge study site is reported elsewhere as part of a separate study (Celedonia et al. 2008a). These fish were tracked in the present study's arrays, and their movement from the University Bridge to the Ballard Locks is reported here.

b The number of fish detected at MetroLab was less than the number of fish detected at the Ballard Locks. The number shown is not the actual number of fish detected at Metro Lab, but instead is the minimum number of tagged fish known to have moved through the MetroLab site based on detections at the Ballard Locks. For the June 1, 2007 Madison Park release, this was mostly because the MetroLab hydrophone array malfunctioned during the first 24 hours after fish were released. Reasons why other fish went undetected may include blind spots in the coverage area or excessive noise (e.g., from boats) in acoustic data files.

in Lake Union within the first 48 hours after release). Tag malfunction, predation, and/or long-term holding in an area not near one of the hydrophone arrays (i.e., between Gas Works Park and MetroLab and/or between MetroLab and Ballard Locks) were the most likely reasons for such a low number.

There did not appear to be a large or consistent release location effect on the proportion of fish detected from one site to the next, excluding movement of Madison Park fish to the University Bridge. There were no large differences between fish released at Portage Bay and fish released at Madison Park in the proportion detected from site to site (e.g., ratio of tracked fish at Gas Works Park relative to those tracked at University Bridge) (Table 4). Also, the proportion of Ballard Locks detections were largely similar between groups released at MetroLab and those released at Portage Bay.

There was a consistent, albeit usually not large, difference in site-to-site detections between years. For example, proportions of fish released at Portage Bay and detected at University Bridge were consistently higher in 2007 (91-95%) than in 2008 (79-83%). The same was true for South Lake Union relative to Gas Works Park (2007, 62-82%; 2008, 50-59%), and for MetroLab to Ballard Locks (2007, 94-100%; 2008, 47-89%), excluding the June 1, 2007 groups which appeared to be the only group strongly influenced by moon apogee. Similar differences were found for the other segments except that 2008 proportions were higher than 2007: University Bridge to Gas Works Park (2007, 69-94%; 2008, 93-100%); Gas Works Park to MetroLab (2007, 18-30%; 2008, 37-48%), again excluding the June 1, 2007 apogee-influenced group. Such things as annual variation in tag malfunction rate and predation rate were likely factors in some of these differences (e.g., Portage Bay release to University Bridge, and University Bridge to Gas Works Park). Some difference may be attributable to artifacts of annual variation in residence times in certain areas (e.g., Lake Union). For example, more fish may have passed the MetroLab site with inactive tag batteries in 2007 because residence time in Lake Union was often longer in 2007 than in 2008.

There was usually at least some decline in the number of tagged fish from one tracking site to the next (Table 4; Figure 14). The most notable declines occurred: between Gas Works Park and MetroLab in both years; between University Bridge and Gas Works Park in 2007; and, between MetroLab and the Ballard Locks in 2008. Only 18-48% of tagged fish detected at Gas Works Park were subsequently detected at MetroLab, except for the June 1, 2007 Madison Park release group (90%). This latter group was the only group to show a strong migratory response to moon apogee, whereby they migrated relatively quickly through most parts of the LWSC. All other groups spent longer periods of time holding in Lake Union. For these long holding-time fish, tag batteries may have been expired by the time they migrated through the MetroLab array. Predation in Lake Union may have also been a factor.

In 2007, there was a steady temporal decline in the proportion of tagged fish from the University Bridge site to Gas Works Park. Early in the study period, all tagged fish tracked at the University Bridge site were later tracked at Gas Works Park. The percent tracked steadily declined with each release group, reaching 69% by the end (Figure 14). There was no similar decline in 2008.

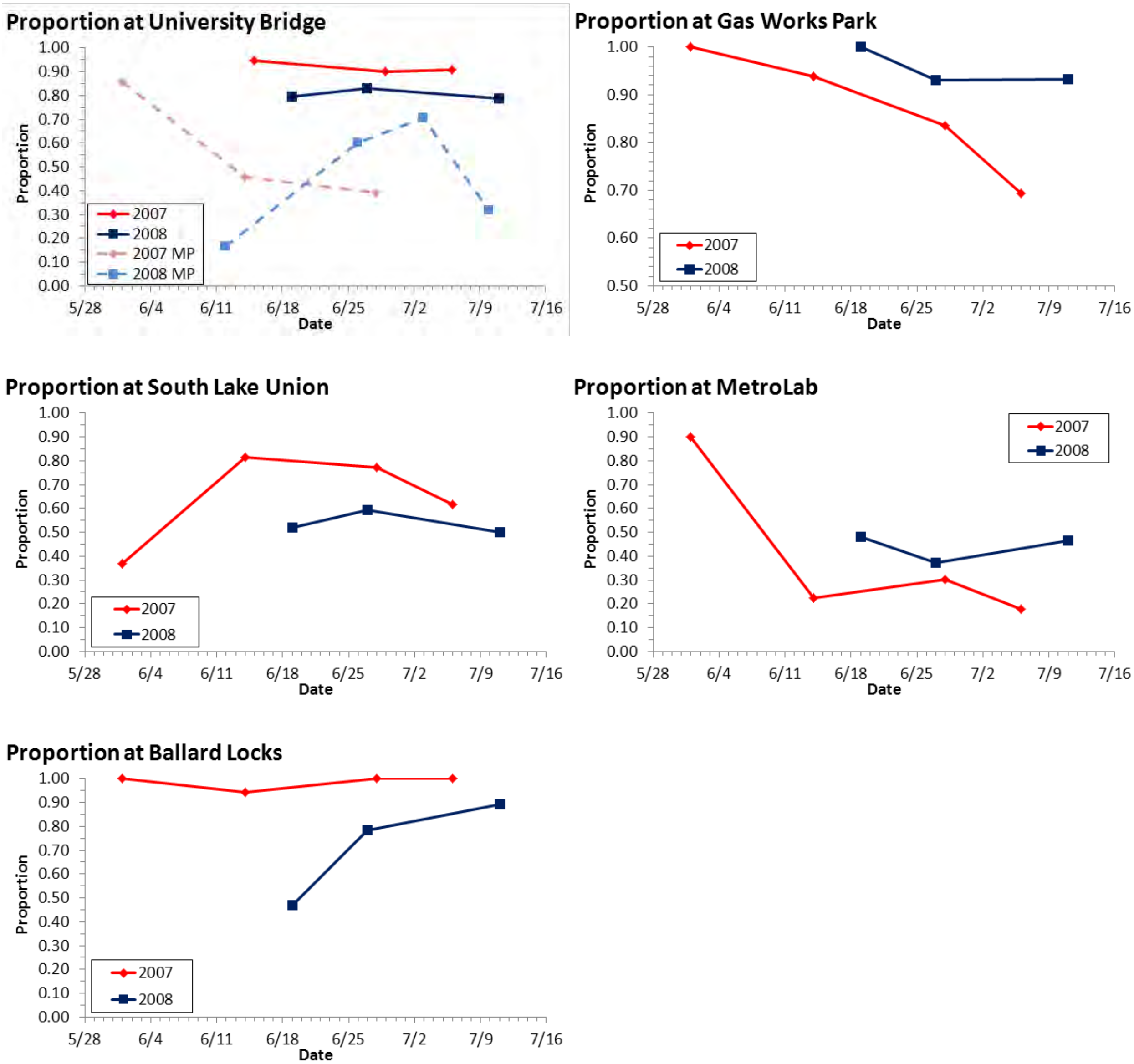

FIGURE 14. Temporal trends in the proportion of tagged Chinook salmon detected at each Lake Washington Ship Canal study site relative to detections at the previous site, June-July, 2007-2008. In some cases, two release groups were combined and represented as one (i.e., June 14 Madison Park and June 15 Portage Bay releases; June 28 Madison Park and June 29 Portage Bay releases; each 2008 MetroLab release was combined with the corresponding Portage Bay release). Madison Park fish at the University Bridge site are shown for reference only: these data are presented elsewhere (Celedonia et al. 2008a; Celedonia et al. 2009). See Table 4 for data.

In 2008, there appeared to be an increase in the proportion of tagged fish detected at the Ballard Locks relative to detections at MetroLab. This may have partially been an artifact of tag battery life: residence times and travel times throughout the LWSC generally decreased as the season progressed, which meant that more fish may have been reaching the Ballard Locks before their tag batteries expired. No similar trend was observed in 2007.

Overall, most fish detected at Gas Works Park were also detected at South Lake Union. In 2007 and 2008, 70% and 54% of tagged fish, respectively, were detected at the South Lake Union site (Table 4; Figure 14). The June 1, 2007 release group (i.e., the apogee-influenced group) had the lowest presence in South Lake Union at 37%. Fish from all other 2007 release groups occurred in South Lake Union at rates of 62-92%, with an overall rate of 76%. In 2008, occurrence rate in South Lake Union was lower but more uniform: all three release groups had rates of 50-59%. We subsampled 117 fish from 2007 that were observed in South Lake Union, and found that most of these fish (79%) made 2-8 trips between the Gas Works Park site and the South Lake Union site (Figure 15). One trip was defined as detection at Gas Works Park followed by detection at South Lake Union. One trip followed by detection at Gas Works Park then South Lake Union again was defined as two trips, and so forth.

Movement patterns through the LWSC

Generally, fish moved from one site to the next toward Puget Sound, exclusive of South Lake Union. However, some fish were observed backtracking to upstream sites. Twenty-one of 288 fish (7.3%) detected at Gas Works Park were later detected back at the University Bridge site. All but one of these individuals returned to Gas Works Park. This behavior was not unexpected given that many fish apparently used large areas of Lake Union as a short- to long-term holding area, and these sites were separated by only 700 m. The fact that more fish were not observed moving between the two areas suggests the area near the University Bridge site was not a preferred holding area. A small degree of backtracking also occurred between MetroLab and Gas Works Park. Four of 106 fish (3.8%) detected at MetroLab were later detected back at Gas Works Park. After returning to the Gas Works Park area, none were subsequently detected at MetroLab. No fish were observed moving backward from the Ballard Locks to the MetroLab.

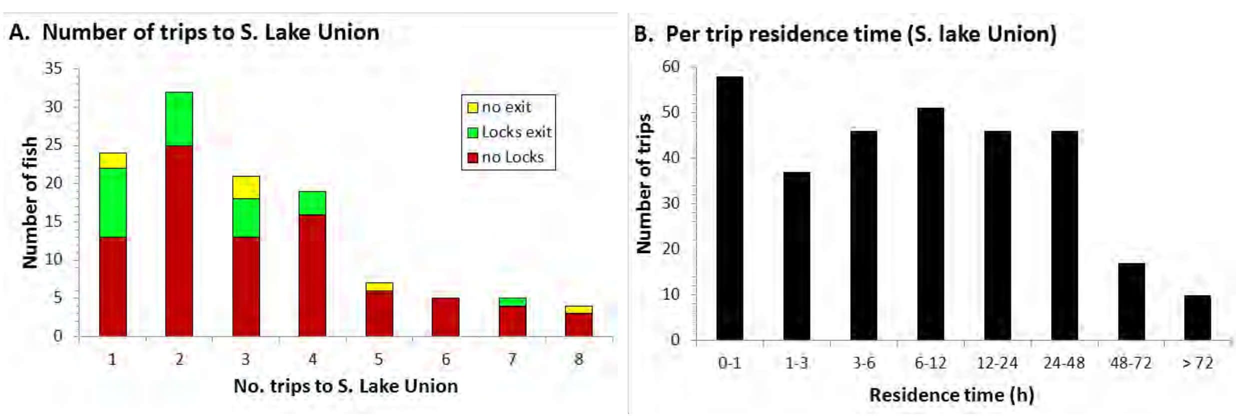

FIGURE 15. Use of South Lake Union by tagged Chinook salmon, June-July, 2007: A) number of trips taken by tagged Chinook salmon to South Lake Union; and, B) residence time in South Lake Union during each trip. One trip was defined as detection at Gas Works Park followed by detection at South Lake Union. One trip followed by detection at Gas Works Park then South Lake Union again was defined as two trips, and so forth. Color codes are as follows: red = fish that were not later observed at Ballard Locks; yellow = fish that were later observed at Ballard Locks but were not observed exiting into Puget Sound; green = fish that were later observed exiting the Ballard Locks into Puget Sound. Data are from 117 fish that were subsampled from the 145 fish observed in South Lake Union in 2007. Residence times are included for trips one through four only.

Overall, many fish traveled relatively quickly through most parts of the LWSC (Figure 16; Appendix A). Lake Union and Salmon Bay were the primary exceptions: fish often spent 1-10 days and more holding in these areas. Fish typically took less than 10 h to travel each of three segments: from Union Bay and Portage Bay to the University Bridge, from the University Bridge to Gas Works Park, and from Gas Works Park to the MetroLab. Travel and residence times were often highly variable and heavily skewed toward longer times. A notable minority of fish from most release groups spent considerably more time in areas that most other fish quickly moved through. For example, median travel time from the SR 520 Bridge site to the University Bridge in late-June and early-July, 2008 was on the order of a few hours (3-6 h). However, some fish spent up to 1-2 days to travel between these sites. Such variability was observed in at least some release groups in all segments of the LWSC.

There did not appear to be any consistent temporal trends between the two study years in travel or residence times (Figure 16; see Appendices A and B for data and results of statistical analyses), with two possible exceptions. Median residence time appeared to decrease in Lake Union and increase at the Ballard Locks as the season progressed in both years (Figure 16). To evaluate statistical significance of these apparent trends, the June 1, 2007 release group was excluded from analysis because of an apparently strong migrational response to moon apogee. No other group showed a similar response to moon apogee. Statistical results were significant for 2007 Lake Union residence time (Kruskall-Wallis, $p < 0.001$), but not for 2008 (Kruskall-Wallis, $p = 0.109$). Similarly, results were significant for 2008 Ballard Locks residence time (Kruskall-Wallis, $p = 0.044$), but not for 2007 (Kruskall-Wallis, $p = 0.390$).

In 2008, there appeared to be a general decline in travel and residence times through the LWSC as the season progressed, with the exception of residence at the Ballard Locks (Figures 13 and 16). These apparent trends were statistically significant for travel time from release at Portage Bay to the University Bridge site (Kruskall-Wallis, $p < 0.001$), and for residence time at the University Bridge (Kruskall-Wallis, $p < 0.001$) (see Appendices A and B for data and detailed results of statistical analyses).

Most fish traveled through the University Bridge site quickly. Forty-percent of both 2007 and 2008 fish were detected on site for less than 1 h, and 82% of 2007 fish and 78% of 2008 fish were detected on site for less than 10 h (Figure 16; Appendix A). However, a small percentage of fish in both years stayed over one day (8% and 10%, respectively). The June 19, 2008 Portage Bay release group had considerably longer residence times than any other group: median 14.1 h compared to medians of 0.4-3.6 h for all other groups. Travel time from University Bridge to Gas Works Park was often short: median travel times were 0.8-2.8 for all groups, and most 90^{th} percentiles were less than 10 h.

Residence times in Lake Union were generally lengthy, with 41% of 2007 fish and 27% of 2008 fish staying over 8 days, and another 17% of 2007 fish and 10% of 2008 fish staying 4-8 days. Considerable variation was observed both within and between groups. The inter-percentile range (10^{th} to 90^{th} percentile) was 5.3-10.6 days for all release groups except one. Median residence time was as long as 9 days (observed in two 2007 groups), and was as short as 2.5 hours (observed in one 2008 group). Median residence times may have been underestimated: the upper end of observed residence times was equivalent to anticipated tag battery life.

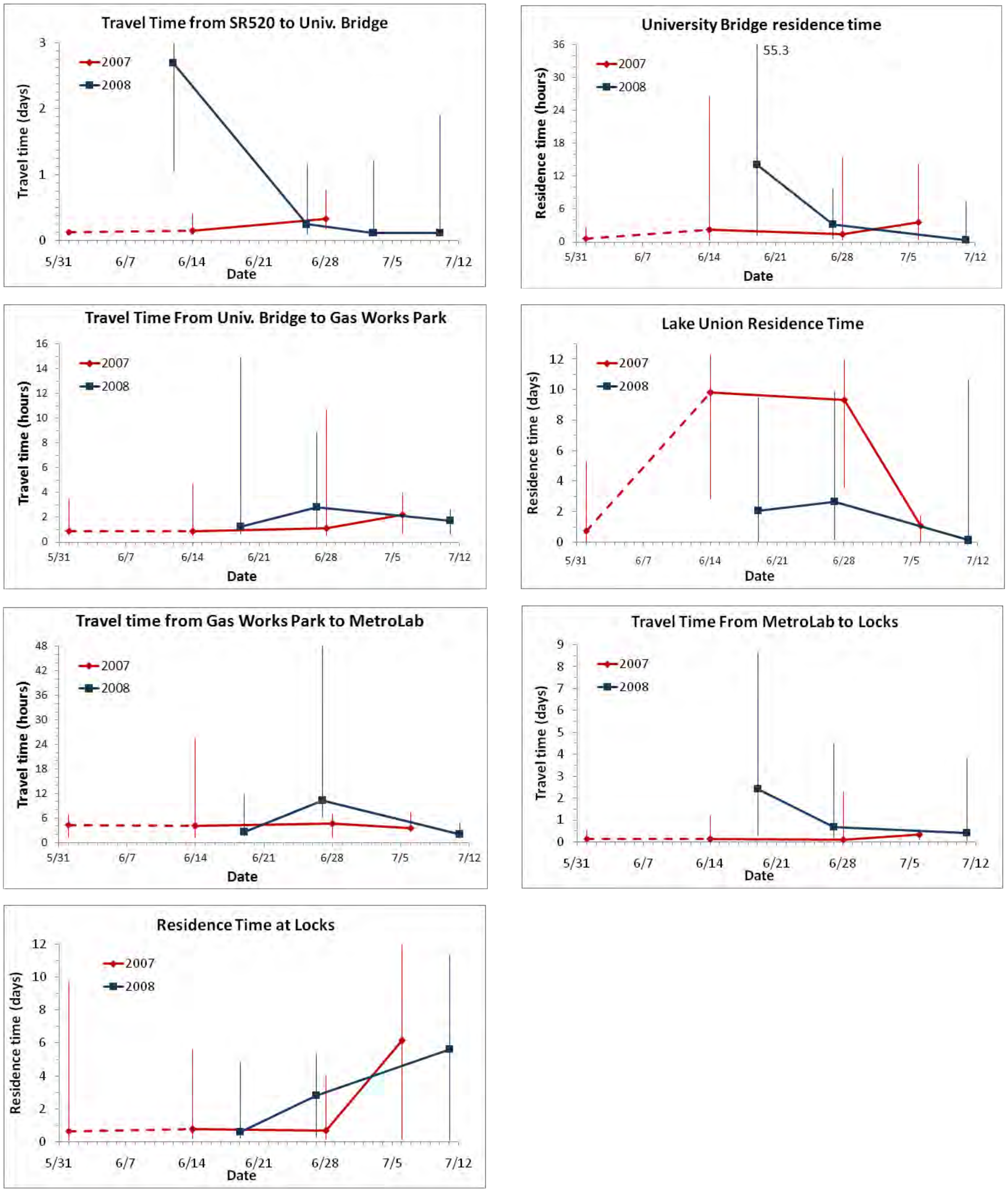

FIGURE 16. Temporal trends in travel and residence times of tagged Chinook salmon at and between locations in the Lake Washington Ship Canal, June-July, 2007-2008. Markers represent medians for each release group of tagged fish; error bars are 10th and 90th percentiles. In some cases, two release groups were combined and represented as one (i.e., June 14 Madison Park and June 15 Portage Bay releases; June 28 Madison Park and June 29 Portage Bay releases; each 2008 MetroLab release was combined with the corresponding Portage Bay release). June 1 and June 14, 2007 are connected with a dotted line because the June 1 release group displayed unique behavioral patterns from all other groups in both years. See Appendix A for data and sample sizes, and Appendix B for results of statistical comparisons.

Many fish spent considerable time in South Lake Union. Per trip residence times were highly variable: many trips lasted less than one hour, whereas others lasted up to 48 hours or more (Figure 15). Per trip residence time did not vary by release day (i.e., early, middle, or late-season) or release location. Median per trip residence time was 7.3-9.2 h for trips one through three, and declined to 1.2-5.0 h for trips four through eight. This difference may have been an artifact of tag battery life limitations rather than something of ecological origin.

Travel times from Lake Union to MetroLab in 2007 and 2008 were often relatively short (median 2.0-4.7 h) and usually not as variable as travel and residence times in other segments of the LWSC (Figure 16). There were two exceptions. The June 14-15, 2007 group had a median travel time on par with most other groups but showed considerably more variability, and the June 27, 2008 group took longer on the whole and showed more variability than any other group (median 10.3 h).

Residence times in Salmon Bay upstream from the Ballard Locks (as indicated by travel times from the MetroLab site to the Ballard Locks) were generally shorter and less variable in 2007 than in 2008. This may have been partially attributable to limitations of tag battery life, generally longer residence times in Lake Union in 2007, and some fish being released at MetroLab in 2008. Median Salmon Bay residence times in 2007 were 2.4-7.6 h, with very few fish taking more than 24 hours. Conversely, median residence times in 2008 were 9.6-57.8 h, and many fish took 2 days and longer (Figure 16). We suspected that fish released at Portage Bay may show shorter residence times compared to MetroLab fish because of the tag battery life that would be expended while the fish traveled from the release site to MetroLab (i.e., only fast-moving Portage Bay fish would make it to the Ballard Locks prior to tag battery expiration). This was not the case, however. Two of the Portage Bay groups had longer - not shorter - median residence times than their corresponding MetroLab groups (Appendix A). Also, statistical evaluation showed that times were not biased by release site (Mann-Whitney U test, $p_{\text{June 19-20, 2008}} = 0.401$; $p_{\text{June 27, 2008}} = 0.390$; $p_{\text{July 11, 2008}} = 0.186$).

Residence times at the Ballard Locks were highly variable within and among release groups. Four groups had median residence times of 0.5-0.8 days, and the other three groups had median times of 2.8, 5.6, and 6.1 days. Considerable variation was observed within each group: the inter-percentile range (10^{th} to 90^{th} percentile) was 3.9-12.0 days for all releases, and the mean inter-percentile range was 7.4 days. Due to the limited battery life of each tag, it is likely that some fish remained in the area after their tags stopped emitting signals, particularly given the prolonged residence times in Lake Union and at the Ballard Locks. Thus, residence times are likely underestimated.

Site-specific behaviors and habitat use

In general, fish were usually found in areas where bottom depths were ≥ 4 m, although shallower areas were used on occasion. Areas directly beneath overwater structures and areas of moderately dense to dense macrophytes were generally avoided. Where overwater structures extended into deeper water (≥ 6 m), zones along the structure edges were commonly used. These zones extended from the edge of the structure to about 20 m from the structure edge. Fish use generally appeared uniform throughout these zones.

University Bridge

This site was used by most fish as a migration corridor or short-term holding area. Slightly more than half of all 2007 and 2008 fish - 51% and 54%, respectively - actively migrated through the site (defined as moving through the site in less than one hour with little or no milling). The remaining fish held on and near the site for more than one hour and were observed milling throughout the site prior to continuing their migration. Of the fish that held, the majority - 60% and 56% in 2007 and 2008, respectively - continued migration and moved off-site within the second hour.

Daytime fish behavior was strongly influenced by the University Bridge. Overall, 59% and 38% of fish in 2007 and 2008, respectively, showed a response to the University Bridge. A response was characterized as an abrupt change in direction upon initial encounter followed by movement parallel with the bridge and/or a milling behavior near the bridge before crossing underneath (e.g., Figures 17 and 18). Plots of fish movement pathways (e.g., Figures 17-19) and spatial frequency distribution plots (Figure 20) showed that the area within 50 m of the eastern edge of the University Bridge was one of the most intensively used parts of the study site. Many fish were observed milling in this area during both the early day and late day periods. Many fish milled in this area for up to several hours before crossing under the bridge and continuing migration. Fish movement pathways dispersed across the width of the channel to the west of the University Bridge. Very few fish responded to the I-5 bridge. These patterns appeared consistent both between and within years.

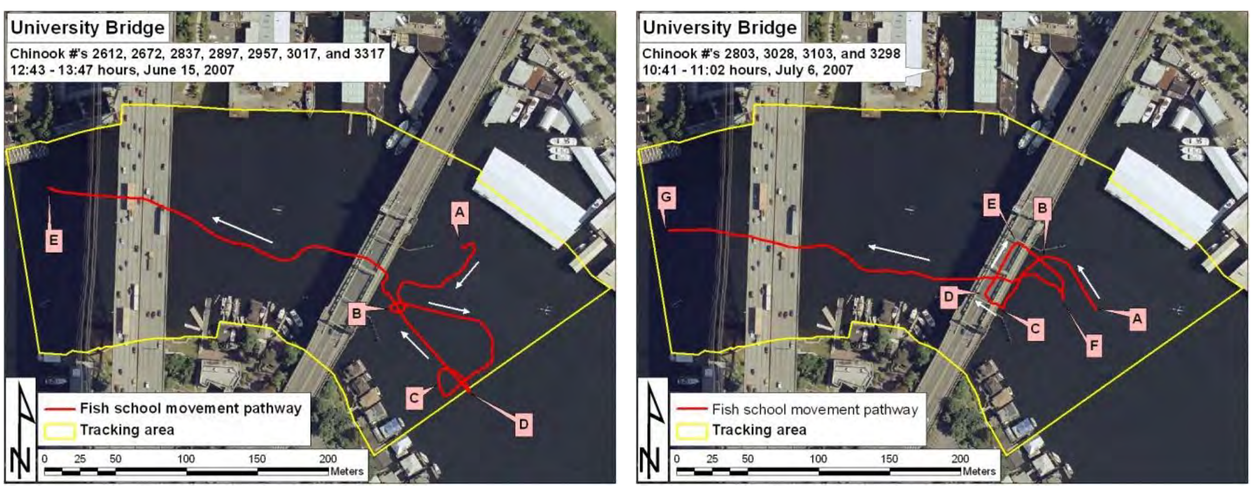

FIGURE 17. Two examples of small schools of tagged Chinook salmon smolts and their response to the University Bridge, June 15 and July 6, 2007. White arrows indicate direction of movement. In the left panel, a school of 7 tagged Chinook salmon enter from the north (A), approach the University Bridge and change direction toward the east (B), temporarily move off-site (C and D), approach the bridge again, parallel the bridge for a short distance, pass underneath, and move off-site to the west (E). In the right panel, a school of 4 tagged Chinook salmon enter from the east (A), change direction in response to the northern wing wall (B), parallel the bridge to the south, abruptly change direction in response to the southern wing wall (C), change direction again (D) and move under and parallel with the bridge, change direction in response to the northern wing wall (E), change direction to the west (F), and pass underneath the bridge and move off-site (G).

FIGURE 18. Behavior of one school of tagged Chinook salmon smolts and response to the University Bridge, July 6, 2007. White arrows indicate direction of movement. The school initially consisted of 11 tagged fish entering from the south-southeast (A). The school encountered the northern wing wall (B) and changed course, moving into an area (C) where they were not tracked from 13:05-13:25 hours. At 13:26 hours (D) the school had only 4 fish remaining. They milled near the bridge, left the site for a brief time (E), and reappeared (F). Point G is the last in the middle panel, and point H is the first in the right panel. The school milled for about 2 hours in a relatively small area immediately adjacent to the eastern edge of the bridge, then moved under the bridge and off-site (I).

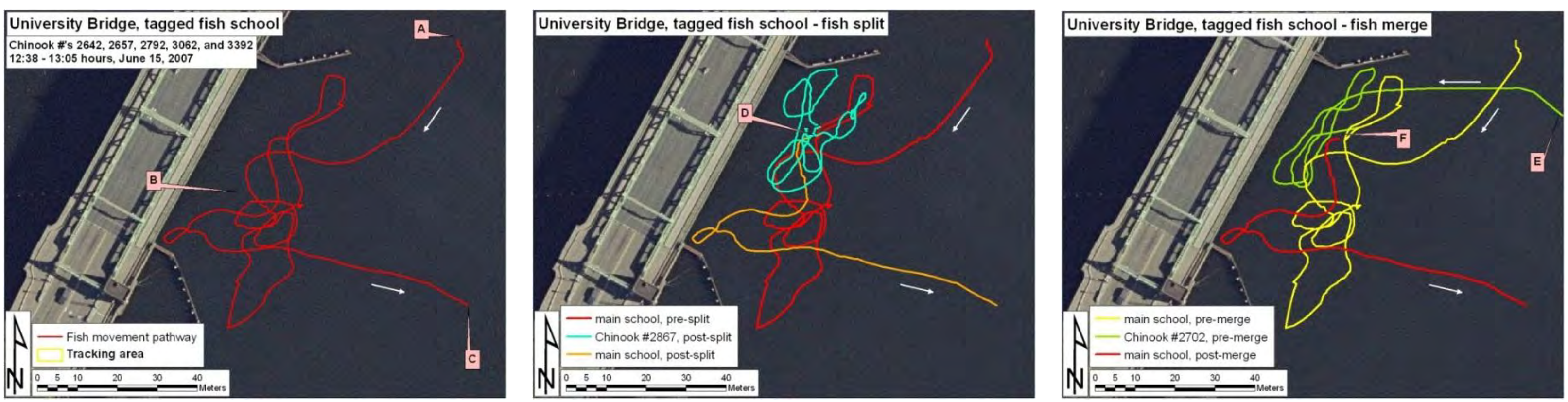

FIGURE 19. School dynamics of one school of tagged Chinook salmon near the University Bridge, June 15, 2007. White arrows indicate direction of movement. The school of five tagged fish entered from the north (A), milled near the bridge for 25 minutes (B), and exited to the east (C). Chinook #2867 left the school at point D (red = pathway before split; orange = school after split; blue = Chinook #2867 after split). Chinook #2702 entered the site (E) and joined the school at point F (yellow = pre-merge school pathway; green = pre-merge pathway of Chinook #2702; red = post-merge school pathway). The merging of Chinook #2702 and splitting of Chinook #2867 occurred at approximately the same time.

University Bridge – Spatial Distribution

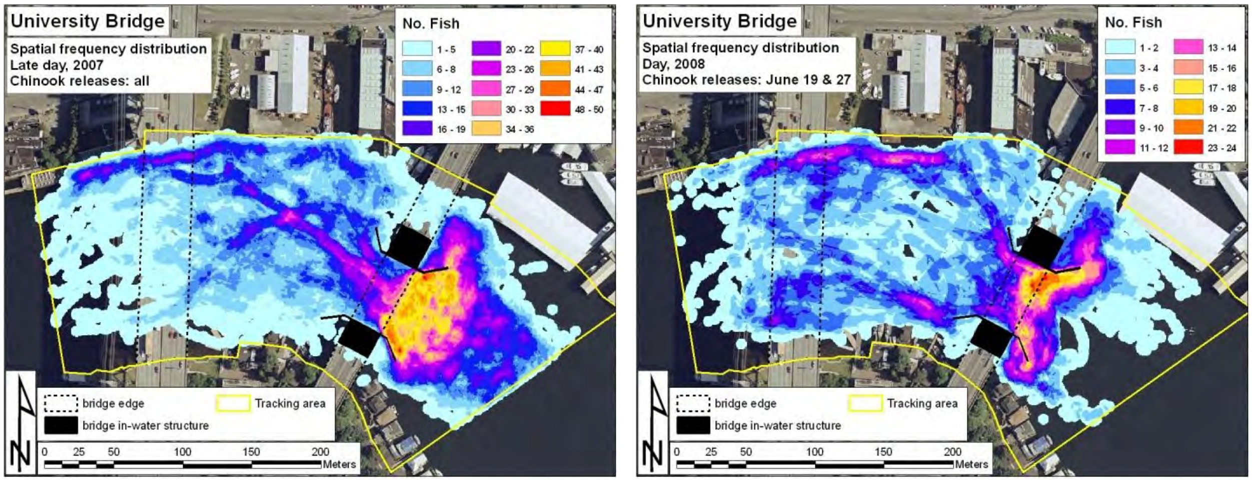

FIGURE 20. Spatial frequency distributions of tagged Chinook salmon smolts at the University Bridge study site during late day, June-July, 2007 (left panel) and day, June, 2008 (right panel). Early day, 2007 and July, 2008 (i.e., July 11, 2008 tagged fish release) were omitted because large numbers of fish moved through the site in schools.

Habitat selection calculations confirmed that the eastern edge of the middle portion of the University Bridge was the most consistently selected part of the site during the day (Figure 21). Most other habitat types were usually selected against or were used in proportion to availability. Open water habitat was selected during nearly all diel periods in 2007, but not in 2008. Habitat selection did not appear to be influenced by temperature. Depth selection, however, did show some changes with increasing temperature during diel periods other than night (Figure 22). Specifically, shallower depths had lower selection ratios and were more often selected against at higher temperatures. In 2007, this corresponded to higher selection ratios and more frequent selection for deeper depths. Fish behavior and habitat selection at night was strongly influenced by artificial lighting. This is discussed in more detail later in the report.

Most fish moved beneath the University Bridge between the bridge support structures (68% and 80% in 2007 and 2008, respectively). After crossing, 57% of the fish moved from the center of the channel to the north or south shoreline, and 21% continued to move westward through the site in the center of the channel without crossing to either shoreline. Eleven percent of the fish crossed the channel completely, most moving from the south shoreline to the north. The remaining fish stayed along either shoreline while migrating, with most in the north.

Several tagged fish showed one or more signs of mortality and predation on and near the site (e.g., Figures 23 and 24). Almost all release groups had at least one individual that showed signs of mortality. The June 29 and July 6, 2007 release groups had exceptionally high percentages of apparent mortality on or near the site: 12% and 23%, respectively.

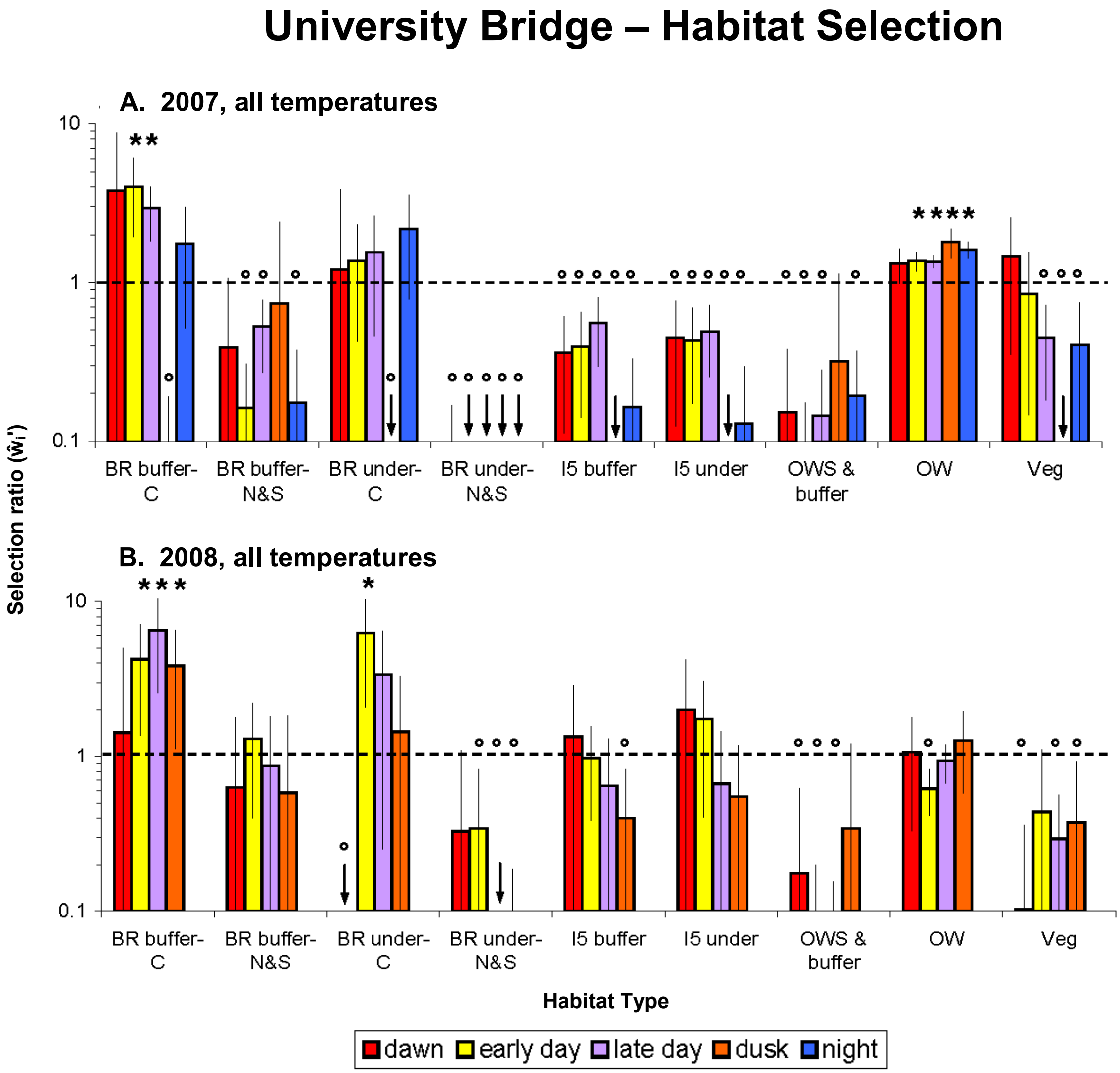

FIGURE 21. Diel habitat selection ($\hat{w}_i$', selection ratio; log scale) of tagged Chinook salmon at the University Bridge study site, June-July, 2007-2008. Each panel shows data from one release group of fish that was generally representative of all release groups, although statistical significance was not always consistent. Panel A consists of fish released on June 15, 2007 and Panel B consists of fish released on June 27, 2008. Other release groups showed similar patterns in selection ratios (e.g., BR buffer-C consistently had high selection ratios). Error bars represent Bonferroni-adjusted 90% confidence intervals. Error bars indicate if selection for (> 1) or against (< 1) a habitat type occurred. An asterisk (*) denotes statistically significant selection for a habitat type and a circle (o) denotes statistically significant selection against. See Table 2 for habitat types. See Appendix G for results of all release groups.

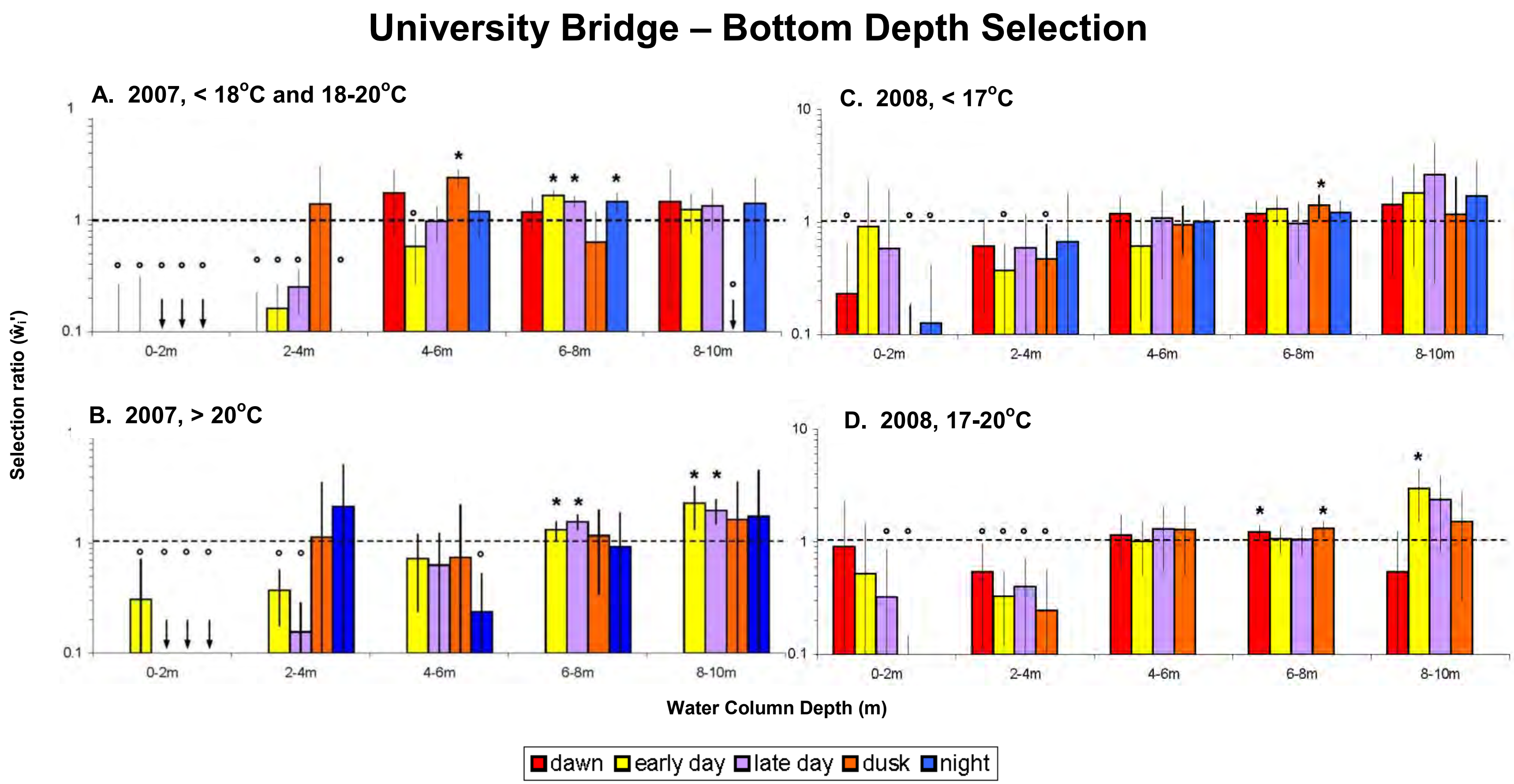

FIGURE 22. Diel bottom depth (water column depth) selection ($\hat{w}_i$', selection ratio; log scale) of tagged Chinook salmon at the Gas Works Park study site, June-July, 2007-2008. Each panel shows data from one release group of fish that was generally representative of the temperature regimes indicated, although statistical significance was not always consistent. Panel A is representative of the < 18°C and 18-20°C temperature regimes in 2007 (data shown are from the June 15, 2007 release group). Panel B is representative of the > 20°C regime in 2007 (data shown are from the July 6, 2007 release group). Panel C is representative of the < 17°C regime in 2008 (data shown are from the June 19, 2008 release group). Panel D is representative of the 17-20°C regime in 2008 (data shown are from the June 27, 2008 release group). The > 20°C regime is not represented because too few fish were present during all diel periods except one. Error bars represent Bonferroni-adjusted 90% confidence intervals. Error bars indicate if selection for (> 1) or against (< 1) a bottom depth occurred. An asterisk (*) denotes statistically significant selection for a bottom depth and a circle (o) denotes statistically significant selection against. See Appendix H for results from all fish.

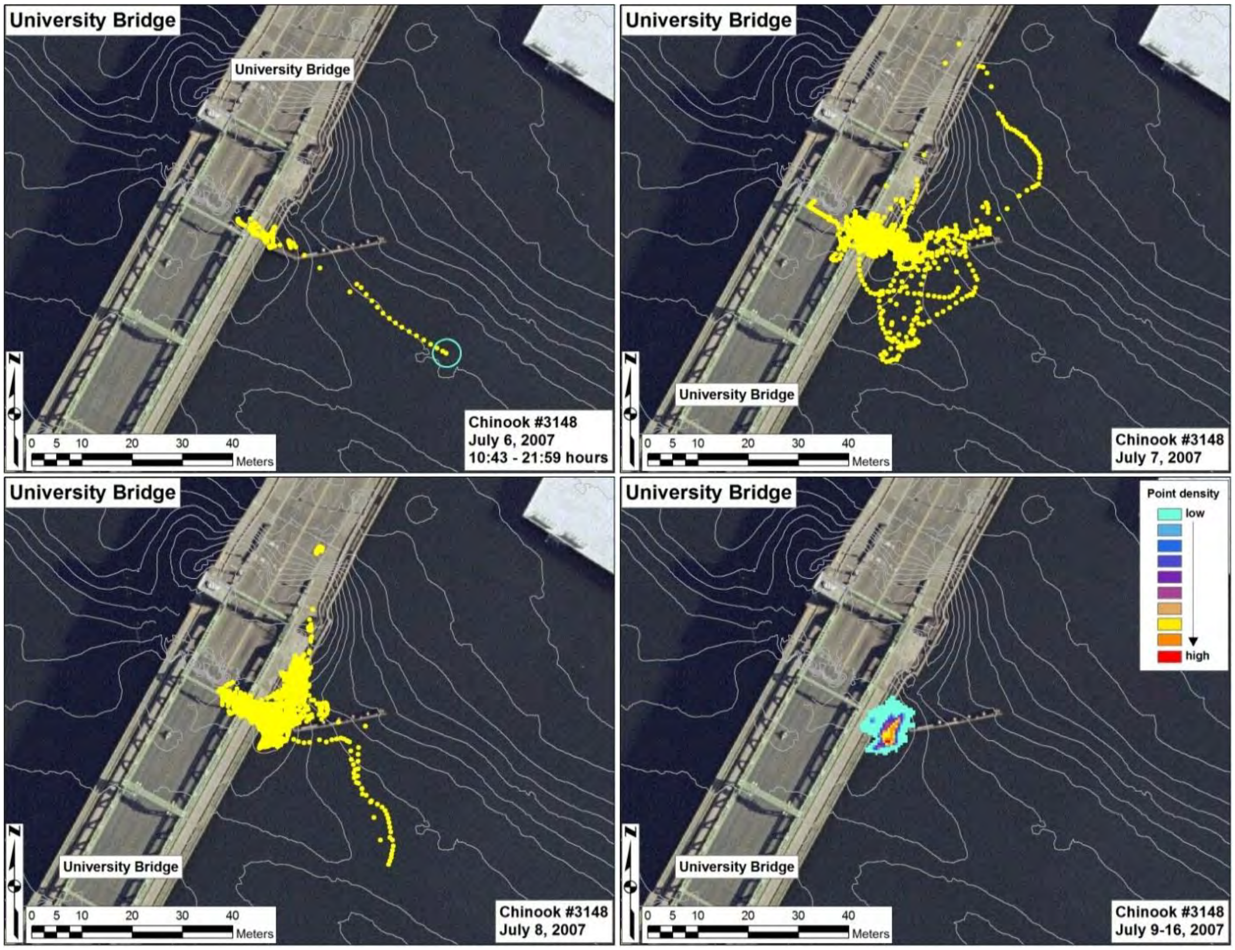

FIGURE 23. Evidence for on-site predation of Chinook salmon #3148 at the University Bridge study site, July 6-16, 2007. Fish enters the study site at 10:43 hours on July 6 (upper left; blue circle indicates first track), and approaches the northern wing wall of the University Bridge. Track becomes very localized for the remainder of the day and through the next two days (upper right; lower left). During this time, the fish appears to have a localized home range and makes brief forays into surrounding area, behaviors indicative of territorial predators such as smallmouth bass. For the next eight days all tracks are clustered in a very small area (lower right) suggesting little if any movement, presumably because the tag was expelled from a predator's digestive system and was lying motionless on the substrate.

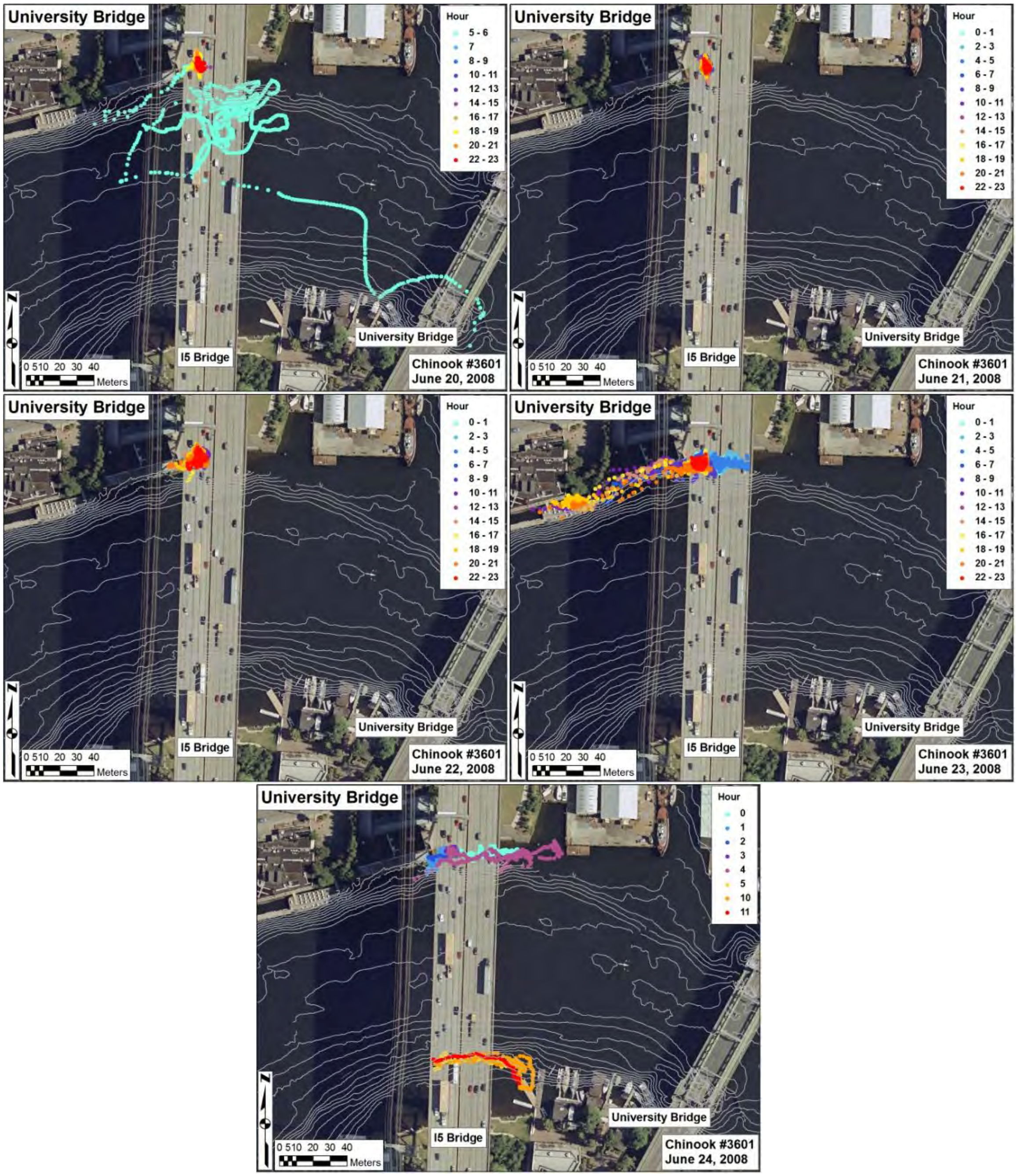

FIGURE 24. Evidence for on-site predation of Chinook salmon #3601 at the University Bridge study site, June 20-24, 2008. Fish enters the study site from the southeast at 05:13 hours on June 20 (upper left), and mills around near the north shore beneath the I-5 bridge. Track becomes very localized for the remainder of the day and through the next two days (upper right; middle left). During this time, the fish appears to have a localized home range indicative of territorial predators such as smallmouth bass. More extensive motion resumes on June 23 (middle right) as the fish appears to maintain the same home range, but makes repeated forays along a uniform depth contour, behaviors also observed in smallmouth bass. Similar behavior is observed the following day (lower left), except this time the fish crosses the channel to the south (apparently off-site to the west), mills along a uniform depth contour along the south shore, and exits to the west. The fish was not tracked at this or any site after this despite about 5-7 days remaining on the tag battery life.

Gas Works Park

The Gas Works Park site was used by most tagged Chinook salmon as a holding and/or rearing area. Behavior here consisted largely of fish milling throughout the site and throughout a larger area that included the study site (e.g., Figure 25). Many fish entered and exited the site repeatedly. Most fish were observed roaming broadly throughout the tracking area with no apparent general direction of travel. Horizontal spatial distribution and habitat selection was largely consistent across diel periods and temperature regimes, although some variation was evident particularly with regard to bottom depth selection. Larger scale variation was evident between years.

In 2007, tagged fish activity was highest in the west and southwest part of the site (Figure 26). Results of habitat and depth selection calculations showed similar results in that open offshore areas 12-14 m deep were consistently selected for during all diel periods, except very early in the study period when bottom depths < 12 m were used much more regularly (Figures 27 and 28).

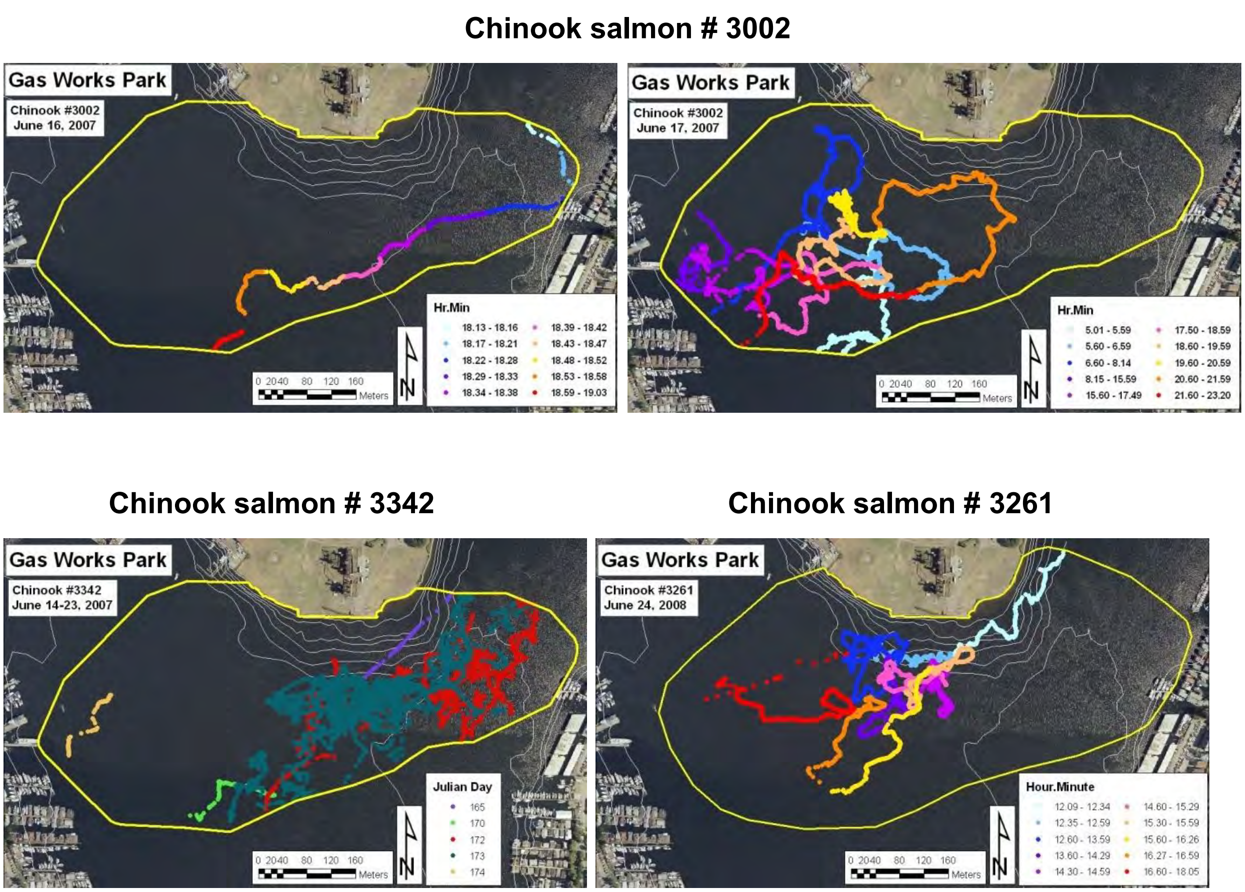

FIGURE 25. Three examples of tagged Chinook salmon movement pathways at the Gas Works Park site, June, 2007-2008. Direction of movement is illustrated with the color bar for tagged Chinook salmon #3002 and #3261.

Gas Works Park – Spatial Distribution

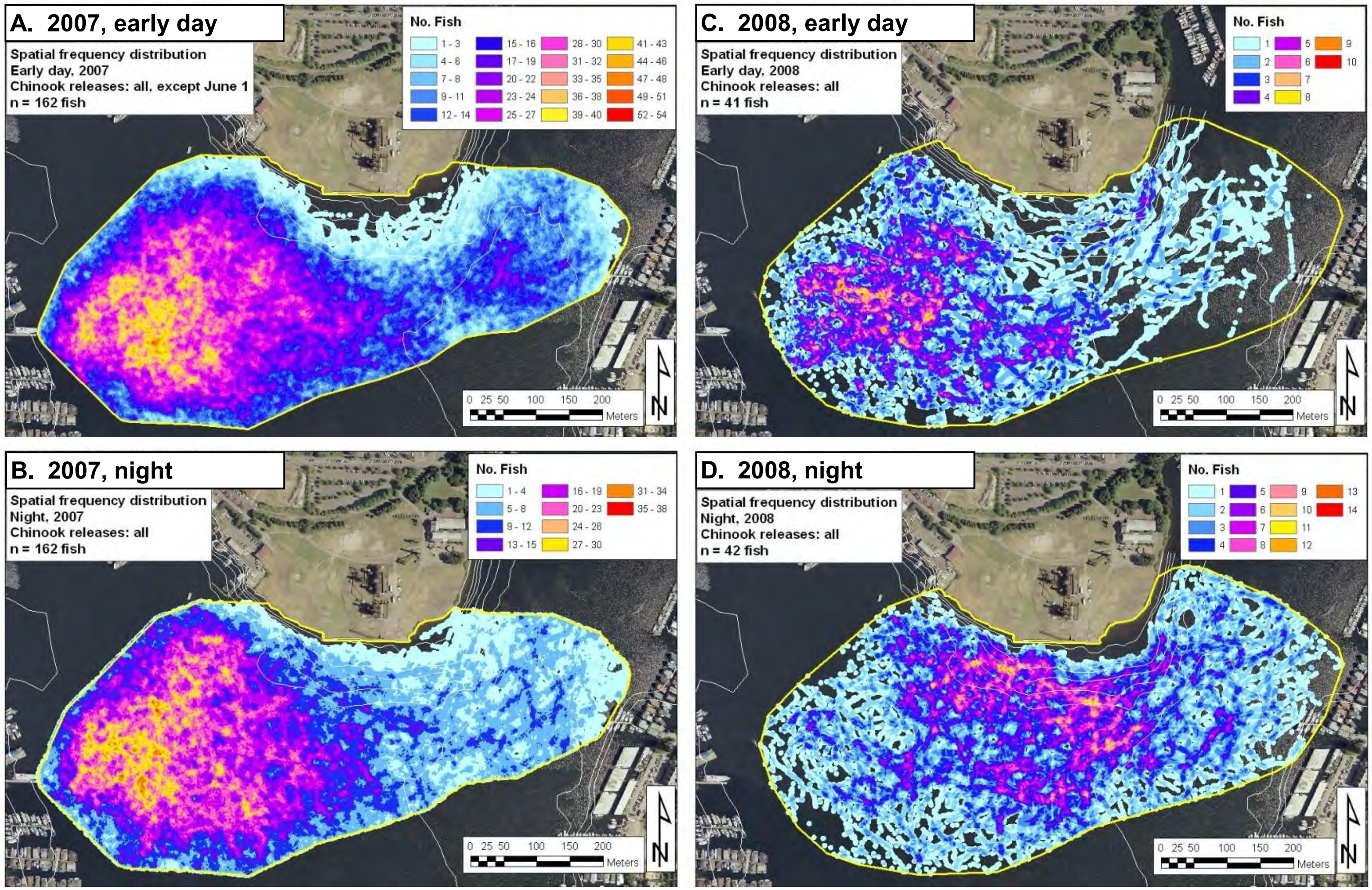

FIGURE 26. Spatial frequency distributions of tagged Chinook salmon smolts during day and night at the Gas Works Park study site, June-July, 2007-2008. Dawn, late day, and dusk were similar to early day in both 2007 and 2008. Distributions were similar across temperature regimes. The June 1, 2007 release was excluded from Panel A because most of these fish exhibited daytime behaviors and depth selection patterns different from all other release groups. Fish in large schools(> 3 fish) were excluded until they separated from the school. This mostly affected Panel C. The yellow polygon in each panel is the tracking area.

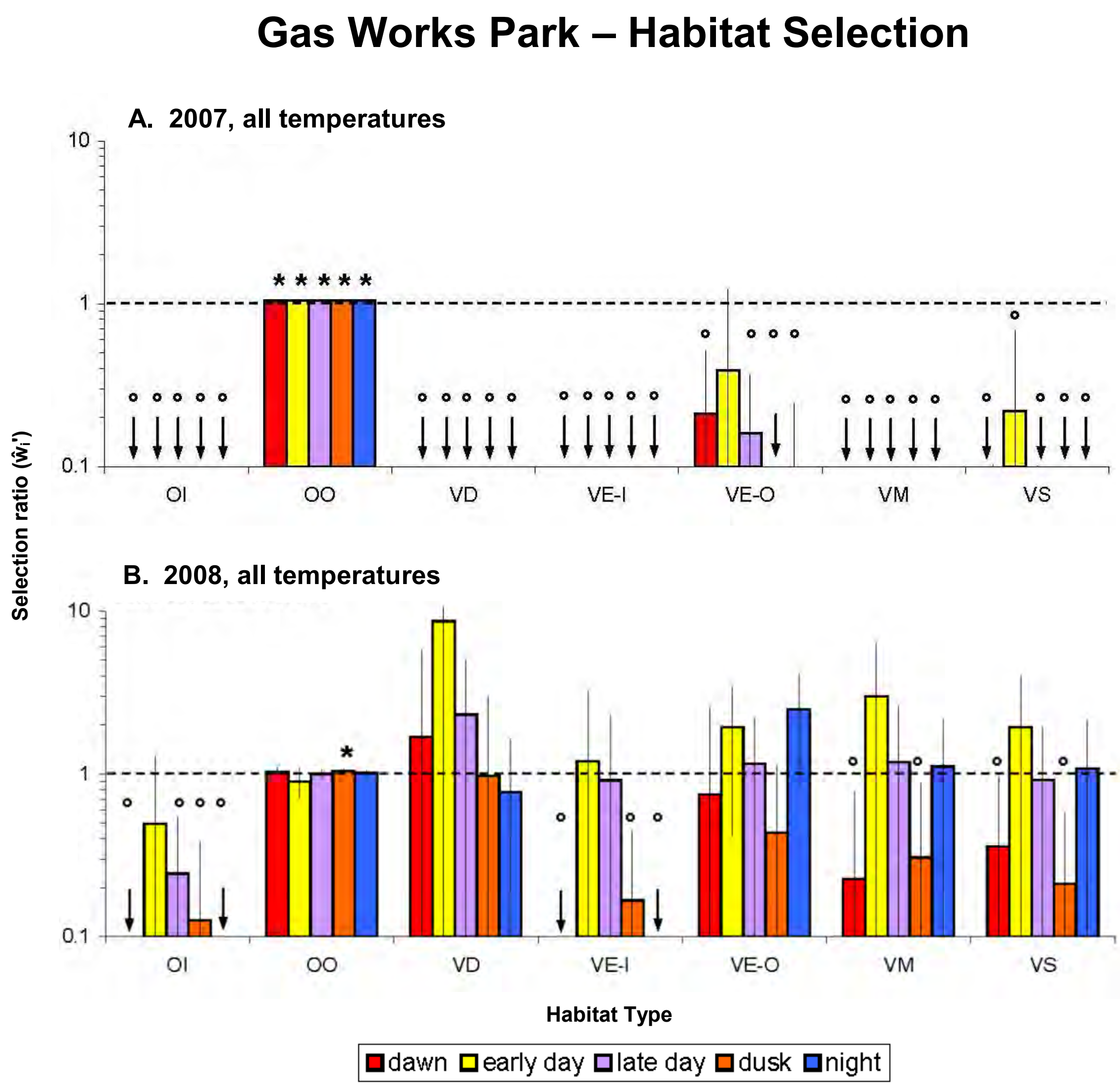

FIGURE 27. Diel habitat selection ($\hat{w}_i$', selection ratio; log scale) of tagged Chinook salmon at the Gas Works Park study site, June-July, 2007-2008. Each panel shows data from one release group of fish that was generally representative of all release groups, although statistical significance was not always consistent. Panel A consists of fish released on June 29, 2007 and Panel B consists of fish released on June 27, 2008. Results were representative of all other release groups of fish within each year. Error bars represent Bonferroni-adjusted 90% confidence intervals. Error bars indicate if selection for (> 1) or against (< 1) a habitat type occurred. An asterisk (*) denotes statistically significant selection for a habitat type and a circle (o) denotes statistically significant selection against. See Table 2 for habitat types. See Appendix I for results of all release groups.

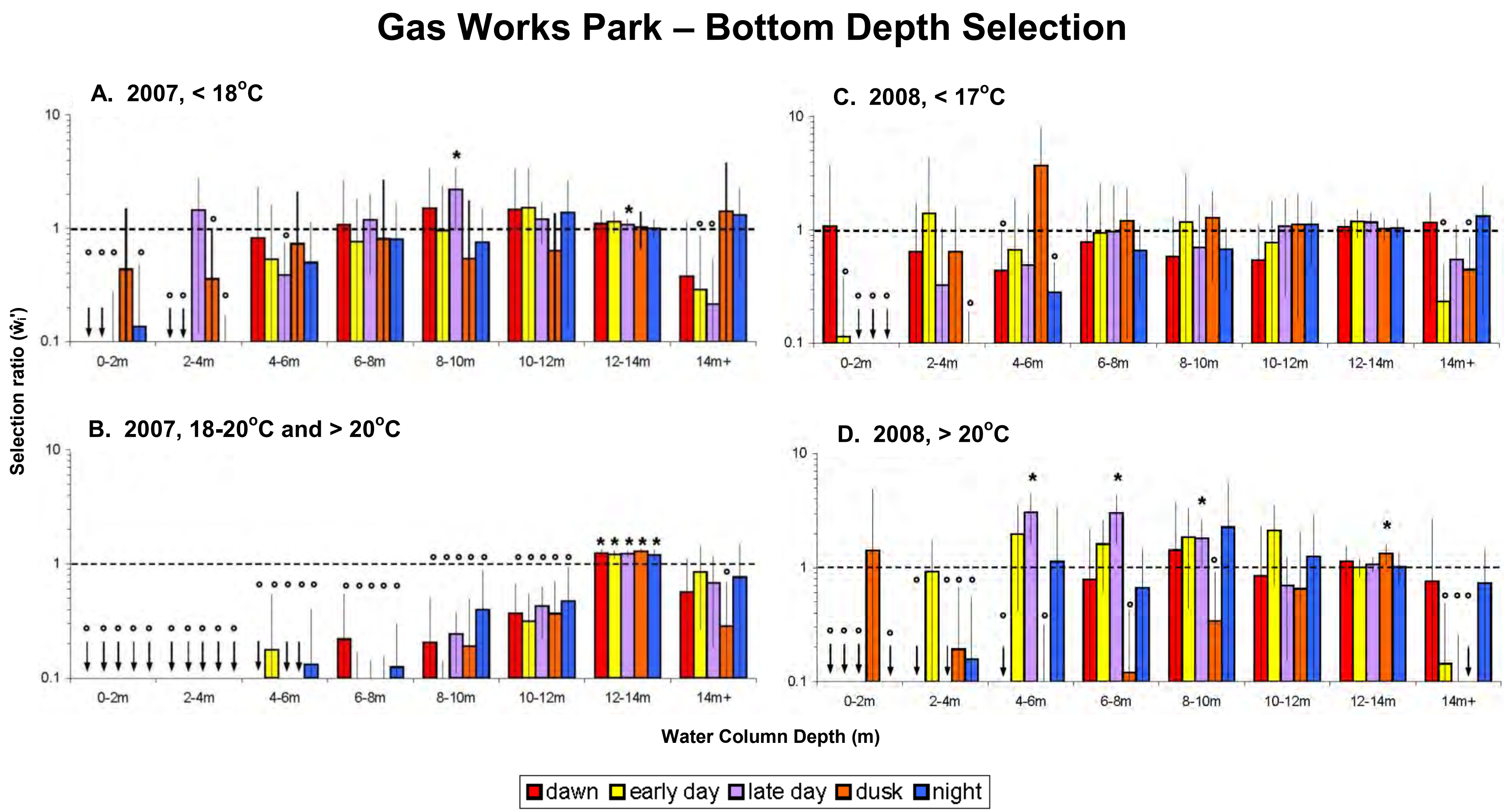

FIGURE 28. Diel bottom depth (water column depth) selection ($\hat{w}_i$', selection ratio; log scale) of tagged Chinook salmon at the Gas Works Park study site, June-July, 2007-2008. Each panel shows data from one release group of fish that was generally representative of the temperature regimes indicated, although statistical significance was not always consistent. Panel A is representative of the early part of the < 18°C temperature regime in 2007 (data shown are fish released on June 1, 2007). Panel B is representative of the late part of the < 18°C regime, and the 18-20°C and > 20°C regimes in 2007 (data shown are fish released on June 29, 2007). Panel C is representative of the < 17°C regime in 2008 (data shown are fish released on June 19, 2008). Panel D is representative of the late part of the > 20°C regime in 2008 (data shown are fish released on July 11, 2008). Error bars represent Bonferroni-adjusted 90% confidence intervals. Error bars indicate if selection for (> 1) or against (< 1) a bottom depth occurred. An asterisk (*) denotes statistically significant selection for a bottom depth and a circle (o) denotes statistically significant selection against. See Appendix J for results from all fish.

During most of the study period, habitat types other than open offshore areas and bottom depths other than 12-14 m were rarely used, except for bottom depths > 14 m which often saw proportional use. Daytime spatial distribution in 2008 was largely similar to that in 2007, except areas closer to shore were used more frequently in 2008 (Figures 26-28). At night, the locus of activity shifted to the northeast and closer to shore in 2008 relative to 2007 (Figure 26). Habitats other than open offshore areas - particularly those associated with vegetation - were used considerably more during all diel periods in 2008 (Figure 27). Correspondingly, areas with bottom depths < 12 m were used more (Figure 28). The 2008 fish did not uniformly select for any bottom depth categories and were more evenly distributed in areas with bottom depths of 4-14 m. With some exceptions, bottom depths of 0-2 m were usually selected against in both years. Contrary to what was observed in 2007, there did not appear to be much of a shift to deeper water as the 2008 study period progressed (Figure 28).

Tagged Chinook salmon smolts were rarely close to shore at the Gas Works Park site. When they were, many fish selected for the beach habitat during the day in both 2007 and 2008 (Figure 29). Selection ratios were also somewhat high during crepuscular and nighttime periods in 2007, but not in 2008. Bulkhead habitats often had low to moderate selection ratios in 2007 and during the day in 2008. Conversely, bulkhead selection ratios were higher than beach and riprap during crepuscular and nighttime periods in 2008. Riprap often had the lowest selection ratios, with notable exceptions of early day in 2007 and dawn 2008.

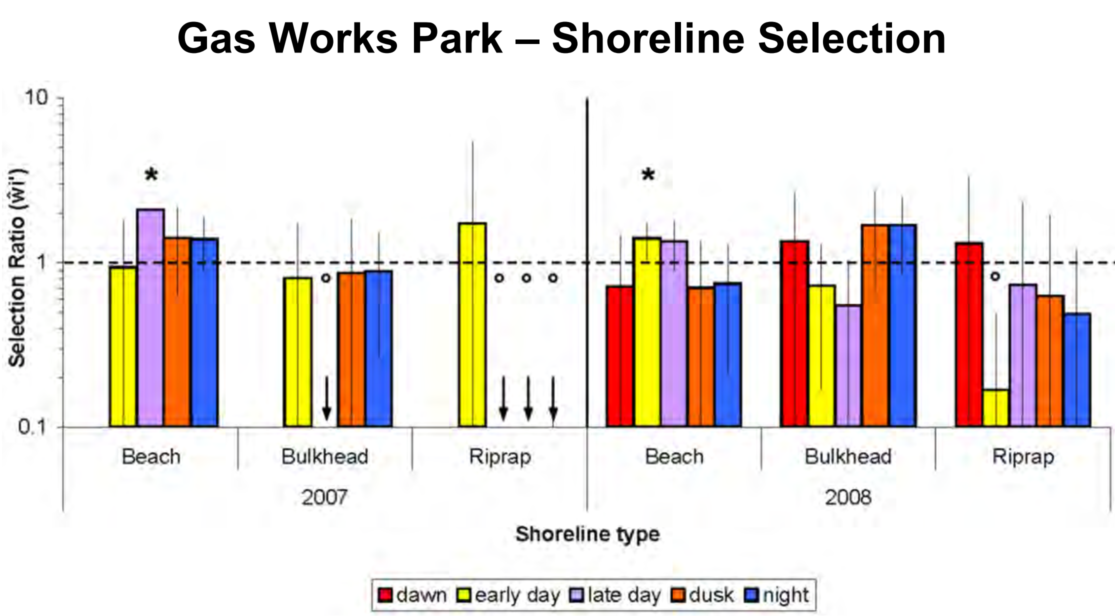

FIGURE 29. Diel shoreline selection ($\hat{w}_i$', selection ratio; log scale) of Chinook salmon at the Gas Works Park study site, June-July, 2007-2008. Error bars represent Bonferroni-adjusted 90% confidence intervals. Error bars indicate if selection for (> 1) or against (< 1) a habitat type occurred. An asterisk (*) denotes statistically significant selection for a habitat and a circle (o) denotes statistically significant selection against.

South Lake Union

Tagged Chinook salmon at South Lake Union showed movement patterns consistent with holding or rearing as opposed to active migration. Fish here were often observed on numerous days milling and meandering throughout the site and/or in specific areas of the site. While in this area, fish made considerable use of areas near overwater structures, primarily during the day on the north side of the site (Figure 30). Fish were rarely observed directly beneath overwater structures, but were often observed near structure edges in a zone extending from the structure edge to 20-25 m from the structure edge. Spatial frequency distributions showed that relatively large proportions of fish (50-80%) often used these areas extensively during the day (Figure 30). With some exceptions, less affinity for structure edges was observed during crepuscular periods and at night. Instead, fish during these periods were often more evenly distributed throughout

South Lake Union – Spatial Frequency Distribution

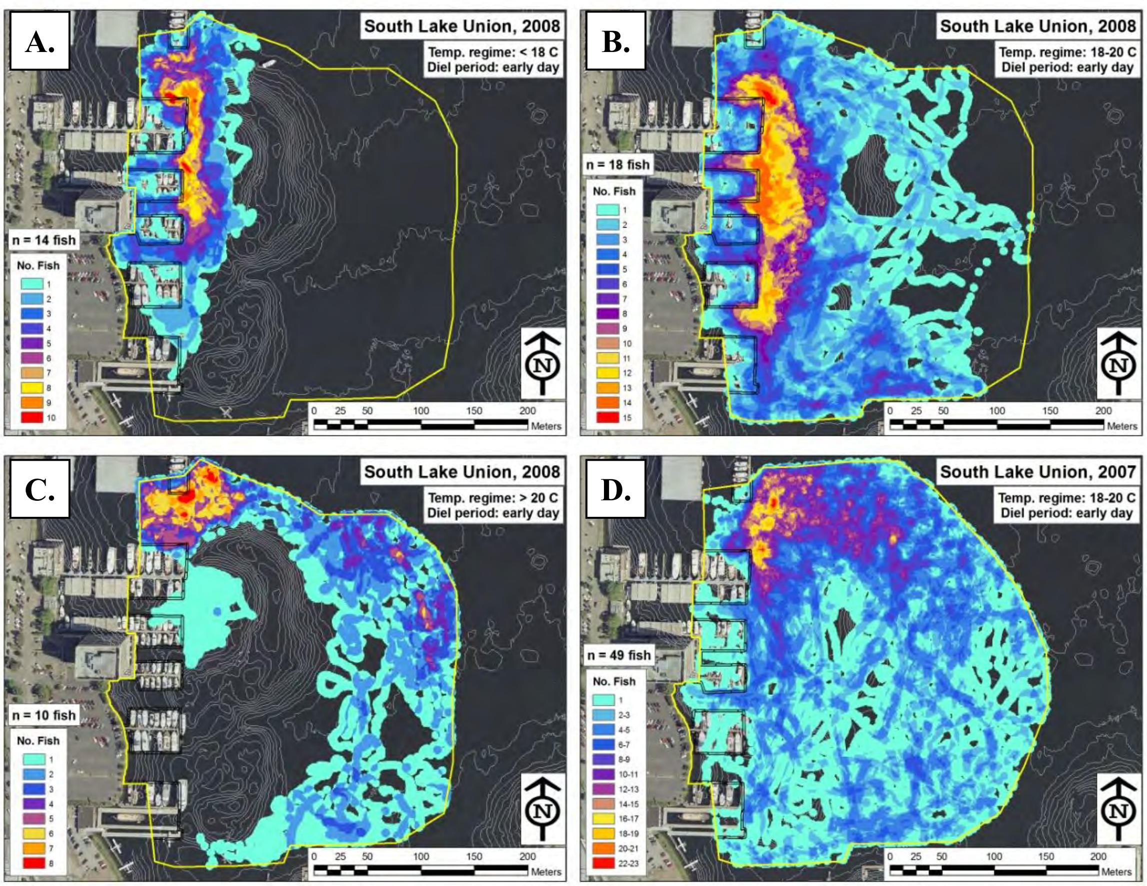

FIGURE 30. Spatial frequency distributions of tagged Chinook salmon at the South Lake Union study site, June-July, 2007-2008. All distributions show the early day time period (one hour after sunrise to 14:00 hours). Distributions are shown for: A) low temperature regime (< 18°C), 2008; B) mid temperature regime (18-20°C), 2008; C) high temperature regime (> 20°C), 2008; and, D) mid temperature regime (18-20°C), 2007. Black lines indicate overwater structures. The inner line is the structure edge and the outer line is 2 m from the structure edge.

the site. Also, 2008 fish showed a stronger relationship with structure edges, particularly in the central part of the site, perhaps due to increased water clarity in 2008. Structure edges in the southern and central portions of the site were used less as temperatures increased in 2008, perhaps because water was shallower here. The very southernmost structures were used somewhat infrequently during the entirety of both the 2007 and 2008 study periods.

Plotted fish tracks and density plots also showed that many fish spent considerable lengths of time near structure edges, from several hours per day up to nearly all hours of a given day. For example, Chinook salmon #2816 entered the study area during the early day on June 28, 2008 (Figure 31). This fish extensively used areas near structures during the day until it exited the site to the east at approximately 22:00 hours. This fish re-entered the site from the east at approximately 02:30 hours the same night and spent several more hours along the edges of

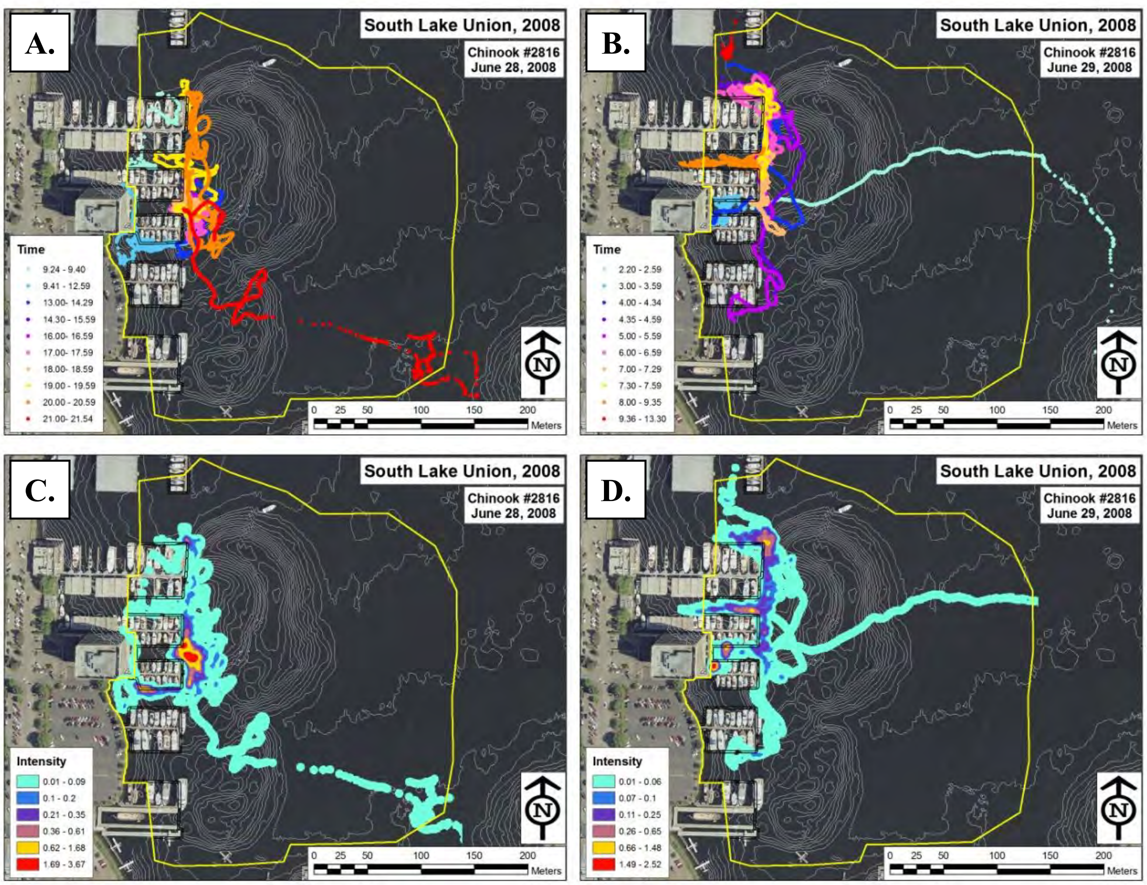

FIGURE 31. Movement pathway and density plot of Chinook salmon #2816 at the South Lake Union study site. General behavioral patterns of this fish relative to the overwater structures on the west side of the site were generally representative of many fish observed here, particularly in 2008. Movement pathways are shown for: A) June 28, 2008; and, B) June 29, 2008. Density plots are shown for the same fish on the same dates: C) June 28, 2008; and, D) June 29, 2008. This fish was later detected at the Ballard Locks at 15:22 hours on June 30, 2008, and was observed exiting into Puget Sound on July 2, 2008 at 10:01 hours.

overwater structures. Density plots of this fish confirmed that much of the time this fish was on-site was spent within 20-25 m of structure edges (Figure 31). This fish was largely representative of many fish tracked at this site, particularly in 2008.

Habitat and bottom depth selection calculations were generally consistent with observations from spatial frequency distribution plots (Figures 32 and 33). However, less selection for structure edges was evident in habitat selection calculations than what was observed in spatial frequency distributions and density plots. This likely occurred for two reasons. First, the dock buffer category that was selected *a priori* and used in calculating habitat selection extended only 5 m from structure edges, thereby excluding a large part of the 20-25 m structure edge zone used by fish. Secondly, structures in the southern part of the site, and to some degree in the central part of the site, saw less use than structures in more northern areas. This had the effect of diluting selection ratios for the site-wide docks buffer category.

Consistent with spatial frequency distributions, habitat selection calculations showed a shift away from structure-oriented habitats (i.e., docks, docks buffer, and intra-pier) as water temperatures warmed during the study period. This was particularly evident in 2007 (Figure 32). A similar but less dramatic shift was apparent in 2008 as most structure-oriented habitats continued to be used to the end of the study period. A corresponding shift to deeper water – particularly to bottom depths of 12-14 m – occurred as water temperatures warmed during the study period (Figure 33). Other habitats occasionally selected for included sparse vegetation and vegetation-edge areas. Habitats often selected against included areas directly beneath structures and areas with moderate and dense vegetation.

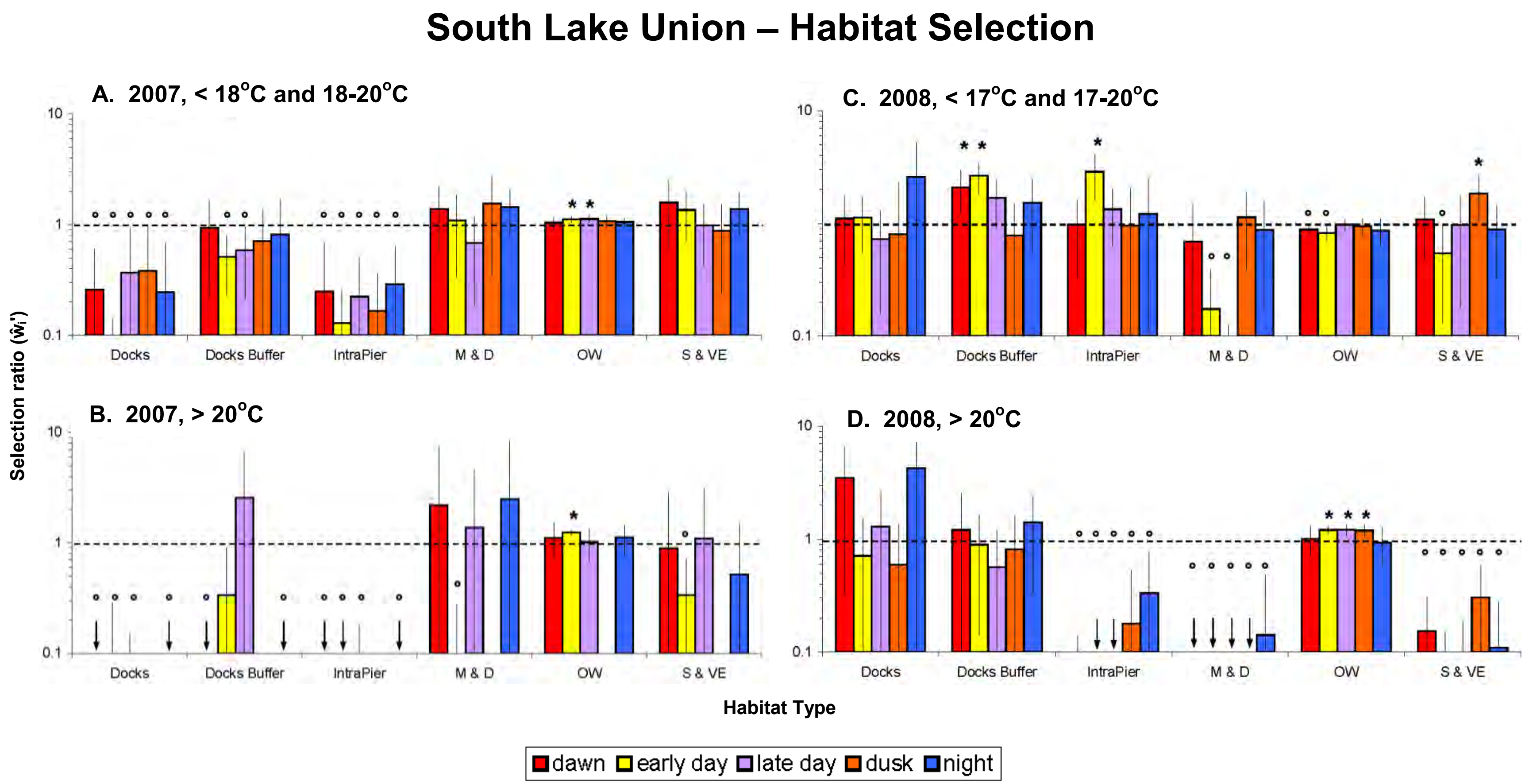

FIGURE 32. Diel habitat selection (ŵ$_i$', selection ratio; log scale) of tagged Chinook salmon at the South Lake Union study site, June-July, 2007-2008. Each panel shows data from one release group of fish that was generally representative of the temperature regimes indicated, although statistical significance was not always consistent. Panel A is representative of the < 18°C and 18-20°C temperature regimes in 2007 (data shown are from the June 15, 2007 release group). Panel B is representative of the late part of the > 20°C regime in 2007 (data shown are from the July 6, 2007 release group). Panel C is representative of the < 17°C and 17-20°C regimes in 2008 (data shown are from the June 27, 2008 release group). Panel D is representative of the late part of the > 20°C regime in 2008 (data shown are from the July 11, 2008 release group). Error bars represent Bonferroni-adjusted 90% confidence intervals. Error bars indicate if selection for (> 1) or against (< 1) a habitat type occurred. An asterisk (*) denotes statistically significant selection for a habitat and a circle (o) denotes statistically significant selection against. See Table 2 for habitat types. See Appendix K for results from all fish.

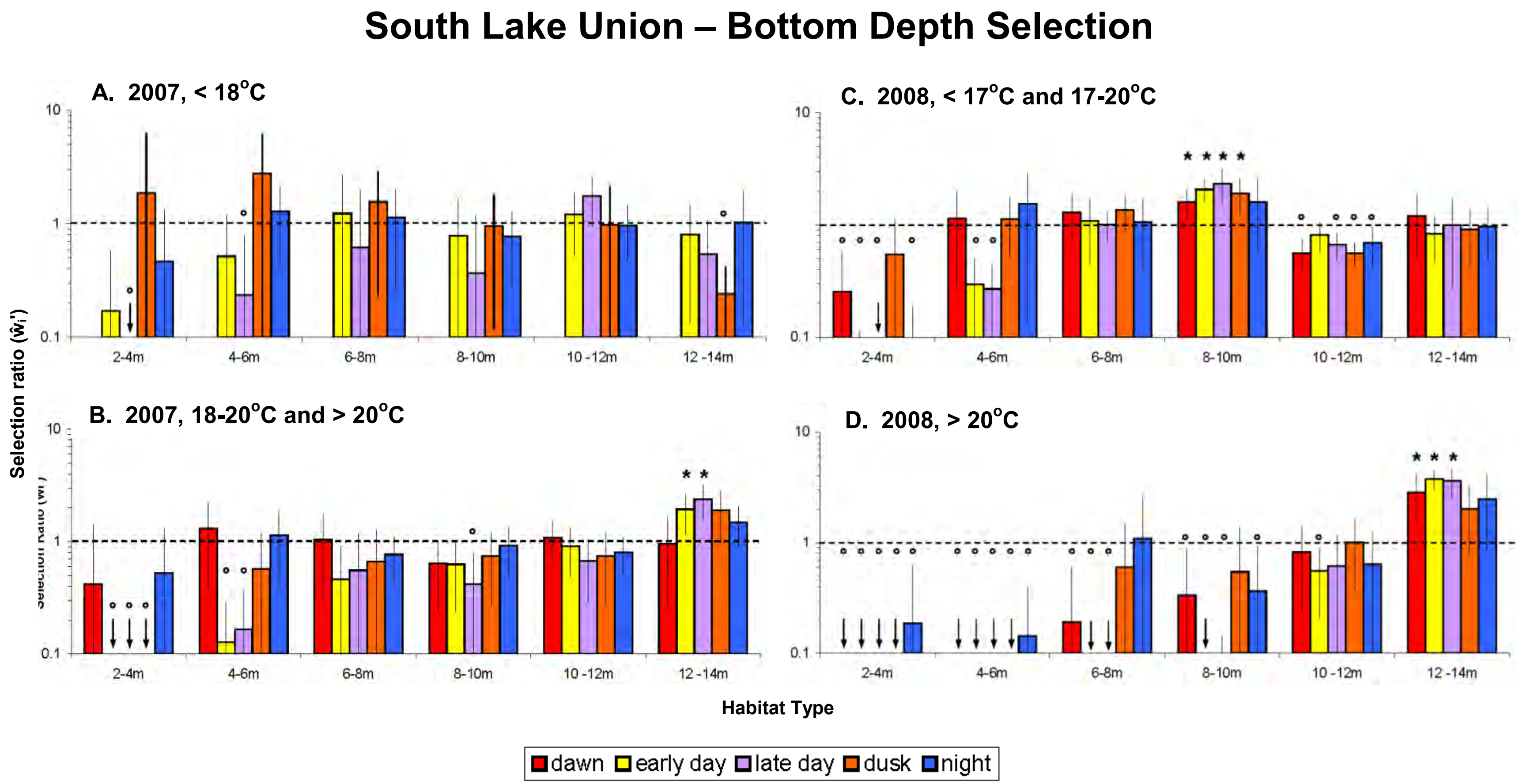

FIGURE 33. Diel bottom depth (water column depth) selection ($\hat{w}_i'$, selection ratio; log scale) of tagged Chinook salmon at the South Lake Union study site, June-July, 2007-2008.. Each panel shows data from one release group of fish that was generally representative of the temperature regimes indicated, although statistical significance was not always consistent. Panel A is representative of the < 18°C and 18-20°C temperature regimes in 2007 (data shown are from the June 15, 2007 release group). Panel B is representative of the late part of the > 20°C regime in 2007 (data shown are from the July 6, 2007 release group). Panel C is representative of the < 17°C and 17-20°C regimes in 2008 (data shown are from the June 27, 2008 release group). Panel D is representative of the late part of the > 20°C regime in 2008 (data shown are from the July 11, 2008 release group). Error bars represent Bonferroni-adjusted 90% confidence intervals. Error bars indicate if selection for (> 1) or against (< 1) a depth occurred. An asterisk (*) denotes statistically significant selection for a habitat and a circle (o) denotes statistically significant selection against. See Table 2 for habitat types. See Appendix L for results from all fish.

Ballard Locks

Fish behavior at the Ballard Locks was generally characterized by long residence times (a few hours up to several days), and extensive milling throughout the site. Of the tagged Chinook salmon that were tracked at the Ballard Locks site, 72% and 52% of 2007 and 2008 fish, respectively, were observed exiting into Puget Sound. In 2007, fish exited via the smolt flumes, the large lock, and the small lock (Figure 34). In 2008, fish exited via the smolt flumes and the large lock only. No fish exited via the small lock in 2008. No fish in either year exited via the saltwater drain or the fish ladder. Ballard Locks operations logs showed that both of these avenues were available 24 hours each day to migrating fish, except for June 2-7, 2007 when only the fish ladder was unavailable. A very small proportion of fish were observed exiting through spillways that lacked smolt flumes. For analytical purposes these fish were considered as exiting through the smolt flumes.

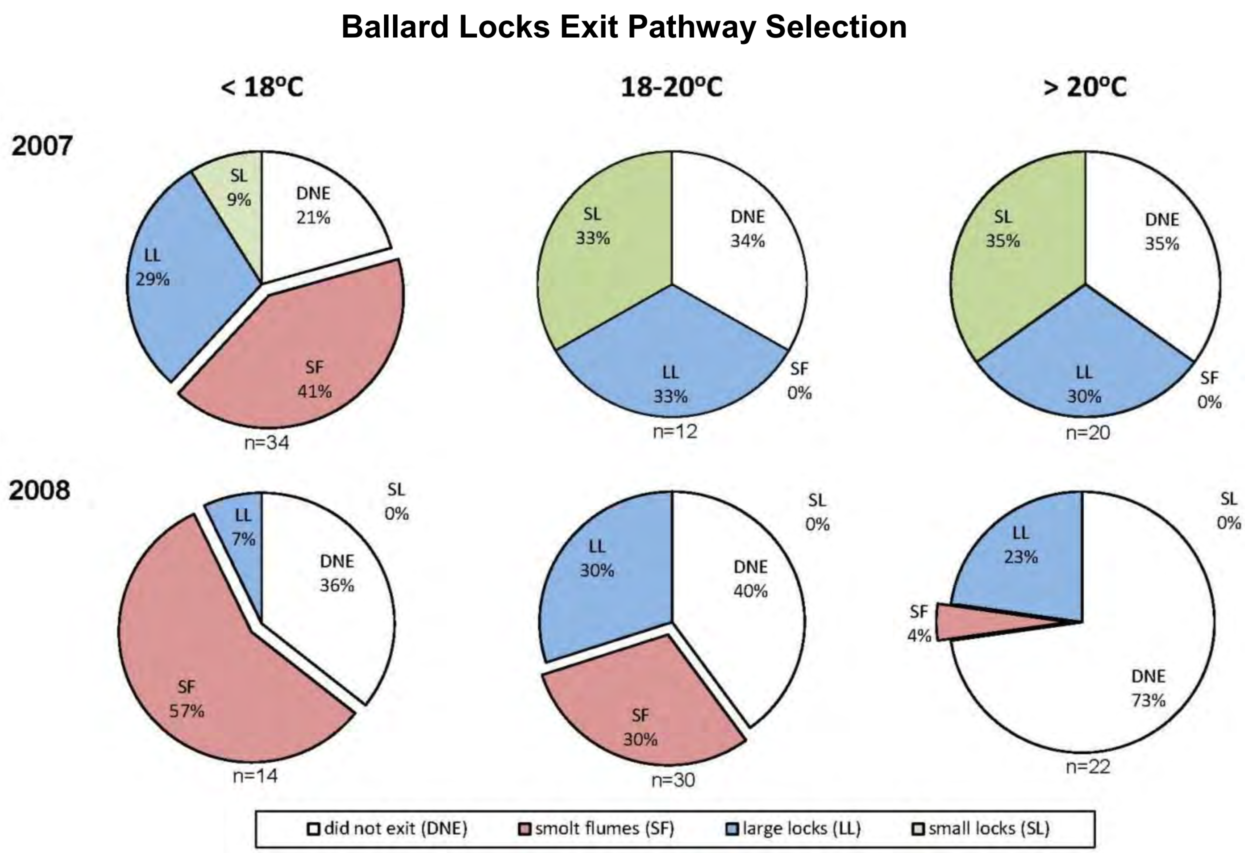

FIGURE 34. Proportion of tagged fish using different exit pathways at the Ballard Locks at three temperature regimes, June-July, 2007-2008. Temperature regimes were established using predominant surface water temperature at 1-2 m depth. See Table 1 for dates corresponding with each temperature regime.

In both 2007 and 2008, increasing surface water temperature corresponded with declines in smolt flume use and increases in the proportion of tagged fish that did not exit (Figure 34). When temperatures were less than 18^{o}C, the majority of tagged fish exited through the smolt flumes (52-89%). In 2007, the smolt flumes were not used at temperatures above 18^{o}C, and in 2008 the proportion declined to 50% and 17% at 18-20^{o}C and > 20^{o}C, respectively. The large lock was a common exit pathway. In general, the proportion of fish using the large lock increased as temperature increased. Between 37-83% of exiting fish exited through the large lock, except in 2008 when only 11% used the large lock at low water temperatures. The small lock was also an important exit pathway, albeit somewhat less so than the large lock. In 2008, the proportion of exiting fish using the small lock increased from 11% at the lowest temperature regime to 50-54% at higher temperatures.

Changes in locks operations may have influence behavior and passage of Chinook salmon. Locks operations differed substantially between 2007 and 2008 (Table 5; Figure 35). Relative to 2007, in 2008 the number of small lockages decreased, the number of large lockages increased, and the number of open smolt flumes increased. These changes may have contributed to the increased use of the smolt flumes observed in 2008. However, the overall percentage of smolts exiting into Puget Sound through all pathways decreased in 2008. Interestingly, exit through the large lock chamber appeared unchanged. It thus appears possible that, when the small lock chamber is effectively shut off as a possible exit pathway, more fish choose to delay longer and/or not exit rather than use the smolt flumes or the large locks.

The exit route used by tagged fish did not appear to be influenced by the shoreline along which the fish entered the site (Figure 36). In 2007, fish entering the site along both the north and south shorelines exited through the large lock most frequently, whereas fish entering in the middle of the channel exited the smolt flumes most frequently. Of fish entering along the north shoreline, 62% exited through the large lock. This seemingly large figure was coincidental, however, as the majority of these fish (64%) moved beyond the entrance to the large lock to the inner forebay area, where they milled around often extensively prior to leaving the forebay and exiting the site. The scenario was reversed in 2008, when fish entering along both shorelines exited through the smolt flumes slightly more frequently, and fish entering in the middle of channel exited through the large lock and the smolt flumes at about the same rate.

The proportion of tagged fish that did not exit increased with increasing temperature in both years. In 2007, this figure increased from 21% at the lowest temperatures, to 35% at the highest (Figure 34). In 2008, this figure increased from 36% to 73% from the lowest to the highest temperatures. Most non-exiting fish had long residence times compared with fish that did exit (Figure 37). This implies that tag battery life was not a factor in the difference between exiting and non-exiting fish. That is, non-exiting fish did not reach the Locks with less remaining battery life than fish that did exit. It is likely that at least some of the non-exiting fish exited after the tag battery expired.

TABLE 5. Mean daily operational configuration of the Ballard Locks while tagged fish were present, June-July, 2007-2008. Shown are the mean number of large and small lockages per day, and the mean number of open smolts flumes per day in both 2007 and 2008, and the percent change from 2007 to 2008.

Operational parameter	2007	2008	% change
mean number of small lockages per day	25.4	1.2	95% decrease
mean number of large lockages per day	7.4	12.9	74% increase
mean number of open smolt flumes per day	1.9	3.6	89% increase

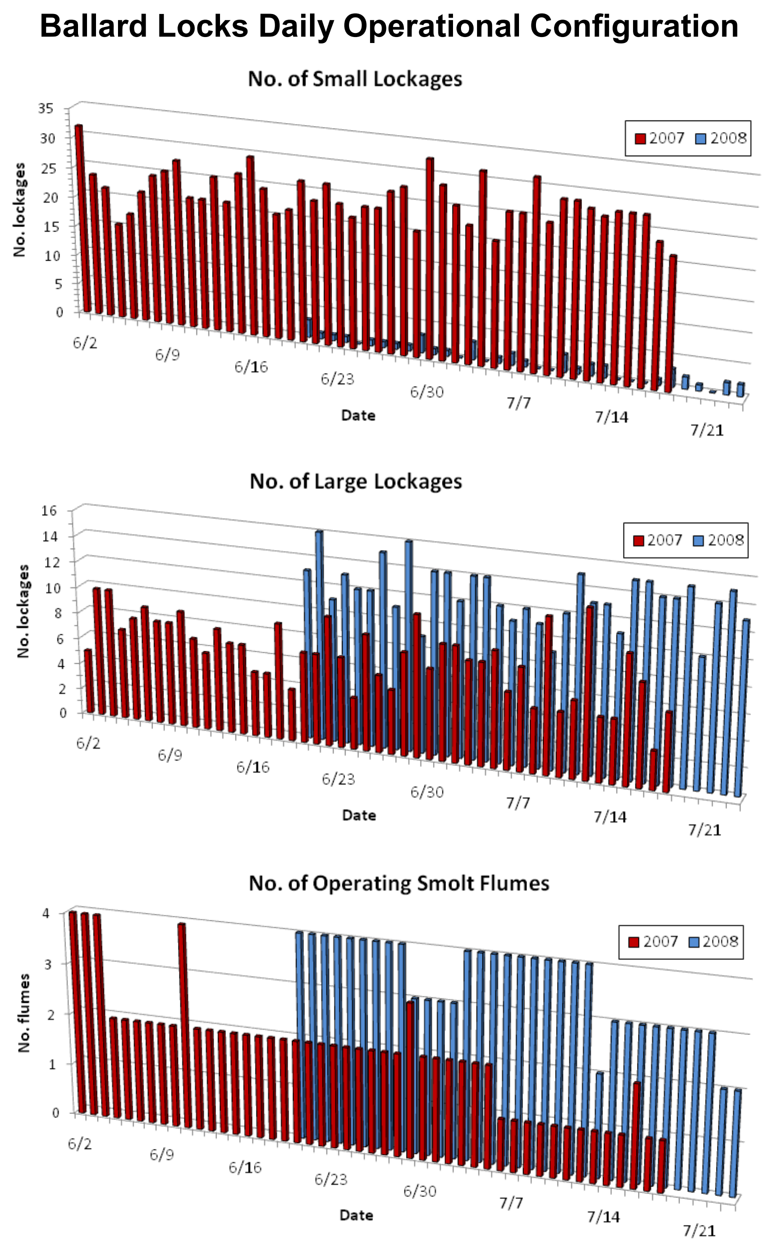

FIGURE 35. Daily operational configuration of the Ballard Locks, June-July, 2007-2008. The number of small lockages (top panel), the number of large lockages (middle panel), and the number of open smolt flumes (bottom panel) are shown for each day that tagged fish were present at the Ballard Locks study site.

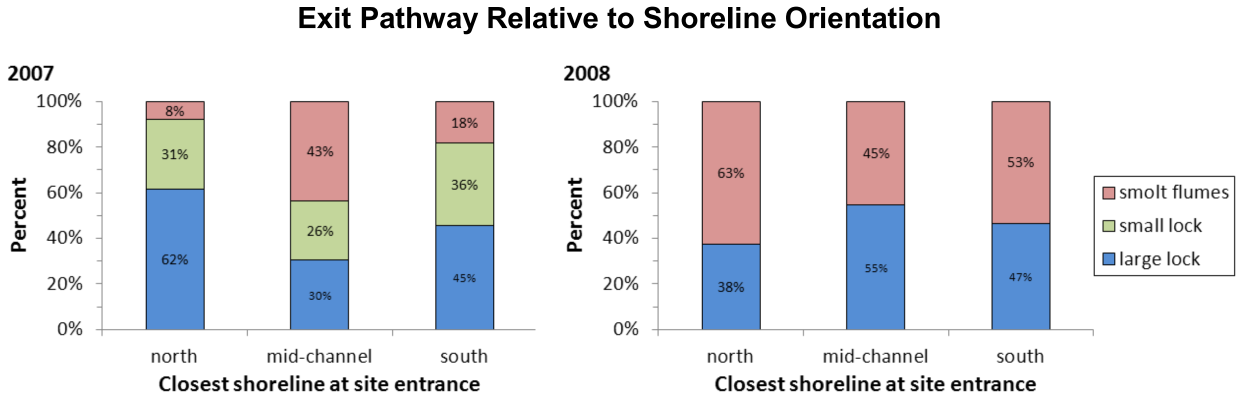

FIGURE 36. Exit routes used by tagged Chinook salmon through the Ballard Locks relative to shoreline orientation at site entrance, June-July, 2007-2008. Shoreline orientation was defined as follows: north = within 30 m of the pier at the approach to the large lock; south = within 30 m of the large dock structure on the southeastern corner of the site; and, mid-channel = the middle 40 m of the channel. See Appendix D for sample sizes.

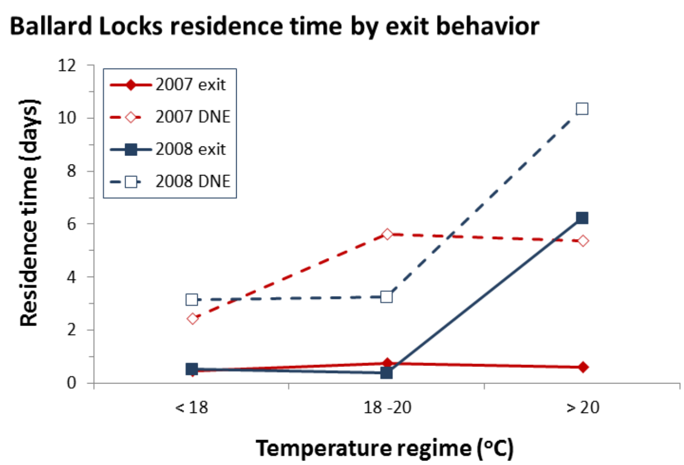

FIGURE 37. Median Ballard Locks residence times of tagged Chinook salmon that exited into Puget Sound (exit) and that were not observed exiting (DNE) at three temperature regimes, June-July, 2007-2008. See Appendix E for sample sizes and variability.

Most tagged Chinook salmon spent several hours to a day or more at and near the study site prior to exiting into Puget Sound (Figure 16). Fish that were not observed exiting into Puget Sound were often observed for several days up to one week or more at and near the study site. Most areas of the study site were used by fish during the study period except for the south marina: only the northern edges of the marina structures saw any appreciable use by tagged Chinook salmon. Not all areas of the site were used at all times. Instead, usage patterns shifted on multiple temporal scales. Changes in usage patterns appeared correlated with diel period and temperature regime. For example, during the lowest temperature regime (< 18°C) in 2007, spatial frequency distributions showed diel shifts in areas of the site frequented by tagged

Chinook salmon (Figure 38). Considerable forebay activity was observed during early day, and this seemed to continually decline through late day, dusk, and night. Activity in the forebay appeared to rise again at dawn. As temperatures rose during the study period, fewer fish were found in the forebay. For example, in 2008, spatial frequency distribution diagrams showed substantial proportions of fish were in the inner forebay at the lowest temperature regime (< 18°C) (Figure 39). These proportions declined at the middle temperature regime (18-20°C), and declined again at the highest regime (> 20°C). The decline in the inner forebay was accompanied by increases in other parts of the site, particularly the deepest areas in front of the large lock and in the north shipyard.

Many fish entered and milled around throughout the inner forebay, including many fish that exited through the locks (small and large) and fish that did not exit. Of all the fish detected at the Locks, 69% in 2007 and 65% in 2008 entered the inner forebay at least once. Most fish that entered the forebay did so within the first 24 hours of entering the site, often within the first few hours. Fish often spent anywhere from a few minutes up to an hour or more in the inner forebay before either exiting through the smolt flumes or exiting the inner forebay to the east. Fish that exited the forebay to the east and that later exited to Puget Sound usually remained in and near the tracking area for very short (less than one hour) to very long (1-2 days or more) periods of time. Fish that entered the forebay but that were not observed exiting into Puget Sound were generally observed in and near the tracking area for longer periods of time (see Appendix F for forebay use data). Many fish that entered the forebay did so only once. However, a sizeable proportion (33-52%) entered the forebay on more than one occasion; that is, they did not exit through the flumes or spillways on their first appearance in the forebay. Some fish entered the forebay on 3-8 separate occasions. Of all fish not exiting through the smolt flumes (i.e., exiting through the small or large locks, or not observed exiting), 51-61% entered the inner forebay at least once. The proportion of fish that entered the inner forebay decreased as water temperatures increased (Figure 40). At the lowest temperature regime (< 18°C), 85-93% of fish entered the inner forebay. This decreased to 67-71% at the middle temperature regime (18-20°C), and 35-42% at the high regime (> 20°C). Also, the proportion of fish that entered the inner forebay and that also exited via the smolt flumes declined as temperatures increased (Figure 40).

We observed five distinct behaviors of tagged Chinook salmon at the Ballard Locks (Table 6; Figure 41). Certain behaviors were often associated with specific parts of the site, and these were largely consistent between years. One notable difference was that in 2008 there was less activity in general in the three areas adjacent to the small lock (the outer forebay, the small lock approach, and the small lock entrance). Fish often oriented along the pier walls at the approaches and entrances to the small and large locks: direct movement along pier walls and milling along pier walls were the most commonly observed behaviors here. Milling along a pier wall was most frequently observed in the large lock approach area. Some localized milling in the large lock approach area was also observed in 2008. Fish in the offshore areas often exhibited direct movement and broad-scale milling; intensive use of localized areas (i.e., localized milling) was not commonly observed in the offshore zones. In the inner forebay, fish often milled throughout the entire area (i.e., localized milling), and some orientation along structure walls was occasionally observed. Behaviors in the outer forebay had characteristics of three areas it bordered (inner forebay, small lock entrance, shallow offshore area), thus appearing as a transitory zone: common behaviors in the outer forebay included direct movement along pier

Ballard Locks – Diel Spatial Frequency Distribution

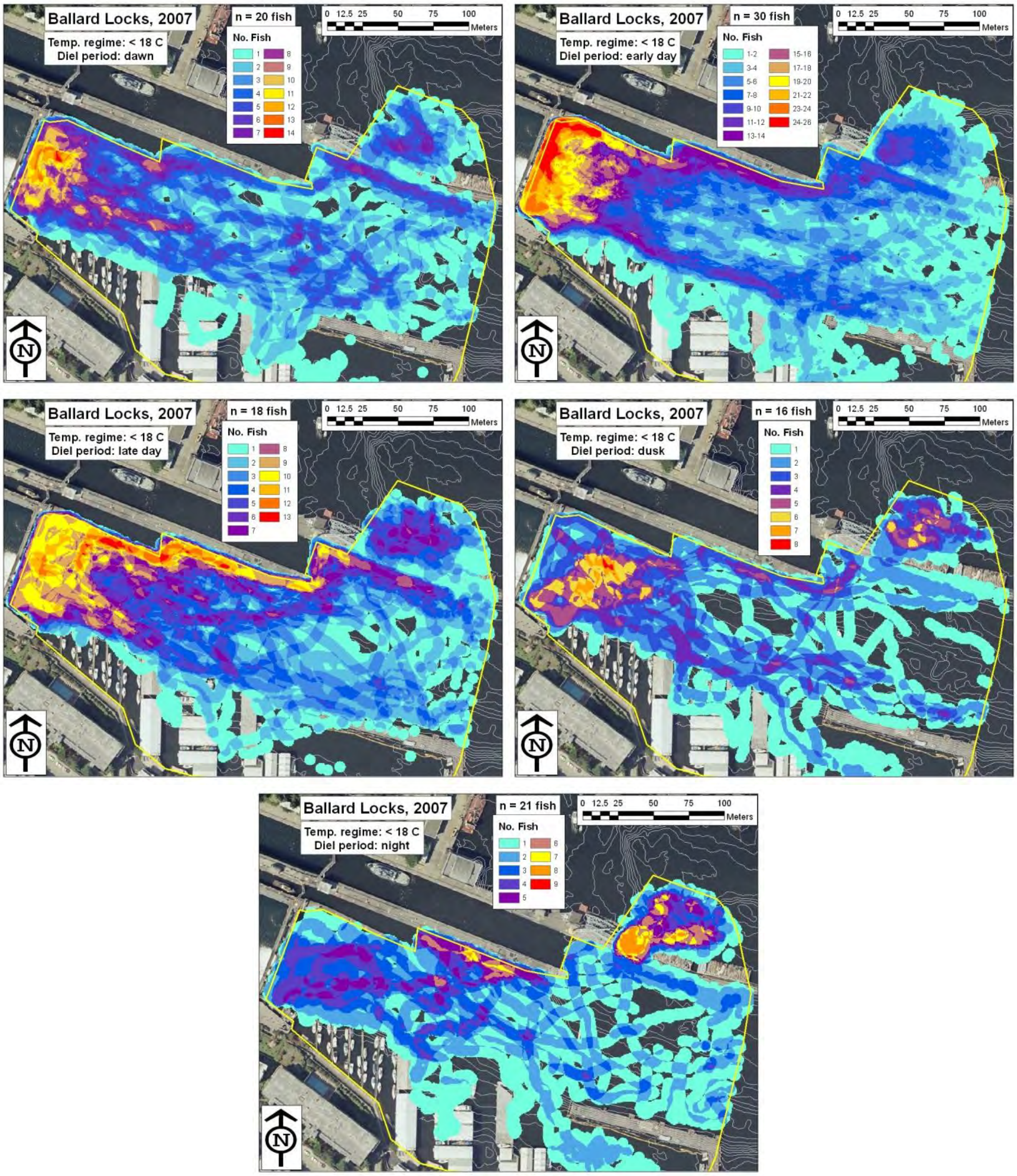

FIGURE 38. Spatial frequency distributions of tagged Chinook salmon at the Ballard Locks study site during dawn, early day, late day, dusk, and night at the lowest temperature regime (< 18°C), June 2-June 22, 2007.

Ballard Locks - Temperature Influence on Spatial Frequency Distribution

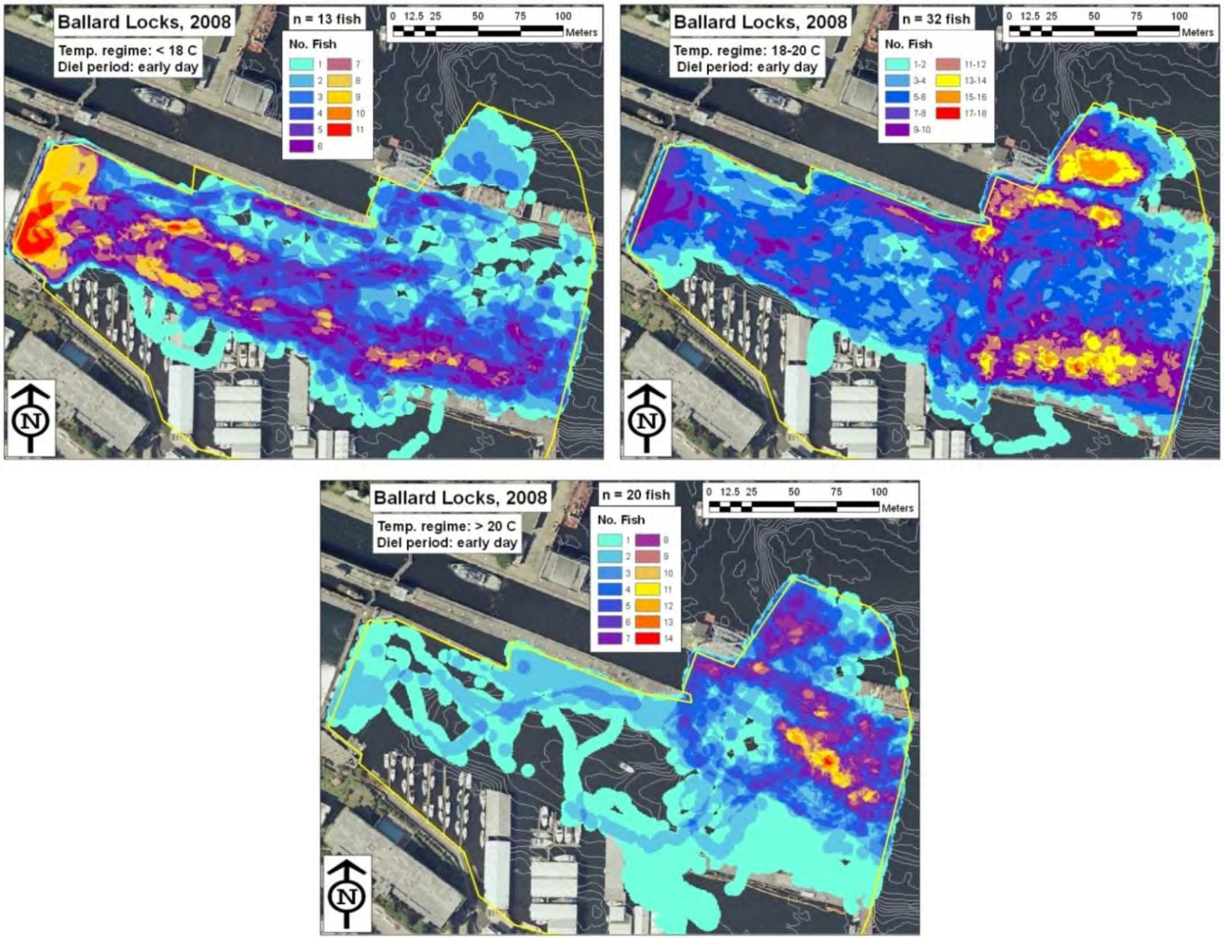

Figure 39. Spatial frequency distributions of tagged Chinook salmon at the Ballard Locks study site during early day at three temperature regimes: low (< 18°C), middle (18-20°C), and high (> 20°C), June 21-July 23, 2008.

walls, direct movement not along pier walls, and broad-scale milling. In the north shipyard, localized milling was often observed, although the small part of the shipyard in our tracking area limited our ability to observe fish here. Many fish spent considerable lengths of time here often at night and often near the pier wall and moored barges (e.g., Figures 38, 42, and 43). Nighttime use may have been associated with artificial lighting in this area: there was a light located on the pier that cast light into the water, measured at 27.2 lux at the water surface. Use of this area during the day and crepuscular periods also appeared to increase with increasing temperature (e.g., Figure 39). Little activity was observed in the south marina area. Fish occasionally moved along the outer edge of the marina and other structures in this area, but often remained outside in other zones (outer forebay, offshore shallow, offshore deep). Some fish occasionally entered the spaces between structures, but often exited shortly after entering.

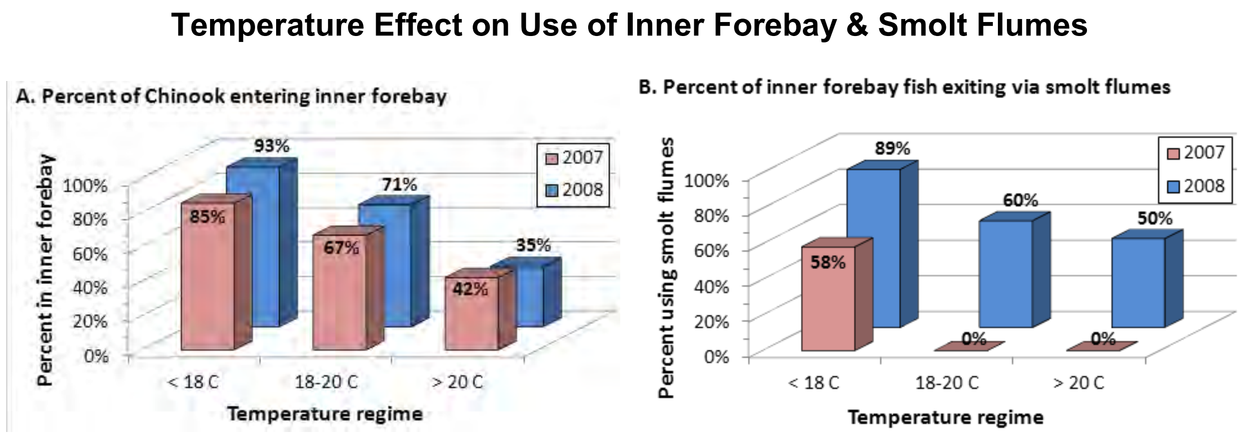

FIGURE 40. Proportion of tagged Chinook salmon entering the Ballard Locks inner forebay (A) and exiting via the smolt flumes (B), June-July, 2007-2008. Of all tagged Chinook salmon detected at the locks, the percent that entered the inner forebay area is shown in (A). Of all fish entering the inner forebay and exiting into Puget Sound, the percent that exited via the smolt flumes is shown in (B). See Appendix C for sample sizes. Temperature regimes were established using predominant surface water temperature at 1-2 m depth. See Table 1 for dates corresponding with each temperature regime.

TABLE 6. Descriptions of five general behaviors observed in tagged Chinook salmon at the Ballard Locks study site, June-July, 2007-2008. See Figure 41 for examples of each behavior.

Behavior	Description
Direct movement	Movement in a generally linear manner from one area of the site to another. Direct movement often punctuated periods of milling (e.g., a fish might be milling in the deep offshore area, then move directly to the inner forebay where it would engage in more milling). Direct movement often covered long distances, generally greater than 100 m.
Near pier walls	Direct movement along pier walls, within 5 m of the wall.
Not near pier walls	Direct movement not within 5 m of a pier wall.
Milling	Circuitous, criss-crossing, back-and-forth movement; fish not travelling in any apparent general direction.
Broad-scale	Milling over a large area, generally greater than 60 m x 60 m in size.
Localized	Milling in a relatively small, confined area, generally less than 60 m x 60 m in size
Along a pier wall	Milling along a pier wall; back-and-forth movement along a pier wall.

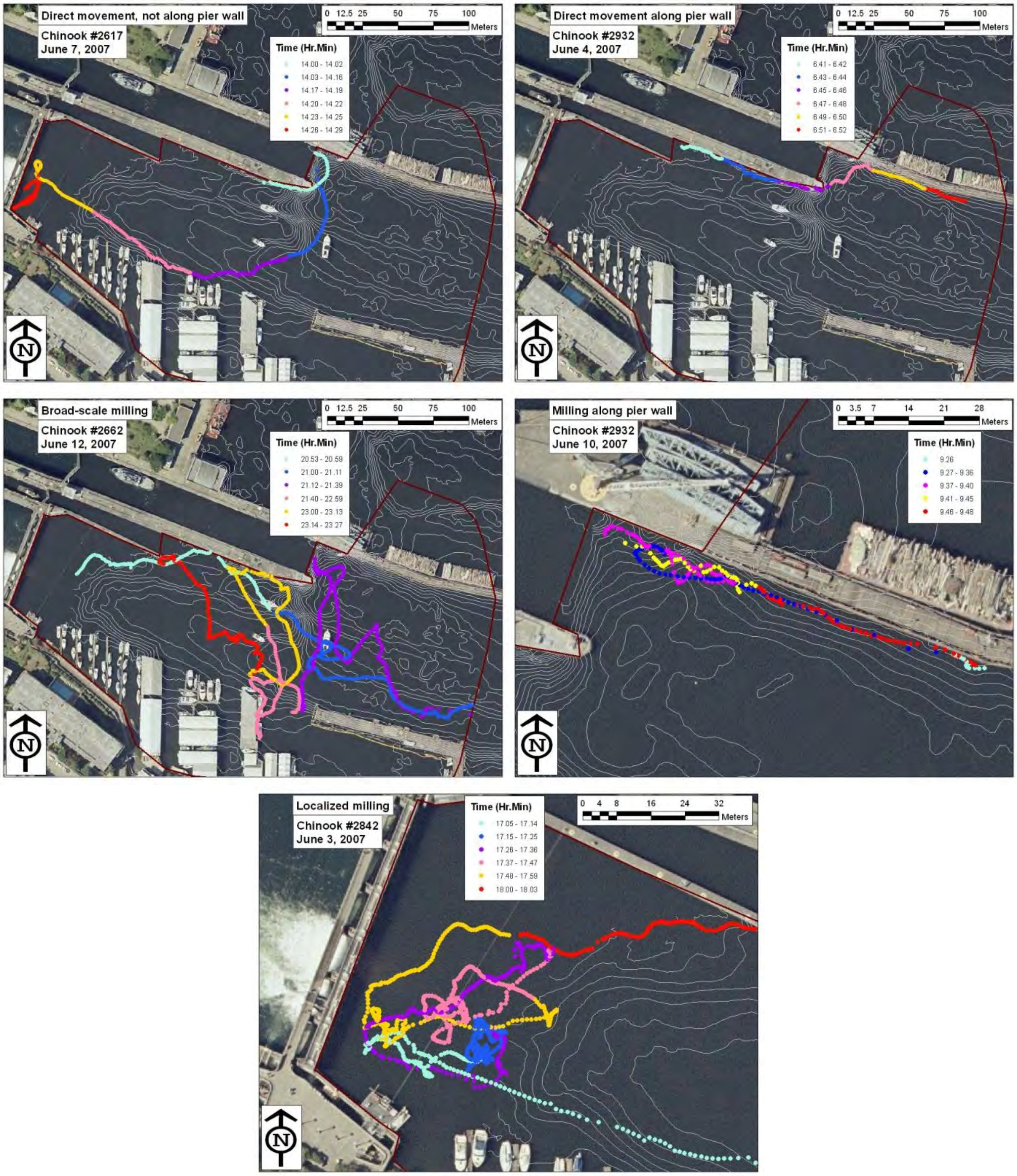

FIGURE 41. Example of five general behaviors observed in tagged Chinook salmon at the Ballard Locks study site, June-July, 2007-2008. Behaviors included: direct movement not along a pier wall, direct movement along a pier wall, broad-scale milling, localized milling, and milling along a pier wall. See Table 13 for complete description of behavior types. The color ramp on each plot indicates the time sequence of the movement pathway.

Chinook salmon #2707

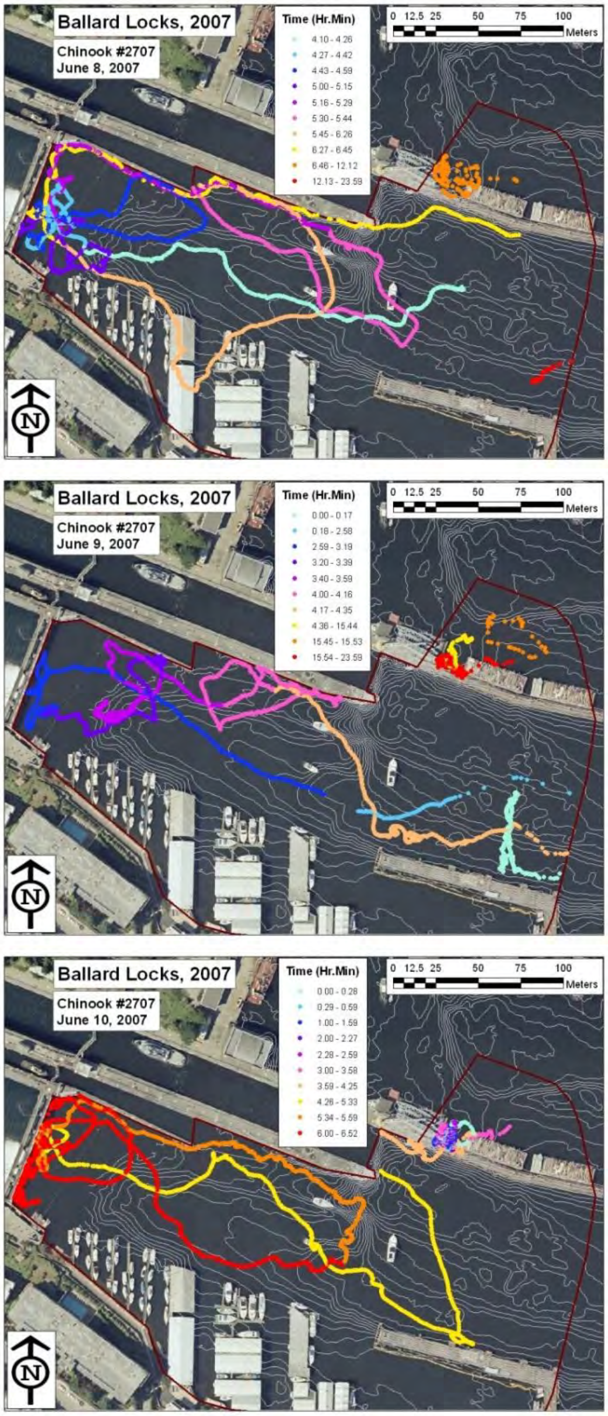

FIGURE 42. Movement pathways of Chinook salmon #2707 at the Ballard Locks study site during June 8-June 10, 2007. This fish exited into Puget Sound via the smolt flumes at 06:52 hours on June 10, 2007. The color ramp on each plot indicates the time sequence of the movement pathway.

Chinook salmon #3033

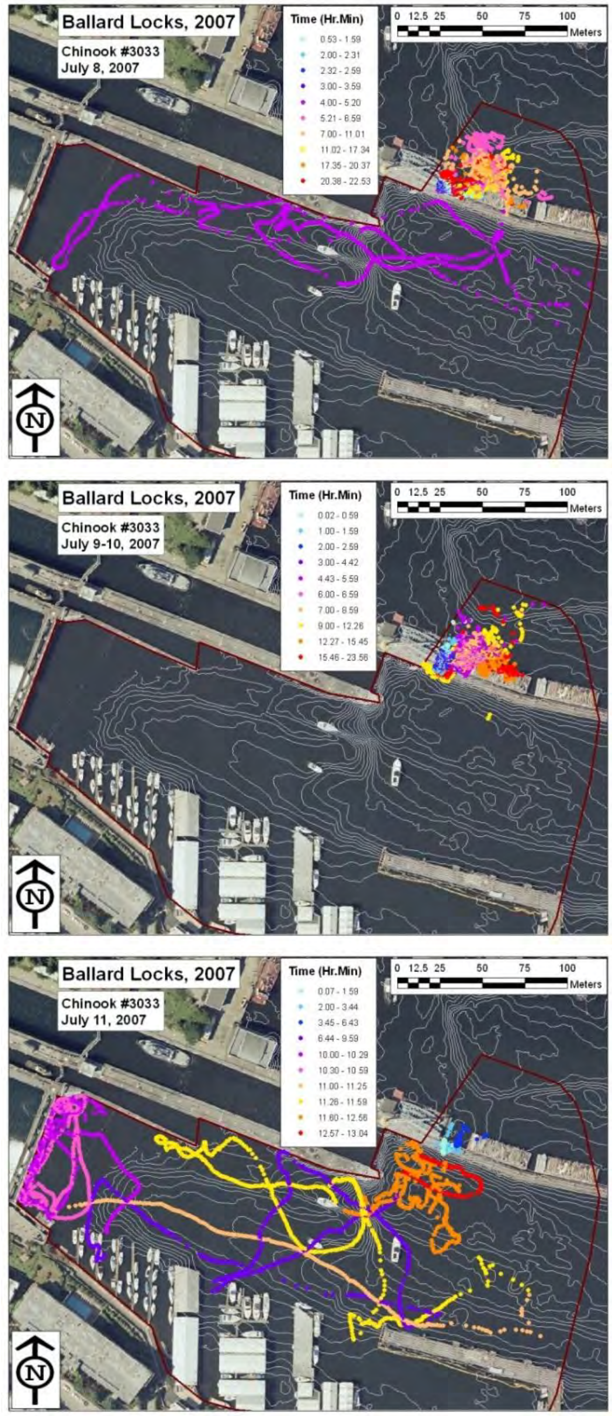

FIGURE 43. Movement pathways of Chinook salmon #3033 at the Ballard Locks study site during July 8-July 11, 2007. This fish exited into Puget Sound via the large lock at 13:04 hours on June 11, 2007. The color ramp on each plot indicates the time sequence of the movement pathway.

Influence of artificial lights on nighttime movement and habitat use

We observed influences of artificial lighting on nighttime movement and habitat use of tagged Chinook salmon at three study sites: University Bridge, South Lake Union, and the Ballard Locks. This study was not intended to provide a thorough evaluation of artificial lighting. However, upon observing in our tracking data indicators that artificial lighting may have influenced tagged Chinook salmon habitat use, we conducted follow-up site visits to provide at least a minimal level of verification. We identified sources of artificial lighting and/or measured light levels near the water surface. These light surveys were not intended to be rigorous: we did not attempt to locate and measure every source of artificial light. Light intensity levels were measured at the water surface with an Extech Instruments light meter to the nearest 0.1 lx.

At the Ballard Locks, areas of the site that were intensively used by tagged Chinook salmon at night were often associated with artificial light (Figures 44 and 45). These included areas at the large lock approach/entrance along the north pier wall, the area immediately to the north of this pier wall, at the small lock approach/entrance along the north pier wall, as well as two other localized areas (Figure 44). Light levels in these areas were generally greater than 10 lx, although one point was measured as low as 0.3 lx (Figure 45). Ambient light levels measured at 11 points throughout the site were generally 0.0 lx (7 points), and was as high as 0.2 lx (3 points). Interestingly, some areas with elevated light levels were not associated with greater use by tagged Chinook salmon. For example, light levels along a line running parallel to and 15 m from the small lock pier wall were generally 3-10 lx (Figure 45). However, we did not observe any elevated use by tagged Chinook salmon in this area. This may have been due to the proximity of this area to higher light levels closer to the pier wall.

At the South Lake Union site, we observed several instances of tagged Chinook salmon spending prolonged periods near known artificial lights at night (Figure 46). Light levels were measured at only two known sources, and were 2.3-6.0 lx about 1 m above the surface of the water. Ambient light levels measured along the shoreline were 0.5-0.7 lx. Artificial light sources were on structures in areas where the water was relatively deep (> 6 m). There were numerous other areas near overwater structures in deep water where some tagged Chinook salmon spent prolonged periods at night. It is uncertain if there was artificial lighting in these areas. A more rigorous light survey is needed to verify all artificial lights sources and the light level at these sources.

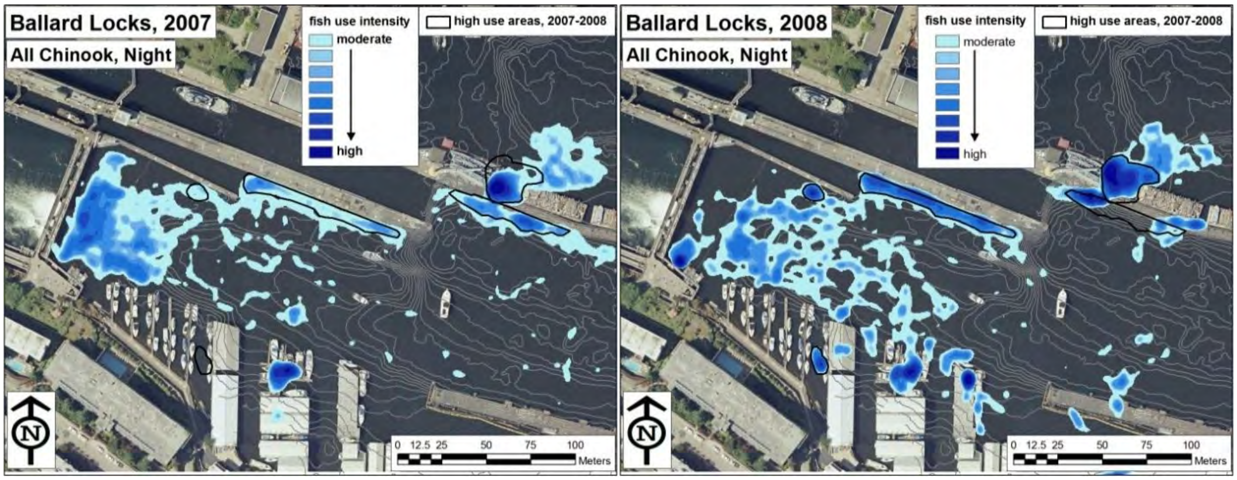

FIGURE 44. Areas of moderate to high intensity use by tagged Chinook salmon at night at the Ballard Locks, June-July, 2007 (left) and 2008 (right). Areas of higher use that were associated with artificial lighting are outlined in black. See Figure 45 for light level measurements in these areas.

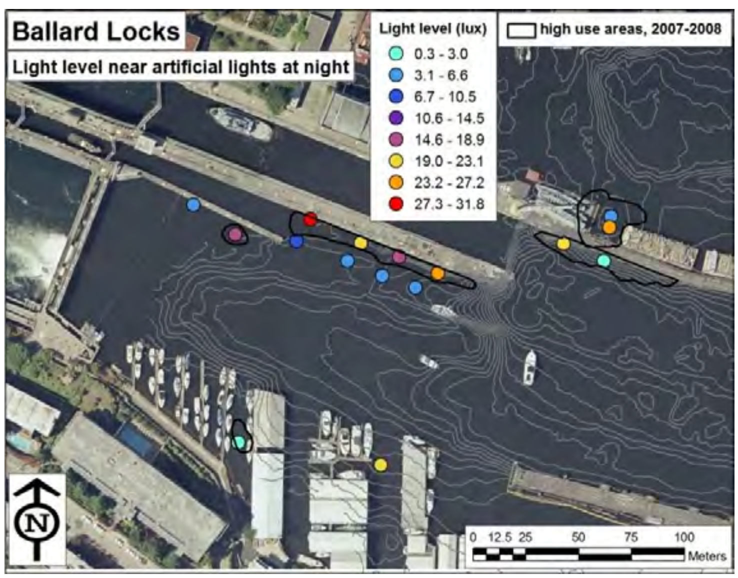

FIGURE 45. Light level readings (lx) in selected areas of the Ballard Locks study site. Selected areas used more intensively by tagged Chinook salmon are outlined in black. See Figure 38 for distribution of tagged Chinook salmon usage intensity. Ambient light level was generally 0.0 lx, although in some areas was as high as 0.2 lx.

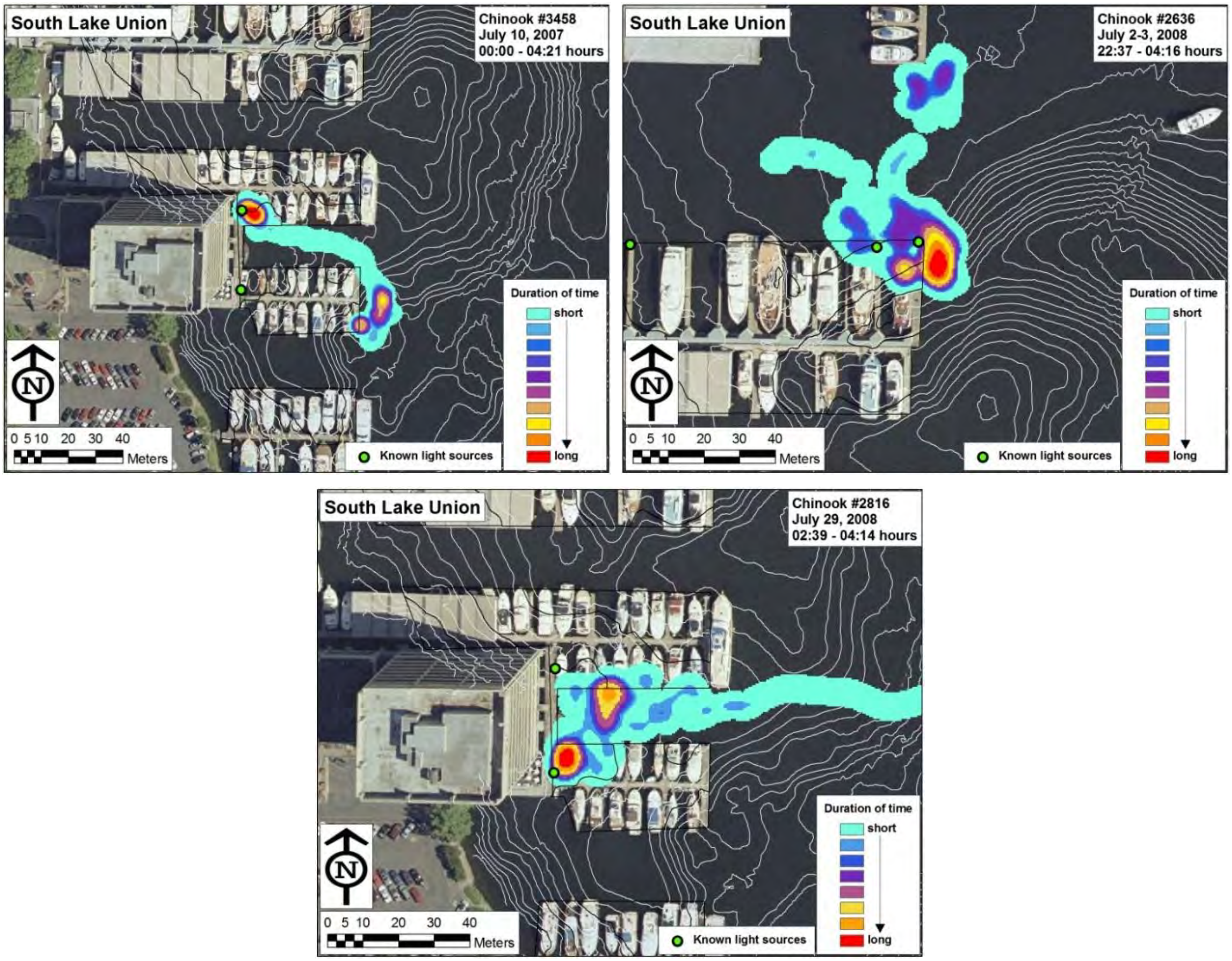

FIGURE 46. Three examples of tagged Chinook salmon use of artificially lit areas at night at the South Lake Union site: Chinook #3458 (upper left), #2636 (upper right), and #2816 (bottom). Sources of known artificial light are shown. Other sources of artificial light may have also been present. Light levels at the two sources in the upper left and bottom images measured about 1 m above the water surface were 6.0 lx (north source) and 2.3 lx (south source). Ambient levels measured along the shoreline were 0.5-0.7 lx. Light levels at the sources in the upper right image were not measured.

At the University Bridge site, there was a notable response of tagged Chinook salmon to artificial lighting on the I-5 bridge deck and the light/shadow edge this lighting created in the water (Figures 47, 48, and 49). Light levels were 1.6-2.0 lx (measured at 3 points) within 1 m of the edge on the light side, and were 0.2-0.5 lx (measured at 6 points) in the shadow area between the lines. Many fish milled along the light/shadow edge on the eastern side of the I-5 bridge and milled between this edge and the University Bridge. These areas were highlighted on both spatial frequency distribution maps (suggesting that many fish spent time milling in this area) and density plots (suggesting that many fish spent prolonged periods here relative to other parts of the site) (Figure 47). Movement pathways of many fish also showed extensive north-south milling along this edge (e.g., Figure 49). Many of these fish also milled in the area between the edge and the University Bridge, often interspersing periods of milling along the light/shadow edge with periods milling between the bridges. There was a marked reduction in activity in the shadow zone beneath and adjacent to the I-5 bridge. This was evident on both density plots and spatial distribution maps (Figure 47). Tracks of tagged fish suggested that many fish either did not enter the shadow area or moved quickly through without spending much time. Movement pathways of some fish suggested that this light/shadow edge influenced their movement. For example, when Chinook salmon #3168 encountered the western light/shadow edge from the east, it twice changed its pathway and moved away from the edge before crossing the edge on its third encounter (Figure 49).

Also at the University Bridge site, we observed areas of high tagged fish use in the mid-channel area adjacent to the University Bridge support structures (Figure 47). These areas were associated with artificial lighting beneath the bridge attached to the support structures (Figures 47 and 50), presumably as a boating navigational aid. We did not measure light levels here.

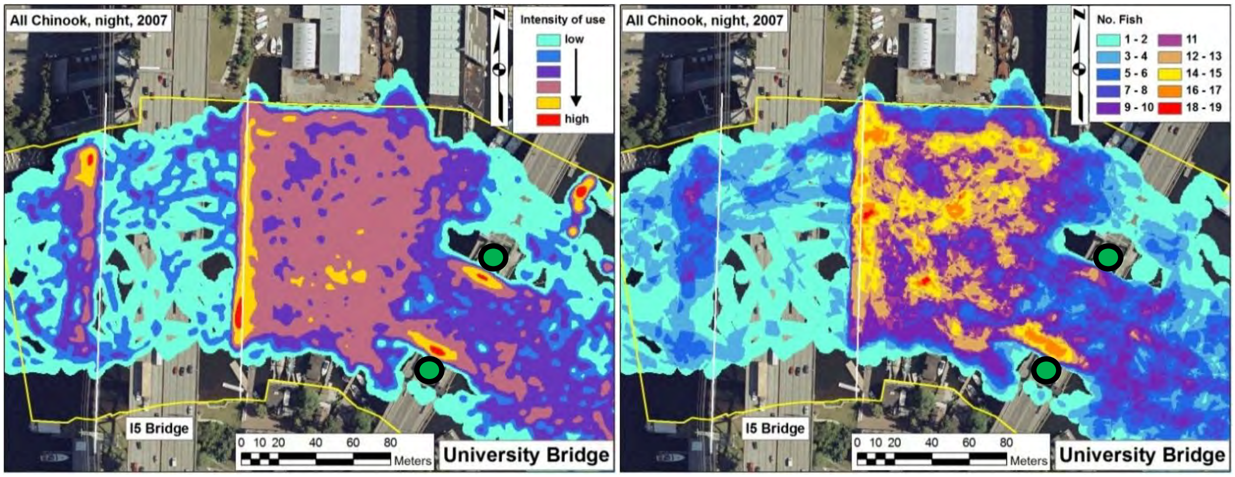

FIGURE 47. Distribution of tagged Chinook salmon at night at the University Bridge study site, June-July, 2007. Density plot (left) shows intensity of fish use for all tracked fish (weighted by time), and spatial frequency distribution (right) shows number of fish tracked by area. The white lines parallel to the I-5 bridge show the location of the light/shadow edge created by artificial lighting on the I-5 bridge deck (see Figure 48). Light levels were 1.6-2.0 lx (measured at 3 points) within 1 m of this line on the light side, and were 0.2-0.5 lx (measured at 6 points) in the shadow area between the lines. Green circles show approximate locations of lights beneath the University Bridge (see Figure 50).

FIGURE 48. Artificial lighting on the I-5 bridge deck spanning the Lake Washington Ship Canal (looking north).

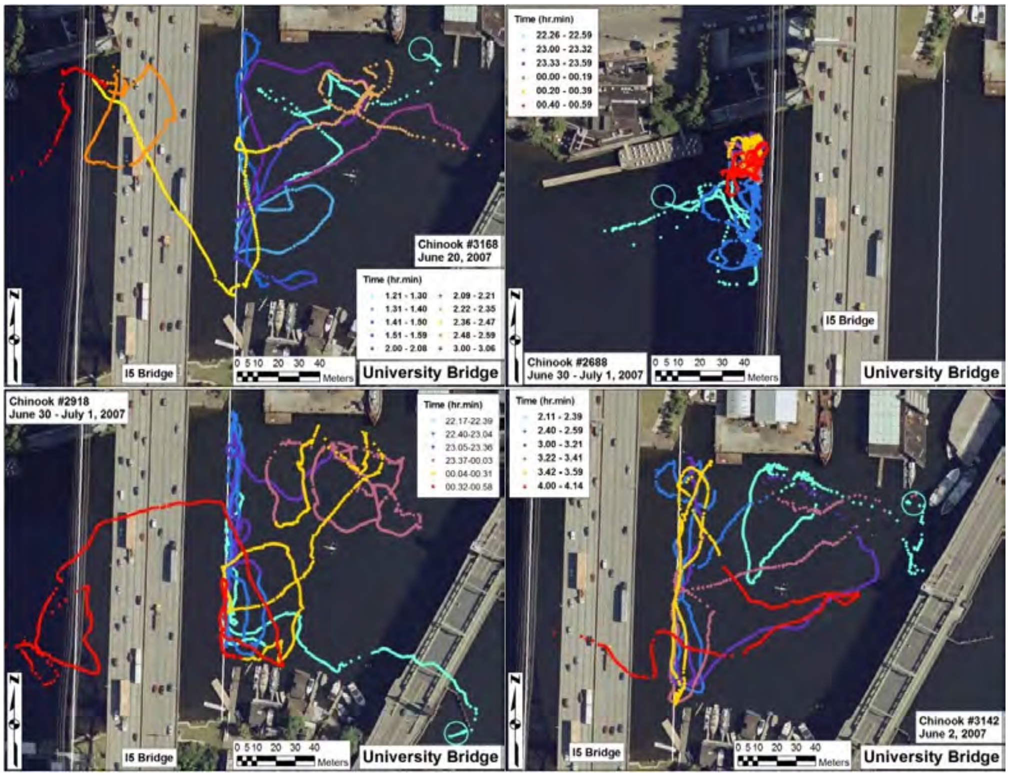

FIGURE 49. Four examples of tagged Chinook salmon behavior near the light/shadow edge created by artificial lighting on the I-5 bridge deck: Chinook #3168 (upper left), #2688 (upper right), #2918 (bottom left), and #3142 (bottom right). The white lines parallel to the I-5 bridge indicate the light/shadow edge created by artificial lighting on the I-5 bridge deck. Light levels were 1.6-2.0 lx (measured at 3 points) within 1 m of this line on the light side, and were 0.2-0.5 lx (measured at 6 points) in the shadow area between the lines. The color scale indicates the time sequence of each track. The blue circle shows the starting point of the fish in each image.

FIGURE 50. Artificial lighting under the University Bridge. Lighting is directed down onto the water surface. Light on the north bridge support structure is pictured. Light on the south support structure is similar. These lights correspond with green circles in Figure 47.

Vertical Position Selection

Fish vertical position selection at the University Bridge site was consistent between temperature regimes within each year, but varied between years. In 2007, positions in the 0-3 m and 3-6 m strata were commonly selected for, and selection for each of these strata was generally equivalent (Figure 51). Deeper strata were consistently selected against. Results from 2008 were equivalent in that the 0-3 m stratum was consistently selected for, but differed in that the 3-6 m stratum was often selected against. In 2008, strata deeper than 6 m were used less and showed stronger negative selection than in 2007. The consistency between temperature regimes within each year suggests that large shifts in vertical position selection associated with increasing temperature did not occur. Also, vertical position selection was generally equivalent between diel periods despite some subtle variations in some temperature regimes. In both years, there was a considerable lack of representation across the entirety of each temperature regime. That is, the substantial majority of observations occurred on the day study fish were released.

With some notable exceptions, fish vertical position selection at the Ballard Locks was largely consistent between temperature regimes and varied between years (Figure 52). In 2007, fish selected for the 0-3 m stratum in the < 18°C temperature regime. Deeper strata were often selected against. The other two temperature regimes showed strikingly different results. Fish in the 18-20°C and > 20°C regimes often selected against the 0-3 m stratum, particularly during the day. Instead, these fish appeared to distribute somewhat evenly across all strata > 3 m. In 2008, fish showed the highest selection for the deepest stratum (> 12 m) during the day. The 0-3 m stratum showed the next highest selection, except for the > 20°C regime. Other strata were often selected against. There did not appear to be any general shifts associated with temperature regime. Some diel patterns were evident. In all temperature regimes in 2007, fish appeared to use shallower strata more and select against deeper strata (> 9 m) during dawn. During the day, there was a notable shift toward more use of deeper strata. In 2008, only the 18-20°C had enough fish to evaluate diel periods other than day. Fish during this time showed elevated selection for the shallowest stratum (0-3 m) at dusk and night. Dawn appeared to be a transitory period. Unlike at the University Bridge site, fish had a more even temporal distribution across each temperature regime.

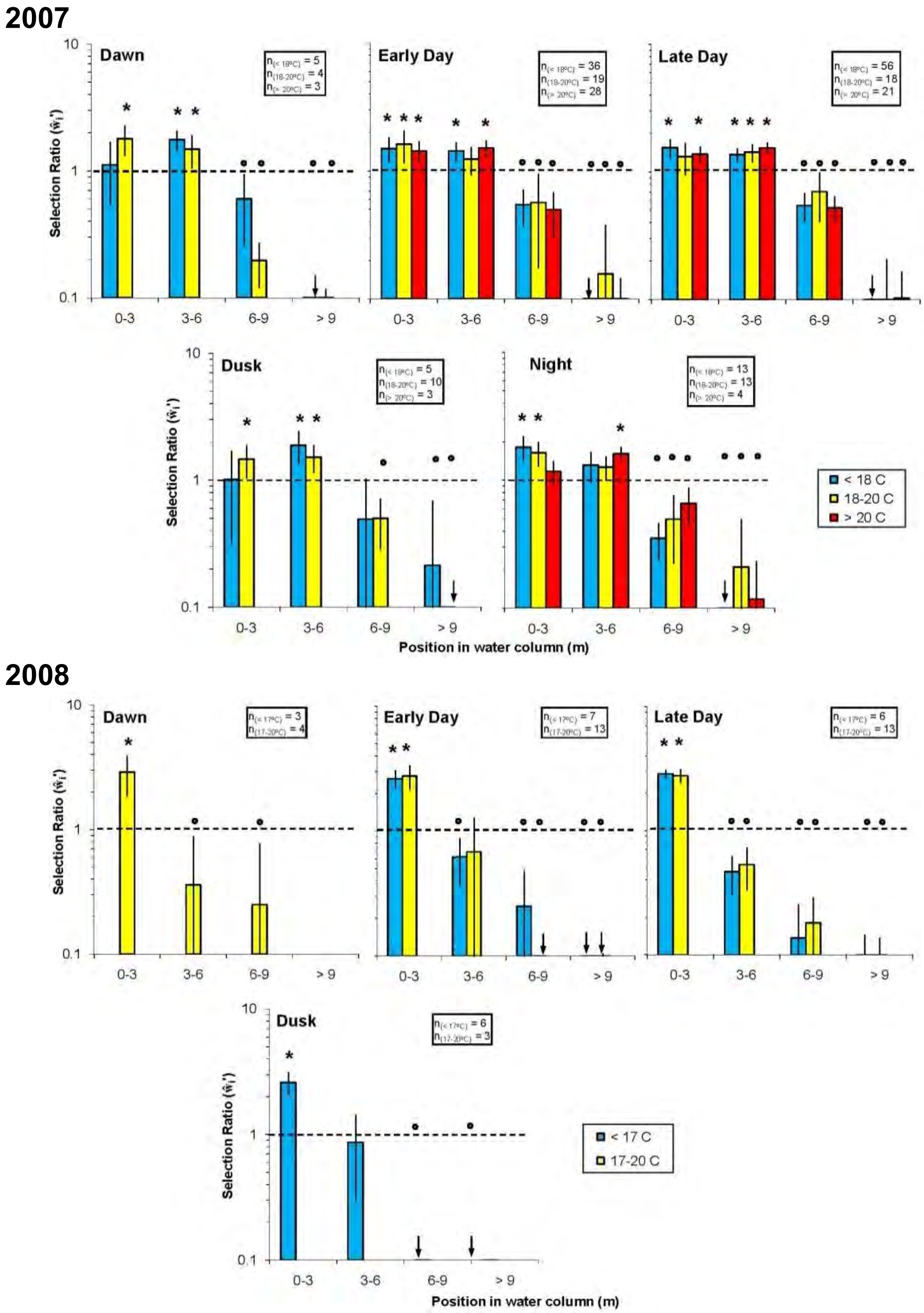

FIGURE 51. Vertical position selection ($\hat{w}_i'$, selection ratio; log scale) of tagged Chinook salmon smolts at three temperature regimes at the University Bridge study site, June-July, 2007-2008. Error bars represent Bonferroni-adjusted 90% confidence intervals. Error bars indicate if selection for (> 1) or against (< 1) a depth stratum occurred. An asterisk (*) denotes selection for stratum and a circle (o) denotes selection against. Data are not shown for the 2008, > 20°C temperature regime because the substantial majority of fish moved through the site in one of two schools. Diel periods with n ≤ 3 tagged fish observed were not graphed.

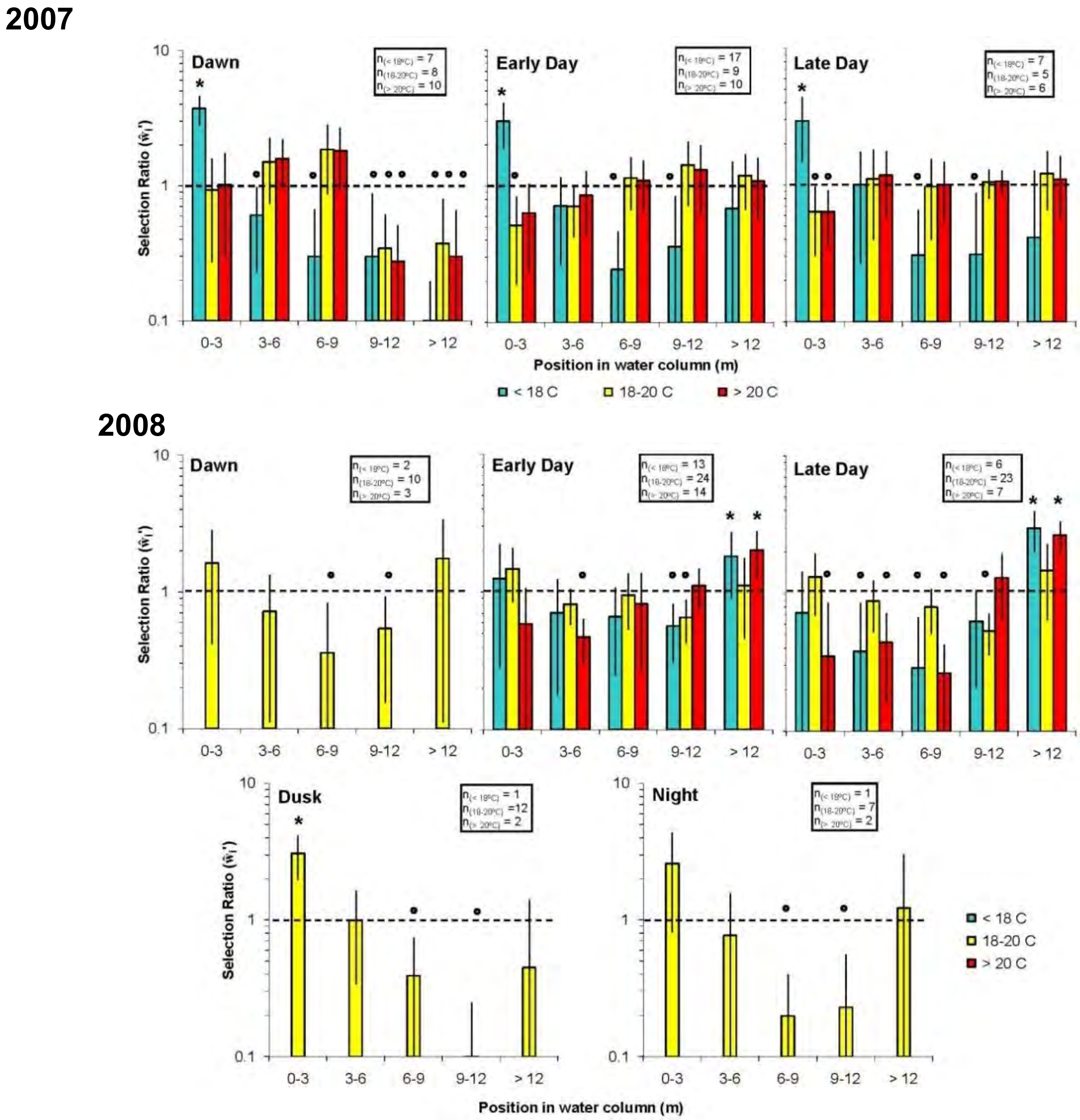

FIGURE 52. Vertical position selection (ŵi', selection ratio; log scale) of tagged Chinook salmon smolts at three temperature regimes at the Ballard Locks study site, June-July, 2007-2008. Error bars represent Bonferroni-adjusted 90% confidence intervals. Error bars indicate if selection for (> 1) or against (< 1) a depth stratum occurred. An asterisk (*) denotes selection for a stratum and a circle (o) denotes selection against. Diel periods with n ≤ 3 tagged fish observed were not graphed.

DISCUSSION

Correlation of results with naturally-produced fish

One of the main goals of this study was to aid in guiding conservation of naturally-produced Chinook salmon smolts migrating through the LWSC. Because we used hatchery-produced fish obtained directly from a hatchery, we must consider whether the size of fish used in this study and the study period during which tagged fish were tracked represent naturally-produced fish. There is limited information on timing and size of naturally-produced Chinook salmon smolts in the LWSC. Several years of PIT tagging data have found naturally-produced and Issaquah Hatchery Chinook salmon exiting the Ballard Locks between about mid-May to late-July or later (DeVries et al. 2002; DeVries et al. 2003; DeVries et al. 2005; DeVries et al. 2007; DeVries et al. 2008). Exactly when fish begin entering the LWSC is unknown, although indications suggest not much earlier than mid-May (DeVries et al. 2005). PIT tagging efforts in the LWSC captured hatchery- and naturally-produced Chinook salmon smolts directly from Lake Union, Portage Bay, and Union Bay in 2001. The size of these fish (90-130 mm FL) correspond closely with those used in our study (100-120 mm FL), although the DeVries et al. (2002) data may have been biased in favor of hatchery-origin fish. In general, hatchery-produced fish are commonly larger than their naturally-produced counterparts. Thus, it is possible that the fish used in this study were larger than naturally-produced fish in the LWSC.

Migratory functions of the LWSC

The results of this and other studies show general consistency in Chinook salmon movement patterns through the LWSC. In our 2004-2005 study (Celedonia et al. 2008b) we suggested that areas of the LWSC can be classified into three categories based on predominant Chinook salmon movement patterns: 1) migrational corridors, where fish spend little time and move through quickly, generally in under an hour; 2) short-term holding areas, where fish mill about at slower velocities for periods of less than 24 hours; and, 3) long-term holding areas, where fish spend 24 hours or more. This study supports these findings. These site-specific migrational functions are generally consistent through June and July, and have also been consistent from year to year. Several areas of the LWSC appear to function primarily as migratory corridors and/or short-term holding areas, including Montlake Cut, Portage Bay, and Fremont Cut (Table 7). Lake Union is primarily a long-term holding area where fish often spend days to weeks. About one-half to two-thirds of fish use the entire lake, including the southern end. Salmon Bay functions as a short- to long-term holding area.

South Lake Union is clearly used by large proportions of fish – one-half to two-thirds in this study. In addition, use of these areas was often not ephemeral. Instead, many fish spent considerable lengths of time in south Lake Union. Because tagged Chinook salmon were common in both north Lake Union (i.e., Gas Works Park site) and south Lake Union, we assume they commonly inhabit all areas of Lake Union as a short- to long-term holding area. Extensive boat electrofishing conducted in 1999 also indicated that juvenile salmonids were widespread throughout Lake Union and the rest of the LWSC (Tabor et al. 2004b). Thus, it could be argued that protection and restoration is just as important throughout Lake Union as anywhere else in the LWSC.

Fish horizontal spatial distribution

Chinook salmon were broadly distributed throughout areas ≥ 4 m deep in all parts of the LWSC studied, although localized areas of some sites are used more intensively at times. We found no evidence of shoreline orientation in any part of the LWSC in this or in the 2004-2005 study (Celedonia et al. 2008b). This stands in contrast to findings in Lake Washington where during the day fish are found primarily in shallow nearshore areas 1-6 m deep (Tabor et al. 2006; Celedonia et al. 2008a; Celedonia et al. 2008b; Celedonia et al. 2009). We first documented this difference in the 2004-2005 study and hypothesized that differences in water clarity between Lake Washington and the LWSC may be the cause. King County water quality monitoring in 2005 showed that Secchi depth in the LWSC was about 2 m shallower than in Lake Washington. Secchi depth in the LWSC was generally less than 4 m and in Lake Washington was greater than 5 m. Subsequent findings suggest other factors besides water clarity may influence spatial distribution of fish in Lake Washington and the LWSC. In 2007, acoustic tracking along the western shore of Lake Washington near the SR 520 bridge observed Chinook salmon nearshore in shallow water (< 6 m depth) despite Secchi depths 4 m and less for much of the study period (Celedonia et al. 2008a). Also, the present study observed broad distribution of fish across areas with bottom depths ≥ 4 m in the LWSC in 2008 when water clarity was quite high (> 5 m Secchi depth).

Differences in predator populations between Lake Washington and the LWSC may partially explain differences in Chinook salmon horizontal spatial distribution and bottom depth selection between the two water bodies. Lake Washington Chinook salmon smolts are planktivorous during June (Koehler et al. 2006) and general behavioral and habitat use patterns observed in Lake Washington are typical of small planktivorous prey fishes (Koehler et al. 2004; Celedonia et al. 2008a; Celedonia et al. 2008b; Celedonia et al. 2009). During the day, smolts are often observed inhabiting shallow littoral areas with aquatic macrophytes. At night, fish are observed in deeper water, and dawn and dusk appear to be transitional periods. Such diel horizontal movements are typical of planktivorous fishes in lacustrine habitats and are largely attributed to food availability and predation risk (Hall and Werner 1977; Hall et al. 1979; Werner et al. 1983; Naud and Magnan 1988; Werner and Hall 1988; Tabor and Wurtsbaugh 1991; Diehl and Eklöv 1995; Jacobsen and Berg 1998; Shoup et al. 2003). During the day, small planktivores inhabit nearshore areas with aquatic macrophytes or other structural complexity to avoid predation by piscivorous fishes. Structural complexity provides a well-documented benefit to small fish by considerably reducing predation rate. However, this comes at a cost. The preferred foraging base - typically *Daphnia* spp. - of small planktivores is often larger and more abundant farther offshore (Wetzel 1975; Hall et al. 1979; Naud and Magnan 1988; Werner and Hall 1988). Thus, open water limnetic areas often provide the best foraging opportunities, but also present the greatest predation risk from piscivorous fishes. Therefore, planktivores use these areas during crepuscular periods and at night when low light levels diminish predation risk from visual predators. Visual predatory fishes that may prey on juvenile Chinook salmon in limnetic and deeper littoral areas of the Lake Washington system include primarily cutthroat trout *O. clarkii*, northern pikeminnow

Ptychocheilus oregonensis, smallmouth bass, and piscivorous birds. Rainbow trout and residual Chinook and coho salmon may also prey on juvenile Chinook salmon.

If given the opportunity, however, planktivores will forage in limnetic waters during the day in order to capitalize on the more productive foraging base. When predation risk is reduced or absent, small fish use open water areas more (Persson and Eklöv 1995; Jacobsen and Berg 1998), particularly when these areas provide better foraging (Werner et al. 1983; Diehl and Eklöv 1995; Shoup et al. 2003). This facilitates quicker growth compared to fish restricted to shallow littoral areas during the day (Werner et al. 1983; Werner and Hall 1988; Diehl and Eklöv 1995). Sampling in 2008 generally found greater zooplankton abundance offshore than nearshore (Figure 11). There is also evidence to suggest that predator populations and behaviors differ between the LWSC and Lake Washington. First, there is a general sense from researchers capturing fish in both water bodies that the abundance of both northern pikeminnow and cutthroat trout are reduced in the LWSC (e.g., Tabor et al. 2004b). In addition, broad-scale acoustic tracking of northern pikeminnow has shown that at least some of these fish may only make nighttime excursions into the LWSC from Lake Washington (Tabor et al. 2010). Juvenile Chinook salmon possess an innate recognition of northern pikeminnow odor, and in laboratory experiments will reduce feeding activity and increase duration of motionless activity when the scent of northern pikeminnow is present (Berejikian et al. 2003). Chemical cues from predators have also been found to substantially alter diel activity patterns and habitat use in prey species. For example, when predator chemical cues are present, crucian carp *Carassius carassius* are aperiodic and show a stronger affinity for vegetated habitats over open water (Pettersson et al. 2001). When predator cues are absent, the carp show strong diel activity patterns and less of an affinity for vegetated habitats. If fewer native predators of Chinook salmon are present in the LWSC during the day, this may explain the greater daytime use of offshore, open water habitats here as compared to Lake Washington. Additional study could more rigorously evaluate differential predator abundances in the LWSC and Lake Washington, and more closely evaluate zooplankton distribution and Chinook salmon diet in the LWSC. Laboratory studies could also evaluate diel activity and habitat use responses of Chinook salmon to chemical cues from northern pikeminnow and cutthroat trout.

Influence of overwater structures

Use of the outside edge of overwater structures that we observed at the South Lake Union site was similar to observations at the SR 520 bridge and a nearby overwater condo structure (Celedonia et al. 2008a; Celedonia et al. 2009). In both the present study and the SR 520 studies, tagged Chinook salmon frequented areas within 20-25 m of structure edges. Chinook salmon and other salmonids have also been observed at high densities along outside edges of overwater structures in Puget Sound (Toft et al. 2007). The authors of the SR 520 studies speculated that use of the structure edges was primarily related to access to superior offshore foraging base and perceived predation risk (i.e., having a nearby source of cover in over- and in-water structures). The fact that Chinook salmon in the LWSC are also found in open offshore areas not near structures may indicate that foraging is not a primary purpose of structure edge use in the LWSC. Instead, use of structure edges in the LWSC may be related more to cover from predators. We observed a general shift in bottom depth selection and habitat use in the LWSC between 2007 and 2008. In 2008, fish at Gas Works Park selected for shallower water and fish in South Lake Union showed greater affinity for structure edges. Both of these could be explained by the increase in water clarity observed in 2008.

Important management implications arise from the possibility that Chinook salmon in the LWSC extensively use edges of overwater structures in deep water. Although these areas may provide access to cover, they may also expose Chinook salmon to increased predation risk from smallmouth bass. Fresh et al. (2001) found high abundance of smallmouth bass beneath and near (within 2 m) overwater structures in Lake Washington and the LWSC. Also, home ranges of smallmouth bass in the LWSC may be smaller near overwater structures (Celedonia et al. 2008b), which may foster higher densities in these areas compared with areas lacking overwater structures. Tabor et al. (2004b) found relatively low levels of smallmouth bass predation (0.4-3.0%) on Chinook salmon from April through July in the LWSC. However, for sampling they exclusively used electrofishing gear, which can only sample depths up to 2-3 m effectively. Acoustic tracking studies in the LWSC and near the SR 520 bridge in June and July have found many smallmouth bass using and selecting for water 4-8 m deep (Celedonia et al. 2008a; Celedonia et al. 2008b; Celedonia et al. 2009; Tabor et al. 2010). Also, Tabor et al. (2004b) noted that their methods likely missed fish beneath large structures. Thus, they may have both underestimated smallmouth bass population and underestimated predation on Chinook salmon by not adequately representing areas where high abundances of both smallmouth bass and juvenile Chinook salmon are often found. Further study is needed to examine the implications of structure edge use on Chinook salmon predation. If structure edge use elevates predation risk, resource managers may consider limiting and/or modifying these types of structures in deep water areas of the LWSC. If structure edges have no effect on predation or diminish predation risk, then resource managers may direct their efforts to other issues impacting fitness and survival of Chinook salmon in the LWSC.

Our results suggest that the University Bridge may present an impediment or hindrance to Chinook salmon migration, and that this may in turn have implications for predation by smallmouth bass. Between 38-59% of tagged Chinook salmon showed some response to the bridge, which often included milling in the area adjacent and immediately to the east of bridge (e.g., Figures 17-20). Milling often occurred in areas adjacent to the wooden wing walls attached to the bridge support structures. These areas were also frequented by smallmouth bass, a potential predator of juvenile Chinook salmon. Acoustic tagged smallmouth bass at this study site often showed positive selection ratios for this area, and density plots further highlighted high use by smallmouth bass (Tabor et al. 2010). Incidentally, we observed a tagged Chinook salmon that was apparently preyed upon - presumably by a smallmouth bass - in close proximity to the northern wing wall (Figure 23). Studies near the SR 520 bridge have documented similar delays in Chinook salmon migration and high degrees of contact along the bridge structure (i.e., milling in close proximity to the structure edge) (Celedonia et al. 2008a; Celedonia et al. 2009). Further study is needed to determine precisely what influence the University Bridge and other such structures have on predation rate of Chinook salmon.

Fish behavior and exit route selection at the Ballard Locks

Water temperature appears to play a critical role in Chinook salmon behavior and choice of exit route at the Ballard Locks. At elevated water temperatures, fewer fish entered the inner forebay, fewer fish exited through the smolt flumes, usage of the areas in front of the large lock and north shipyard increased, and more fish held for prolonged periods at and near the study site. These findings raise important management implications for fish passage at the Ballard Locks. PIT tagging studies (DeVries et al. 2005; DeVries et al. 2007; DeVries et al. 2008) observed decreasing detection rates of PIT tagged fish at the smolt flumes as water temperatures increased. Detection rates through the flumes began to decline at around 15-17°C and stabilized at very low numbers as temperatures exceed 19-20°C. The authors hypothesized that this may be at least partially due to temperature-induced changes in passage behavior (DeVries et al. 2007; DeVries et al. 2008). Our findings confirm this hypothesis. In both 2007 and 2008 we observed diminishing proportions of fish using the flumes as temperatures increased. These declines occurred at about the same temperatures observed in the PIT tagging studies. On the whole, we observed the highest proportions of fish using the flumes at temperatures less than 18°C, and observed a decline through the 18-20°C range. Because our studies started relatively late in the outmigration season, we cannot be certain if flume usage at lower temperatures (< 18°C) was already in decline or not. Few smolts used the smolt flumes at temperatures greater than 20°C.

Fish may choose deeper exit routes (e.g., the large lock) as surface water temperatures increase (DeVries et al. 2007; DeVries et al. 2008). Our findings partially confirm this hypothesis. The proportion of exiting fish using the small and large locks increased from 11-48% when temperature was less than 18°C, to 83-100% at temperatures above 20°C. However, we also observed a considerable increase in the proportion of fish not exiting the system. These fish were often observed at and near the study site for several days up to one week or more. We did not observe any of these fish “backtracking” through the system (i.e., we did not observe any at the MetroLab site after seeing them at the Ballard Locks). Because of the short battery-life of our tags, the fate of these fish was uncertain. They may have residualized or they may have passed through to Puget Sound after the tag battery died. The increasing number of fish spending prolonged times at the Ballard Locks prior to exit may represent an inhibition to use even the available deeper water exit routes (small and large locks) at higher temperatures. This could contribute to greater residualism than what would otherwise occur in the absence of the Ballard Locks. Additional study might capitalize on new acoustic tracking technological developments - primarily in the area of longer tag battery life - to evaluate the fate of these fish and determine the influence of the Ballard Locks on residualism later in the outmigration season.

Despite the decreasing entrance into shallower water areas (i.e., the forebay) with increasing temperature, concomitant shifts in vertical distribution were inconsistent. In 2007, there appeared a substantial shift in vertical position selection: fish selected for the upper layer (0-3 m) at lower temperatures (< 18°C), and shifted to deeper strata at higher temperatures. This was only partially replicated in 2008, however. In general, fish at all temperature regimes, including the lowest (< 18°C), showed the highest selection for positions deep in the water column (> 12 m). The elevated water clarity observed in 2008 may have been partially responsible for fish remaining lower in the water column at lower temperature regimes, although it is uncertain if water clarity alone could account for such a dramatic shift between years. At higher temperature regimes, fish in 2008 had the highest daytime selection ratios for the deepest strata (> 9-12 m), whereas in 2007 there was more of an even distribution throughout strata greater than 3 m. This may have also been at least partially attributable to increased water clarity in 2008: fish may remain lower in the water column as an anti-predation behavior when water is clear. An apparent temperature-related shift was observed from the middle (18-20^{o}C) to the highest regime (> 20^{o}C) in 2008 during the day: at higher temperatures there was a notable drop in selection for 0-9 m strata, and increase in selection for deeper positions in the water column (> 9 m deep). This provides further evidence that surface-oriented passage routes such as the smolt flumes become inadequate at higher temperatures, and that deeper-water exit pathways should be considered more closely for their adequacy in passing Chinook salmon.

Loss of tagged fish due to predation

We have routinely observed direct and indirect evidence of predation in all of our acoustic tracking studies in Lake Washington and the LWSC. Direct evidence includes on-site fish tracks that clearly were not Chinook salmon (e.g., Figures 23 and 24; Celedonia et al. 2008a). These tracks were highly localized and resembled home ranges and other behaviors of smallmouth bass (Celedonia et al. 2008a; Celedonia et al. 2008b; Celedonia et al. 2009; Tabor et al. 2010). Indirect evidence of predation has included: 1) tags that are detected (but not tracked) that show no movement for prolonged periods and extending for the remainder of tag battery life; and 2) loss of tagged fish between sites (e.g., tracked or detected at one site but not the next). The former can only be explained by predation, by sources of mortality other than predation, or by tag shed (i.e., tag falling out of the incision). The latter may include these, as well as tag malfunction, residualism, and prolonged holding in one or more areas.

We do not believe that tag shed contributed much if any to tagged fish loss. We have tagged over 1,000 juvenile fish since 2004 and none has ever lost a tag during the usual 18-48 hour recovery period. It is highly unlikely that considerable percentages (4-20%) of tagged fish would then shed their tags shortly after release. Sources of mortality other than predation were likely not major contributors. Prior to release, fish exhibiting signs of insufficient recovery (e.g., lethargy, abnormal swimming behaviors, etc.) were removed from the sample, and released fish appeared very active and exhibited seemingly normal swimming patterns immediately prior to release. There is some evidence to suggest that fish tagged in a similar manner and hatchery fish in general may suffer relatively high levels of mortality after release. This has often been attributed to predation and starvation. Starvation likely operates on longer temporal scales than those of this study; thus, we do not believe this to be a major cause of tagged fish loss.

Residualism and prolonged holding may have influenced loss rates between some sites (e.g., Gas Works Park and MetroLab), but not others. For example, the area between University Bridge and Gas Works Park is relatively short. It would be surprising to find that the Chinook salmon "lost" in this area actually held or reared here for the duration of tag battery life (several days to nearly two weeks). Loss of tagged fish from one site to the next was generally on the order of about 4-20%, considering only movements through migratory corridors and short-term holding areas. This range of loss is consistent with other similar studies (Celedonia et al. 2008a; Celedonia et al. 2008b; Celedonia et al. 2009). There was a notable increase in loss rate from the Portage Bay release site to the first study site (University Bridge) from 2007 to 2008. In 2007, 5-10% of released fish were lost. In 2008, this figure climbed to 17-21%. Interestingly, a similar increase in tagged fish loss was observed in the SR 520 bridge studies. In 2007, 2-10% of released fish were lost (Celedonia et al. 2008a), and 11-21% were lost in 2008 (Celedonia et al. 2009). One possibility for this increase in both studies is that the smaller size of fish released in 2008 compared to 2007 made them more vulnerable to predation. Another possibility is different manufacture of tags used in the two years. We used tags manufactured in 2008 for a separate study in 2009 and discovered that some tags turned on correctly, but inexplicably ceased functioning shortly thereafter (M. Celedonia, unpublished data). The extent to which this occurred in either 2007 or 2008 is unknown. A third possibility is some bias between the two years in how the fish were handled and/or in the aquatic environment. We would have expected less post-release problems resulting from handling in 2008 because the in-situ tag programmer was not used. Other possibilities include residualism or fish holding for prolonged periods (longer than tag battery life) prior to encountering the first study site.

Some release groups experienced a disproportionately high tag loss rate at specific locations and evidence suggests that predation was the likely cause. One MetroLab release group (June 21, 2008) experienced a 62% loss rate between release and the Ballard Locks. These fish did not remain at the release site and they were not detected at either the Ballard Locks or Gas Works Park sites. In 2005, one group (n = 7) lost 43% of fish near the Seattle Tennis Club site (Celedonia et al. 2008b). These fish were briefly tracked on site shortly after release, and the tracks were more suggestive of smallmouth bass than Chinook salmon (M. Celedonia, unpublished data). Each tag signal then became stationary for the duration of tag battery life (about 9-10 days) suggesting that the tags were excreted and lying on the substrate. Similarly, in 2007, two Portage Bay release groups lost 24% (June 29, 2007 release) and 31% (July 6, 2007 release) of fish between the University Bridge and Gas Works Park sites. Several of these fish - five from June 29 and eight from July 6 - were lost just to the west of the University Bridge site: tags were stationary and detected for the remainder of tag battery life by one or two of the western-most hydrophones, characteristics indicative of predation. Three fish from the June 15, 2007 release were lost in a similar manner. The increasing trend in loss over time at this location may be correlated with increasing water temperature and subsequent increases in predator activity. However, similar trends were not observed here in 2008, nor were they observed in fish released at Madison Park (SR 520 bridge study fish) in 2007 (Celedonia et al 2008a).

Fish vertical distribution in the water column

There was considerable difference in fish vertical position between the University Bridge and Ballard Locks sites. Fish at the University Bridge site were more surface oriented and were primarily found in the upper 0-6 m of the water column. There was minimal use of strata > 9 m deep. Conversely, fish at the Ballard Locks were more evenly distributed throughout the water column and often showed greater selection for strata > 6 m deep. Some factors that may have contributed to such a difference may include difference in water quality conditions and predator abundance between the two sites. Water at the Ballard Locks was more saline, dissolved oxygen was uniform throughout the water column, and there was generally a smaller thermal gradient between the surface and the bottom. Also, there are believed to be fewer predators at the Ballard Locks.

There did not appear to be any large scale shifts in vertical position distribution with increasing temperature. This was particularly surprising at the University Bridge site in 2008, where fish selected for the upper 0-3 m of the water column even when water temperature was > 17°C. These findings suggest that factors other than temperature drive vertical position selection of Chinook salmon in the LWSC, even at relatively high surface water temperatures. One possible exception was at the Ballard Locks in 2007. At low temperatures, fish were highly surface oriented, showing strong positive selection for positions in the upper 3 m. At higher temperatures, selection shifted to deeper water positions. No such shift was observed in 2008.

Influence of artificial lighting

Nighttime observations at three sites (University Bridge, South Lake Union, Ballard Locks) suggested that areas with artificial lighting are frequented by Chinook salmon, and that Chinook salmon spend prolonged periods in these areas. Similar observations were made along the SR 520 bridge: tagged Chinook salmon frequented and spent prolonged periods in areas where lighting on the bridge deck cast light into the adjacent water (Celedonia et al. 2008a). In an experiment in south Lake Washington on February 23, 2005, juvenile Chinook salmon (mean, 50 mm FL) were four times more abundant in lighted areas than in non-lighted areas (R. Tabor, unpublished data). These areas with artificial lighting may attract fish which allows them to feed throughout the night.

Commonly, small zooplanktivorous fishes feed heavily at dawn and dusk and do not feed much at night (Hall et al. 1979; Wurtsbaugh and Li 1985). However, they may feed throughout the night during full moon conditions (Gliwicz 1986). By feeding during the night, consumption rates and growth rates of juvenile Chinook salmon might be improved, thus resulting in improved fitness. However, Koehler et al. (2006) found the growth of juvenile Chinook salmon in Lake Washington was at or near the maximum potential. Therefore, it is doubtful that juvenile Chinook salmon would gain much benefit from artificial lighting.

Although lighted areas may allow zooplanktivorous fishes an opportunity to forage throughout the night, they may attract piscivorous fishes and birds (Nightingale et al. 2006). Even if piscivorous fishes are not attracted to lighted areas, the predation rate by piscivorous fishes that inhabit the lighted area may be dramatically higher than that in other areas (Tabor et al. 2004a). The reactive distance of piscivorous salmonids (including cutthroat trout which are abundant in Lake Washington) increases rapidly as light levels are increased (Mazur and Beauchamp 2003). Research at petroleum platforms has shown that artificial lighting allows fish to feed on zooplankton that have concentrated in the light field; however, they may be more vulnerable to large piscivorous fishes (Stanley and Wilson 1997; Keenan et al. 2003). In Lake Tanganyika in Africa, fishermen use lights to attract zooplanktivorous fishes, which in turn attract large piscivorous fishes (Coulter 1990).

The extent of juvenile Chinook salmon predation by piscivores near artificial lighting is unknown. In Lake Washington, we have observed great blue herons and western grebes feeding around lights but no information is available on their nighttime diet. Piscivorous fishes may also be attracted to lighted areas due to an aggregation of small fishes like juvenile Chinook salmon. Cutthroat trout appear to feed heavily at night in Lake Washington because of reflected artificial lighting from surrounding urbanized areas (Mazur and Beauchamp 2006). The question of whether artificial lighting in the LWSC increases predation on Chinook salmon requires further study. To the extent that artificial lighting has deleterious consequences to Chinook salmon, such lighting on bridges, boat docks, and other such structures should be designed to minimize the amount of light that reaches the water surface, albeit with the proper considerations for human safety.

TABLE 7. Summary of movement patterns, habitat use, and other behavioral characteristics of Chinook salmon smolts in major areas of the Lake Washington Ship Canal.

Area	Primary Chinook salmon migratory function(s)	Time spent in area	Spatial distribution	Bottom depth selection	Factors contributing to variability in horizontal spatial distribution	Vertical distribution (position in water column)	Use of structure edges[g]	Attraction to artificial lighting at night	Predation threat[h]
Montlake Cut	migratory corridor, short-term holding	< 24 hours[a,b]	not studied	not studied	not studied	not studied	n/a	not studied	not studied
Portage Bay	migratory corridor, short-term holding	< 24 hours[c,d]	broad; usually > 2 m bottom depth	> 4-6 m	unknown; possibly water clarity	primarily 0-6 m; notable 6-9 m; minimal > 9 m	yes	yes	moderate to high
Lake Union	long-term holding	1-2 days up to 2 weeks[c,d,e,f]	broad; usually > 2 m bottom depth	> 4-6 m	water clarity, water temperature	unknown	yes	yes	moderate to high
Fremont Cut	migratory corridor, short-term holding	< 24 hours[d]	not studied	not studied	not studied	not studied	n/a	not studied	not studied
Salmon Bay/Ballard Locks	short- to long-term holding	a few hours up to 1 week or more[d,e,f]	varies; exit route and temperature driven	varies; exit route and temperatur e driven	water temperature, diel period	highly variable, from extreme surface (0-3 m) to extreme deep water (> 12 m), to even distribution throughout	yes	yes	low to moderate

a Celedonia et al. (2008a).
b Celedonia et al. (2009).
c Celedonia et al. (2008b).
d Present study.
e Acoustic tag battery life was approximately two weeks. Therefore, maximum time spent may be underestimated.
f DeVries et al. (2005)
g Structure edge use was generally within 20 m of the structure edge at bottom depths ≥ 6 m.
h Based on spatial and temporal overlap with potential predator habitat, and other evidence of possible predation.

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APPENDICES

APPENDIX A. Tagged Chinook salmon travels times between sites and site area residence times, June-July, 2007-2008. Median times (in hours) are shown for: time from last detection at SR 520 bridge to first detection at University Bridge (U. Br.) for 2007 Madison Park (MP) release groups, and time from release to first detection at U. Br. for all Portage Bay release groups; area residence time at U. Br.; time from last detection at U.Br. to first detection at Gas Works Park (GWP); area residence time at GWP; area residence at South Lake Union (SL); time from last detection at GWP to first detection at King County Environmental Lab (ML); time from last detection at ML to first detection at the Ballard Locks (LU); and area residence time at LU. Tenth and 90th percentiles of each time category are shown in [ ], and the numbers of fish comprising each observation are in ( ).

Release site	Release date	Travel to U. Br.	U. Br. residence	U. Br. to GWP	GWP residence	SL residence	GWP to ML	ML to LU	LU residence
2007									
MP	all releases	3.57 [2.03 - 34.56]	0.62 [0.36 - 10.86]	0.87 [0.58 - 4.36]	101.40 [2.72 - 243.38]	61.22 [6.01 - 200.32]	4.98 [0.99 - 12.95]	2.22 [1.56 - 15.62]	15.04 [2.50 - 201.65]
	06/01	2.98 [2.06 - 5.27]	0.58 [0.30 - 2.83]	0.92 [0.77 - 3.52]	17.21 [1.61 - 128.26]	21.67 [9.48 - 185.70]	4.22 [1.19 - 6.81][a]	2.82 [1.76 - 12.09][a]	14.57 [2.11 - 233.04]
	(n = 36)	(n = 26)	(n = 25)	(n = 25)	(n = 30)	(n = 11)	(n = 14)	(n = 14)	(n = 27)
	06/14	3.54 [1.82 - 42.51]	0.58 [0.36 - 17.22]	0.88 [0.57 - 2.27]	131.73 [25.22 - 266.88]	84.16 [7.52 - 199.10]	7.30 [1.41 - 21.47]	1.92 [1.52 - 20.43]	18.80 [5.07 - 82.49]
	(n = 59)	(n = 28)	(n = 28)	(n = 25)	(n = 26)	(n = 24)	(n = 8)	(n = 8)	(n = 9)
	06/28	7.92 [3.06 - 34.84]	0.83 [0.41 - 8.95]	0.77 [0.52 - 4.85]	191.93 [93.25 - 243.27]	76.64 [5.69 - 222.73]	5.28 [1.24 - 5.46]	1.62 [1.42 - 2.48]	11.88 [3.81 - 16.85]
	(n = 64)	(n = 25)	(n = 25)	(n = 24)	(n = 25)	(n = 18)	(n = 7)	(n = 7)	(n = 8)
PB	all releases	3.18 [1.43 - 9.42]	3.12 [0.52 - 23.58]	1.52 [0.55 - 7.05]	210.92 [10.23 - 294.31]	70.60 [2.77 - 226.72]	3.5 [1.76 - 10.60]	10.24 [1.75 - 46.82]	36.58 [2.46 - 201.04]
	06/15	2.28 [1.43 - 5.85]	2.78 [0.75 - 29.90]	0.94 [0.48 - 5.30]	266.88 [94.94 - 296.18]	59.02 [2.01 - 83.20]	2.90 [1.35 - 33.82]	16.68 [2.76 - 39.47]	10.92 [5.89 - 126.19]
	(n = 56)	(n = 50)	(n = 50)	(n = 50)	(n = 50)	(n = 38)	(n = 8)	(n = 6)	(n = 6)
	06/29	4.90 [2.16 – 21.20]	2.98 [0.33 - 16.03]	1.53 [0.55 - 13.37]	239.72 [75.40 - 289.63]	125.95 [7.86 - 256.54]	4.95 [3.02 - 7.70]	10.6 [1.69 - 108.48]	46.13 [3.52 - 125.34]
	(n = 60)	(n = 50)	(n = 50)	(n = 41)	(n = 41)	(n = 33)	(n = 11)	(n = 10)	(n = 12)
	07/06	2.82 [1.03 – 3.82]	3.63 [0.51 - 14.21]	2.21 [0.71 - 3.99]	25.89 [1.70 - 41.46]	111.02 [5.22 – 188.51]	3.49 [3.11 - 7.49]	7.59 [2.30 - 13.40]	216.20 [2.80 – 292.03]
	(n = 54)	(n = 40)	(n = 40)	(n = 34)	(n = 34)	(n = 20)	(n = 6)	(n = 6)	(n = 6)
2008									
PB	all releases	2.45 [0.85 - 50.5]	3.63 [0.28 - 30.23]	1.78 [0.65 - 8.07]	44.27 [0.72 - 237.17]	103.17 [5.50 - 272.64]	3.23 [1.05 - 15.24]	24.92 [4.48 - 106.31]	50.98 [6.13 - 218.58]
	06/19	16.1 [3.61 - 121.78]	14.06 [1.12 – 55.28]	1.22 [0.63 - 14.93]	49.37 [1.17 - 227.61]	42.67 [1.31 - 127.31]	2.55 [1.60 - 11.75]	45.36 [19.28 - 106.02]	11.05 [5.11 - 83.26]
	(n = 34)	(n = 27)	(n = 26)	(n = 26)	(n = 27)	(n = 14)	(n = 13)	(n = 8)	(n = 8)
	06/27	2.73 [0.95 - 18.1]	3.18 [0.55 - 9.65]	2.83 [1.08 - 8.88]	63.18 [3.24 - 237]	191.61 [17.05 - 276.22]	10.33 [6.43 - 48.48]	40.22 [6.50 - 103.18]	42.65 [8.11 - 113.73]
	(n = 35)	(n = 29)	(n = 29)	(n = 27)	(n = 27)	(n = 16)	(n = 10)	(n = 7)	(n = 7)
	07/11	0.85 [0.85 - 2.44]	0.36 [0.28 - 7.44]	1.73 [0.65 - 2.65]	2.46 [0.64 - 255.96]	180.36 [13.20 – 275.97]	2.00 [1.04 - 4.81]	12.27 [3.51 - 95.30]	149.95 [9.35 - 267.50]
	(n = 38)	(n = 30)	(n = 30)	(n = 28)	(n = 28)	(n = 14)	(n = 13)	(n = 10)	(n = 11)
ML	all releases	-	-	-	-	-	-	8.28 [1.93 - 178.08]	75.38 [2.28 - 262.7]
	06/20	-	-	-	-	-	-	91.93 [8.06 - 216.88]	29.76 [8.89 - 159.95]
	(n = 21)	-	-	-	-	-	-	(n = 8)	(n = 8)
	06/27	-	-	-	-	-	-	7.88 [5.22 - 107.13]	76.77 [3.40 - 123.52]
	(n = 13)	-	-	-	-	-	-	(n = 11)	(n = 11)
	07/11	-	-	-	-	-	-	5.08 [1.71 - 89.31]	105.72 [1.16 - 273.40]
	(n = 24)	-	-	-	-	-	-	(n = 22)	(n = 22)

[a] Acoustic tracking gear at the MetroLab site malfunctioned on the day of tagged fish release (June, 2007, 12:30 hours) and remained inoperable for nearly 24 hours after release. Many fish appeared to move through during this time based on detections at the next downstream site (i.e., Ballard Locks).

APPENDIX B. Results of statistical test used for evaluating site-to-site travel times of tagged Chinook salmon smolts, June-July, 2007-2008. P-values are shown for: time from last detection at SR 520 bridge to first detection at University Bridge for 2007 Madison Park (MP) release groups and time from release to first detection at University Br. For Portage Bay release groups; area residence time at University Br.; time from last detection at University Br. to first detection at Gas Works Park (GWP); area residence time at GWP; time from last detection at GWP to first detection at King County Environmental Lab (ML); area residence at ML; time from last detection to first detection at the Ballard Locks (LU); and area residence time at LU.

	Travel to University Br.	University Br. residence	University Br. to GWP	GWP residence	GWP to ML	ML residence	ML to LU	LU residence
2007 Madison Park release groups								
All groups (Kruskal-Wallis one-way analysis of variance, $\alpha = 0.05$)	<0.001*	0.390	0.386	<0.001*	0.592	0.188	0.144	0.472
Multiple comparisons (Bonferroni-adjusted Mann-Whitey U test, $\alpha_{FW} = 0.05$)								
June 1, June 14 ($\alpha_{PC} = 0.017$)	0.219	0.417	0.388	<0.001*	0.385	0.632	0.413	0.661
June 1, June 28 ($\alpha_{PC} = 0.017$)	<0.001*	0.197	0.147	<0.001*	0.588	0.093	0.042	0.480
June 14, June 28 ($\alpha_{PC} = 0.017$)	0.050	0.465	0.834	0.127	0.464	0.122	0.378	0.102
2007 Portage Bay release groups								
All groups (Kruskal-Wallis one-way analysis of variance, $\alpha = 0.05$)	<0.001*	0.480	0.074	<0.001*	0.866	0.772	0.645	0.435
Multiple comparisons (Bonferroni-adjusted Mann-Whitey U test, $\alpha_{FW} = 0.05$)								
June 15, June 29 ($\alpha_{PC} = 0.017$)	<0.001*	0.226	0.116	0.077	0.680	0.509	0.745	0.554
June 15, July 6 ($\alpha_{PC} = 0.017$)	0.505	0.433	0.025	<0.001*	0.606	0.796	0.262	0.317
June 29, July 6 ($\alpha_{PC} = 0.017$)	<0.001*	0.836	0.766	<0.001*	0.801	0.615	0.664	0.261

APPENDIX B. (cont.)

	Release to University Br.	University Br. residence	University Br. to GWP	GWP residence	GWP to ML	ML residence	ML to LU	LU residence
2008 Portage Bay release groups								
All groups (Kruskal-Wallis one-way analysis of variance, $\alpha = 0.05$)	<0.001*	<0.001*	0.091	0.109	<0.001*	0.034*	0.191	0.034*
Multiple comparisons (Bonferroni-adjusted Mann-Whitey U test, $\alpha_{FW} = 0.05$)								
June 19, June 27 ($\alpha_{PC} = 0.017$)	<0.001*	<0.001*	0.105	0.337	0.003*	0.026	0.643	0.165
June 19, July 11 ($\alpha_{PC} = 0.017$)	<0.001*	<0.001*	0.742	0.186	0.118	0.356	0.062	0.026
June 27, July 11 ($\alpha_{PC} = 0.017$)	<0.001*	0.005*	0.032	0.047	<0.001*	0.030	0.329	0.077
2008 MetroLab release groups								
All groups (Kruskal-Wallis one-way analysis of variance, $\alpha = 0.05$)	-	-	-	-	-	0.033*	0.014*	0.497
Multiple comparisons (Bonferroni-adjusted Mann-Whitey U test, $\alpha_{FW} = 0.05$)								
June 20, June 27 ($\alpha_{PC} = 0.017$)	-	-	-	-	-	0.225	0.039	0.563
June 20, July 11 ($\alpha_{PC} = 0.017$)	-	-	-	-	-	0.061	0.009*	0.302
June 27, July 11 ($\alpha_{PC} = 0.017$)	-	-	-	-	-	0.007*	0.158	0.445

APPENDIX C. Numbers of tagged Chinook salmon detected at the Ballard Locks and exit pathways used, summarized by temperature regime and inner forebay entrance, June-July, 2007-2008. Number of fish that entered the inner forebay (forebay) and those that did not (no) are shown. See Figure 5 for inner forebay location. See Table 1 for dates corresponding with each temperature regime.

	Temperature regime					
	< 18°C		18-20°C		> 20°C	
Exit Pathway	Forebay	No	Forebay	No	Forebay	No
2007						
Did not exit	5	2	2	2	0	7
Large & small locks	10	3	6	2	8	4
Smolt flumes	14	-	0	-	0	-
2008						
Did not exit	4	1	7	6	5	9
Large & small locks	1	0	6	3	1	4
Smolt flumes	8	-	9	-	1	-

APPENDIX D. Exit routes of tagged Chinook salmon relative to shoreline entrance at the Ballard Locks study site, June-July, 2007-2008. Shoreline orientation was defined as follows: north = within 30 m of the pier at the approach to the large lock; south = within 30 m of the large dock structure on the southeastern corner of the site; and, mid-channel = the middle 40 m of the channel.

	Exit route				
Shoreline orientation at site entrance	Large lock	Smolt flumes	Small lock	Did not exit	Total
2007					
North	8	1	4	7	20
South	5	2	4	3	14
Mid-channel	7	10	6	8	31
2008					
North	3	5	0	12	20
South	7	8	0	8	23
Mid-channel	6	5	0	12	22

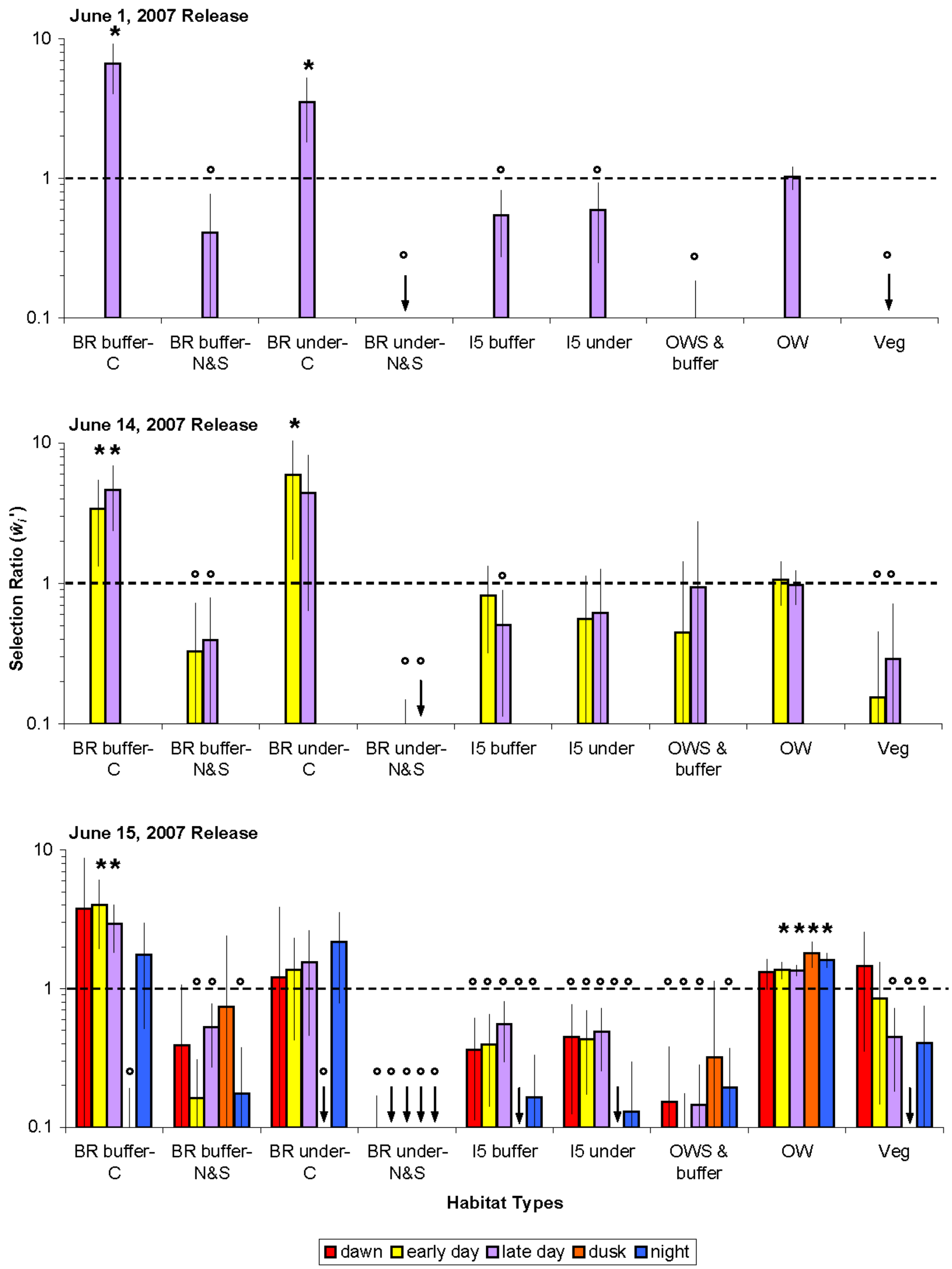
APPENDIX E. Residence times of tagged Chinook salmon that exited the Ballard Locks site into Puget Sound (exited) and those that were not observed exiting (DNE) at three temperature regimes, June-July, 2007-2008.

	Temperature regime		
	< 18°C	18-20°C	> 20°C
2007			
DNE	58.5 [12.11 - 278.22] (n = 7)	134.88 [30.01 - 198.55] (n = 4)	128.93 [33.52 - 249.99] (n = 7)
Exited	10.58 [1.44 - 135.20] (n = 27)	16.19 [4.43 - 20.85] (n = 8)	16.85 [3.67 - 90.86] (n = 13)
2008			
DNE	75.38 [5.81 - 115.8] (n = 5)	70.28 [11.58 - 138.95] (n = 12)	236.02 [76.46 - 289.69] (n = 16)
Exited	12.8 [3.38 - 102.7] (n = 9)	8.74 [0.95 - 57.50] (n = 18)	156.48 [101.51 - 235.98] (n = 6)

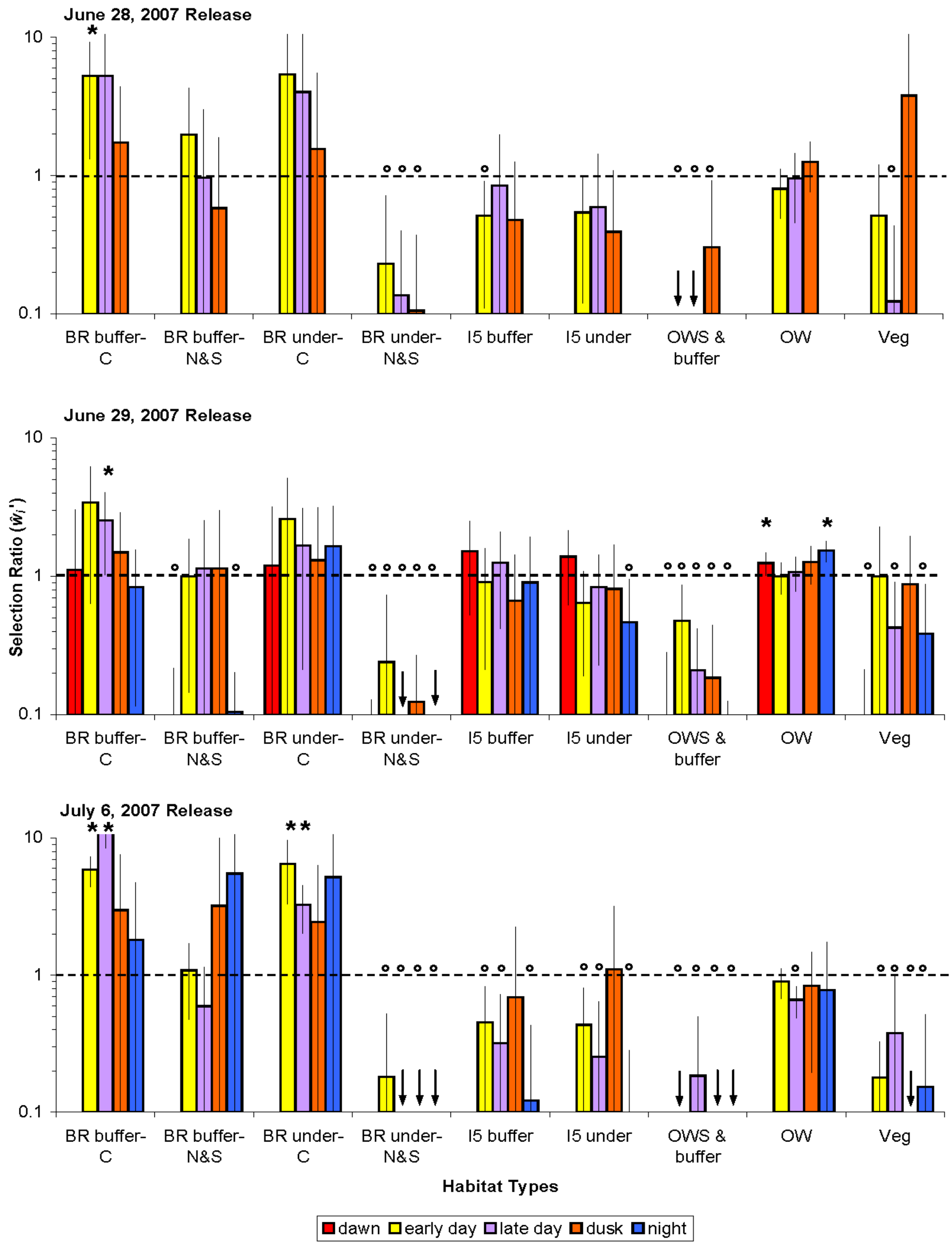
APPENDIX F. Length of time tagged Chinook salmon took to enter the forebay after first entering the Ballard Locks study site, duration of first forebay encounter, and length of time fish were detected on and near the study site after leaving the forebay to the east (for fish that did not exit through the smolt flumes during their first forebay encounter). Median times are shown, and 10th and 90th percentiles are given in [ ]. Data are presented separately for fish that eventually exited into Puget Sound (exited) and for fish that were not observed exiting into Puget Sound (DNE), at three temperature regimes, June-July, 2007-2008.

	Temperature regime		
	< 18°C	18-20°C	> 20°C
Before first forebay entrance			
2007			
DNE	0.18 [0.14 - 5.24]	1.48 [0.38 - 2.59]	-
	(n = 5)	(n = 2)	-
Exited	0.32 [0.14 - 16.17]	1.06 [0.18 - 8.56]	0.25 [0.11 - 12.19]
	(n = 23)	(n = 6)	(n = 9)
2008			
DNE	0.5 [0.26 - 4.12]	10.1 [0.4 - 94.09]	4.71 [0.47 - 9.79]
	(n = 4)	(n = 7)	(n = 4)
Exited	1.1 [0.32 - 10.08]	3.8 [0.34 - 13.11]	14.13 [4.99 - 60.91]
	(n = 9)	(n = 15)	(n = 3)
Duration of first forebay stay			
2007			
DNE	1.02 [0.23 - 3.27]	2.3 [0.54 - 4.06]	-
	(n = 5)	(n = 2)	-
Exited	0.35 [0.09 - 0.99]	0.17 [0.05 - 0.27]	0.1 [0.02 - 0.31]
	(n = 23)	(n = 6)	(n = 9)
2008			
DNE	0.64 [0.2 - 1.26]	0.22 [0.08 - 1.43]	0.9 [0.28 - 2.84]
	(n = 4)	(n = 7)	(n = 4)
Exited	0.27 [0.15 - 1.04]	0.25 [0.05 - 1.47]	0.52 [0.30 - 0.74]
	(n = 9)	(n = 15)	(n = 3)
After first forebay entrance			
2007			
DNE	166.65 [25.72 - 260.73]	67.33 [18.45 - 116.21]	-
	(n = 5)	(n = 2)	-
Exited	3.29 [0.63 - 168.98]	4.3 [0.57 - 17.38]	1.43 [0.84 - 31.00]
	(n = 22)	(n = 6)	(n = 9)
2008			
DNE	27.98 [8.85 - 40.18]	28.1 [7.99 - 114.03]	212.83 [57.03 - 259.02]
	(n = 4)	(n = 7)	(n = 4)
Exited	2.42 [1.72 - 100.6]	2.09 [0.41 - 37.48]	191.58 [151.37 - 196.33]
	(n = 7)	(n = 10)	(n = 3)

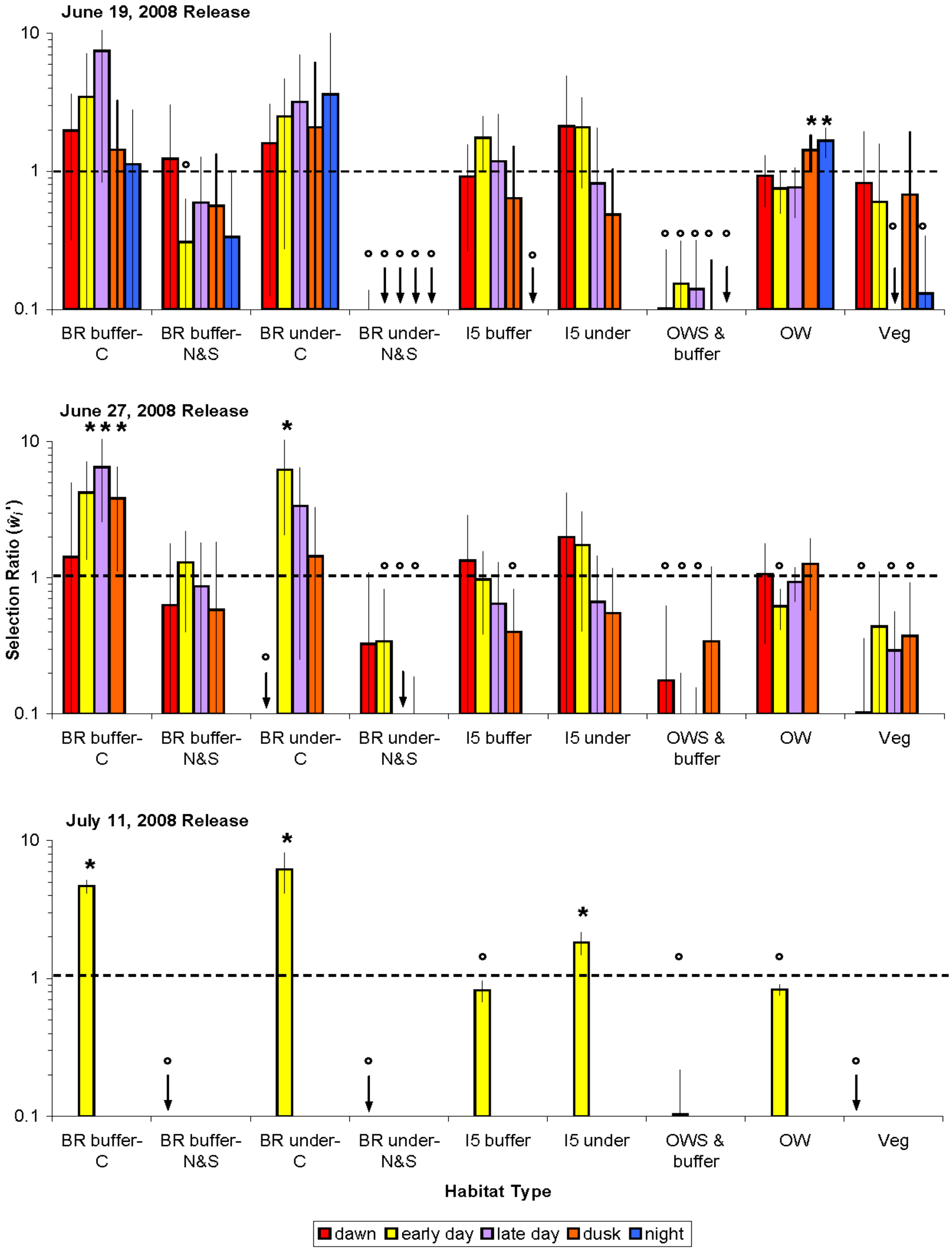
APPENDIX G. Diel habitat selection ($\hat{w}_i$', selection ratio; log scale) of Chinook salmon at the University Bridge bridge study site in, June-July, 2007-2008. Error bars represent Bonferroni-adjusted 90% confidence intervals. Error bars indicate if selection for (> 1) or against (< 1) a habitat type occurred. An asterisk (*) denotes selection for a habitat and a circle (o) denotes selection against. See Table 2 for habitat types.



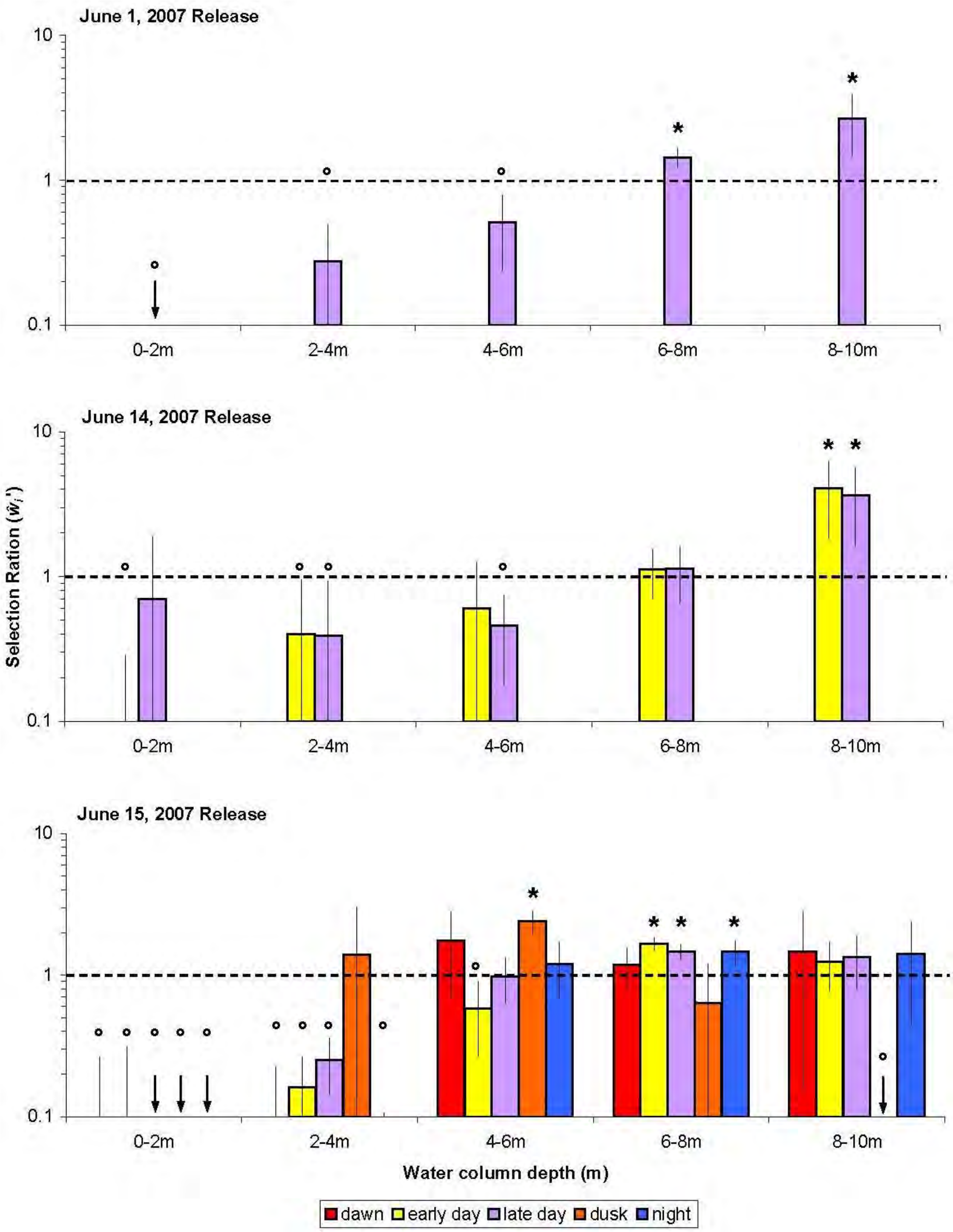
APPENDIX G. (cont.)



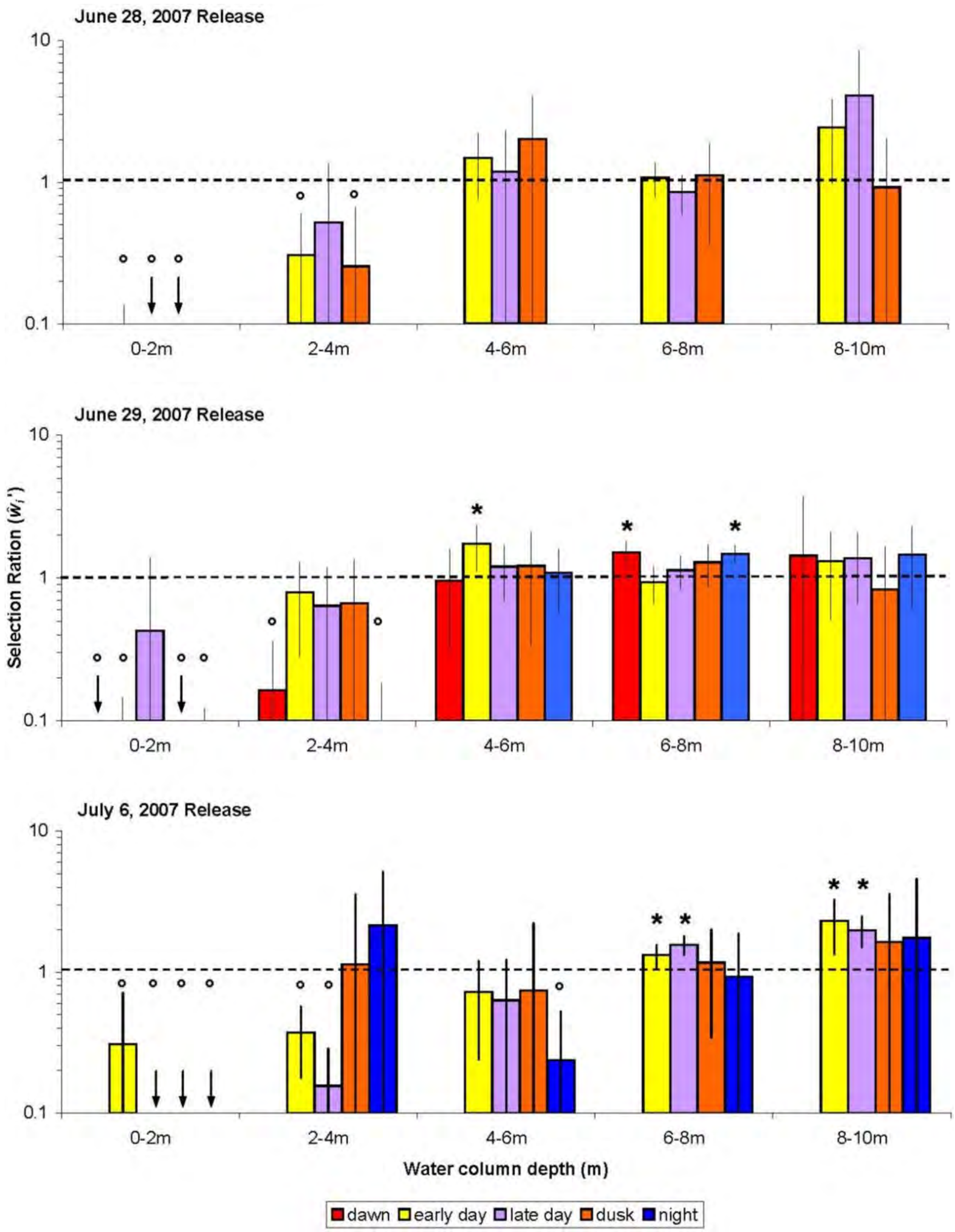
APPENDIX G. (cont.)



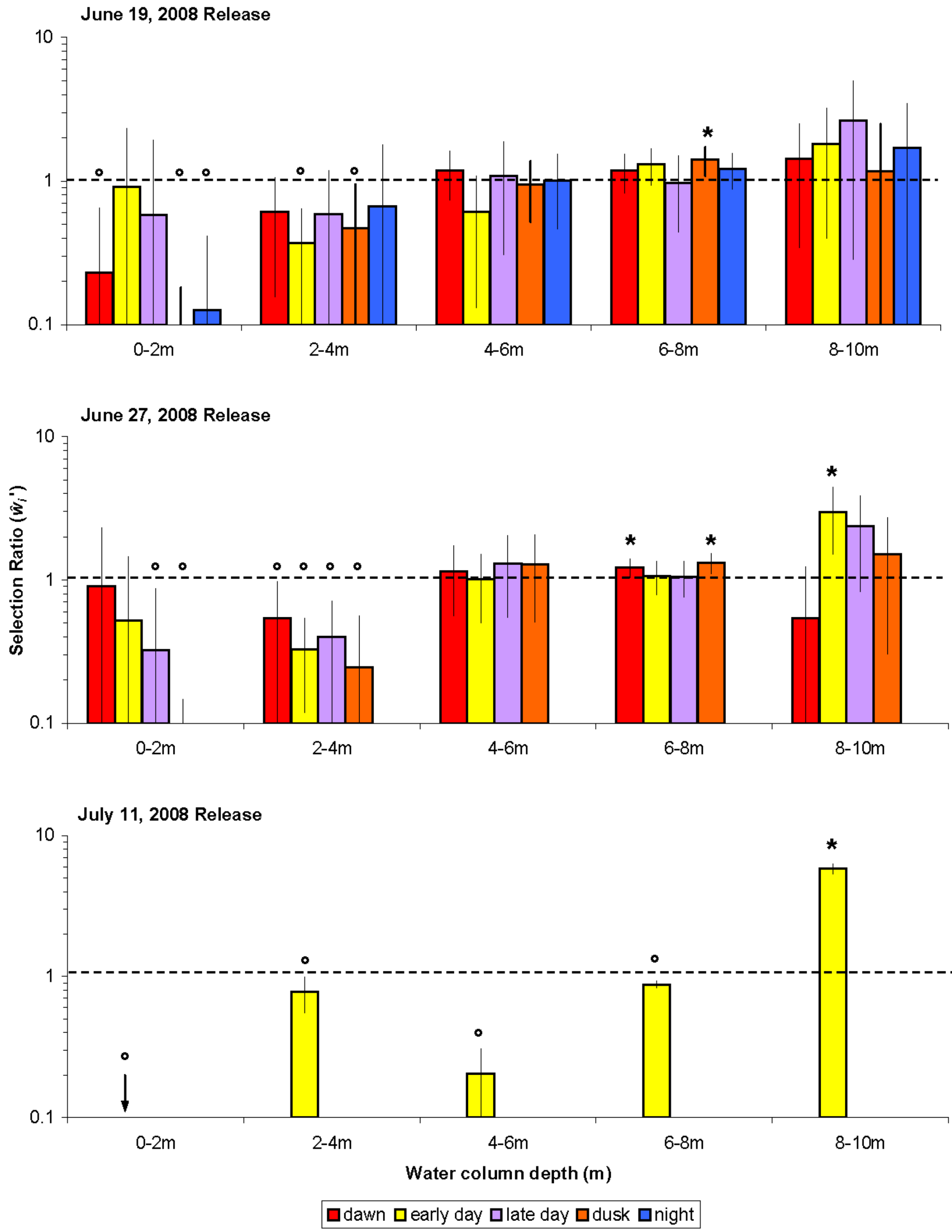
APPENDIX H. Diel bottom depth (water column depth) selection ($\hat{w}_i$', selection ratio; log scale) of Chinook salmon at the UniversityBridge/I-5 bridge study site, June-July, 2007-2008. Error bars represent Bonferroni-adjusted 90% confidence intervals. Error bars indicate if selection for (> 1) or against (< 1) a habitat type occurred. An asterisk (*) denotes selection for a habitat and a circle (o) denotes selection against.



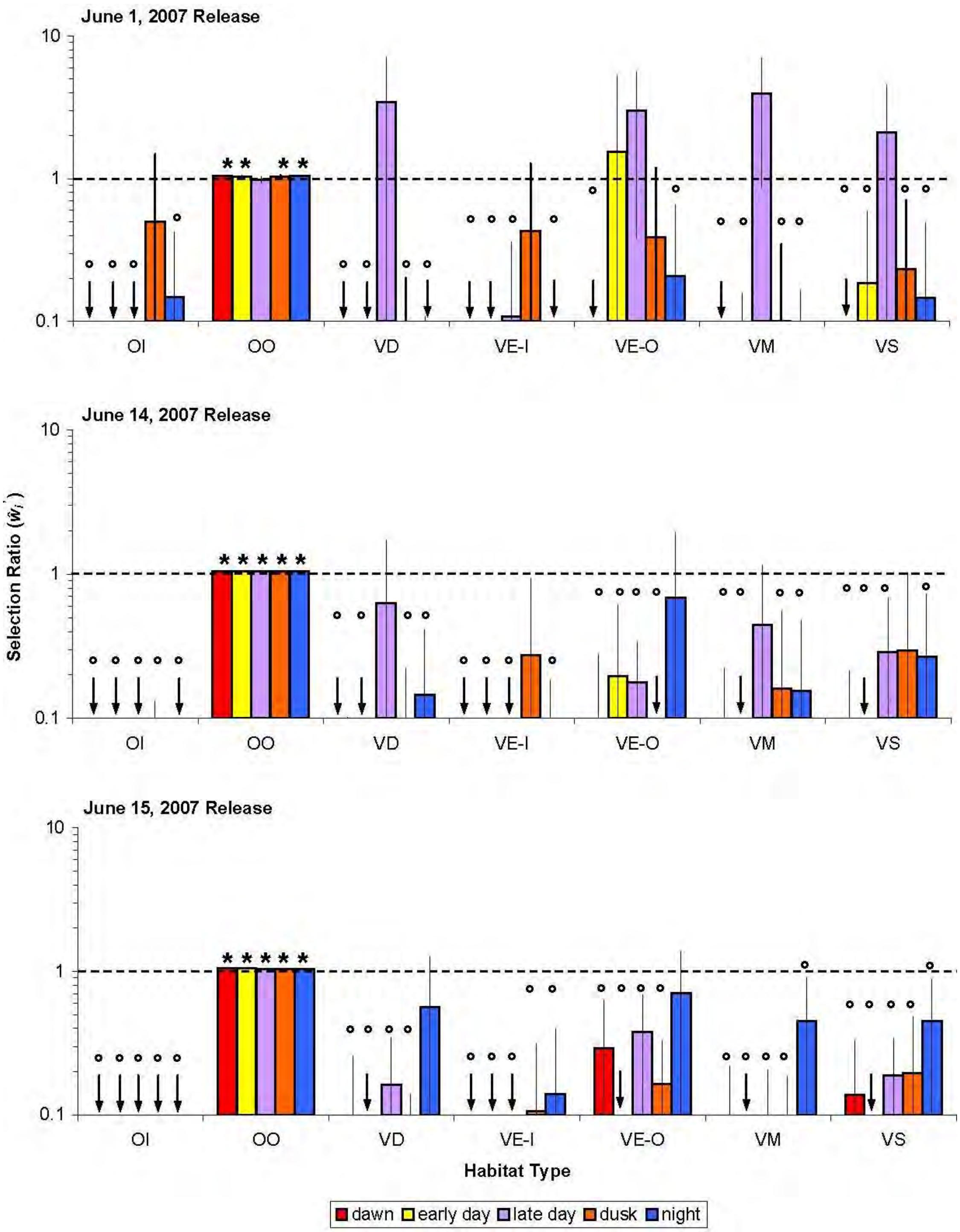
APPENDIX H. (cont.)



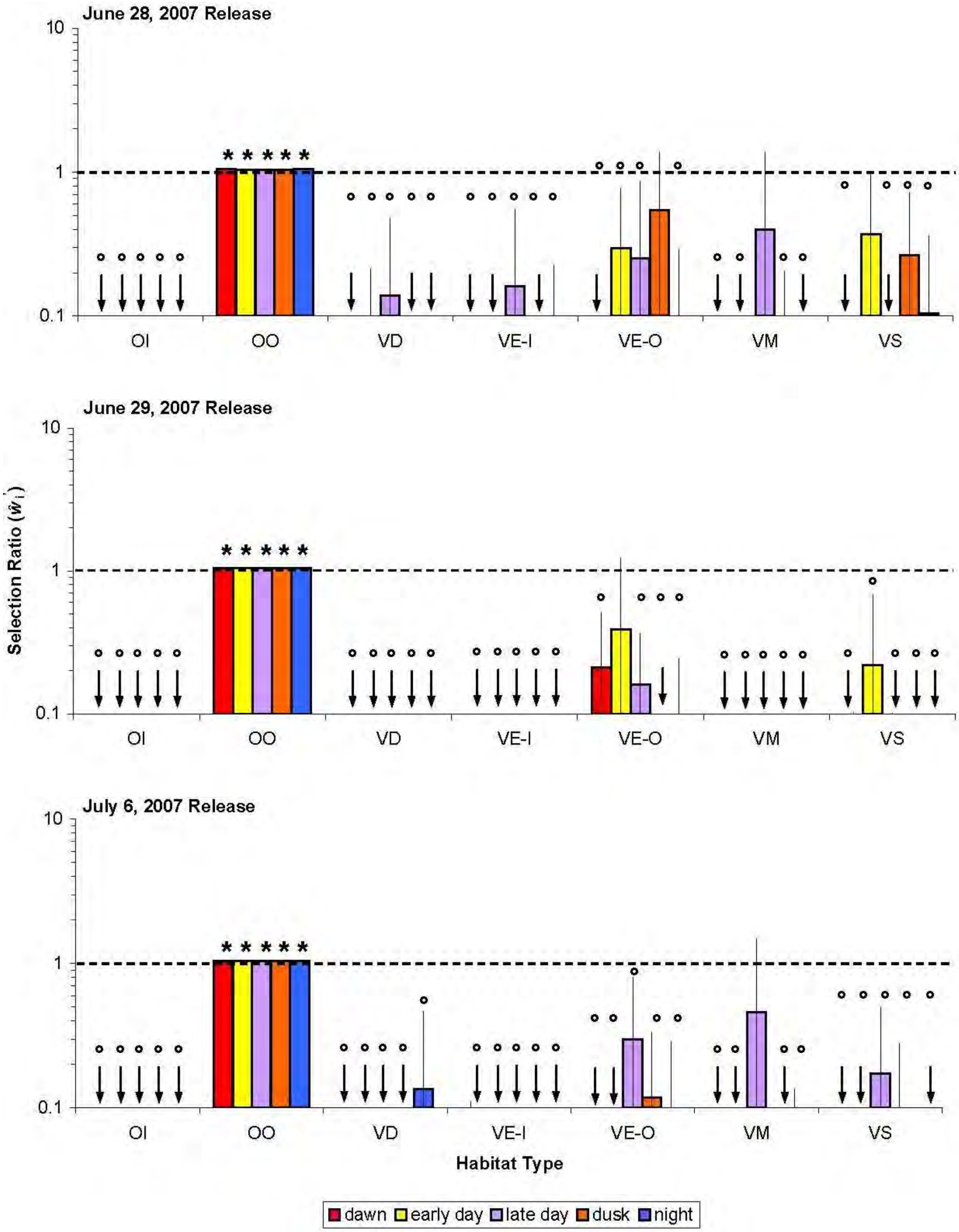
APPENDIX H. (cont.)



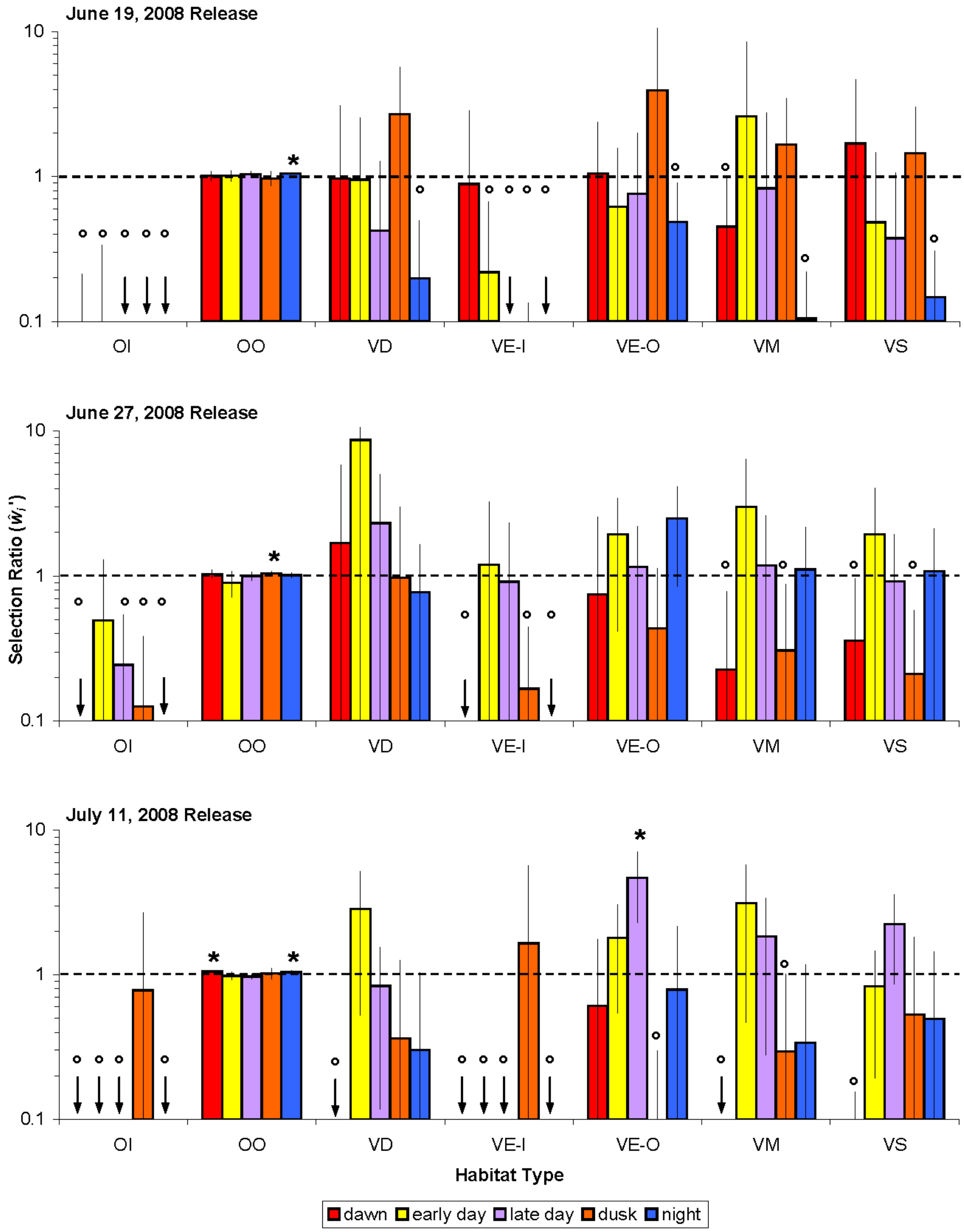
APPENDIX I. Diel habitat selection ($\hat{w}_i$', selection ratio; log scale) of Chinook salmon at the Gas Works Park study site, June-July, 2007-2008. Error bars represent Bonferroni-adjusted 90% confidence intervals. Error bars indicate if selection for (> 1) or against (< 1) a habitat type occurred. An asterisk (*) denotes selection for a habitat and a circle (o) denotes selection against. See Table 2 for habitat types.



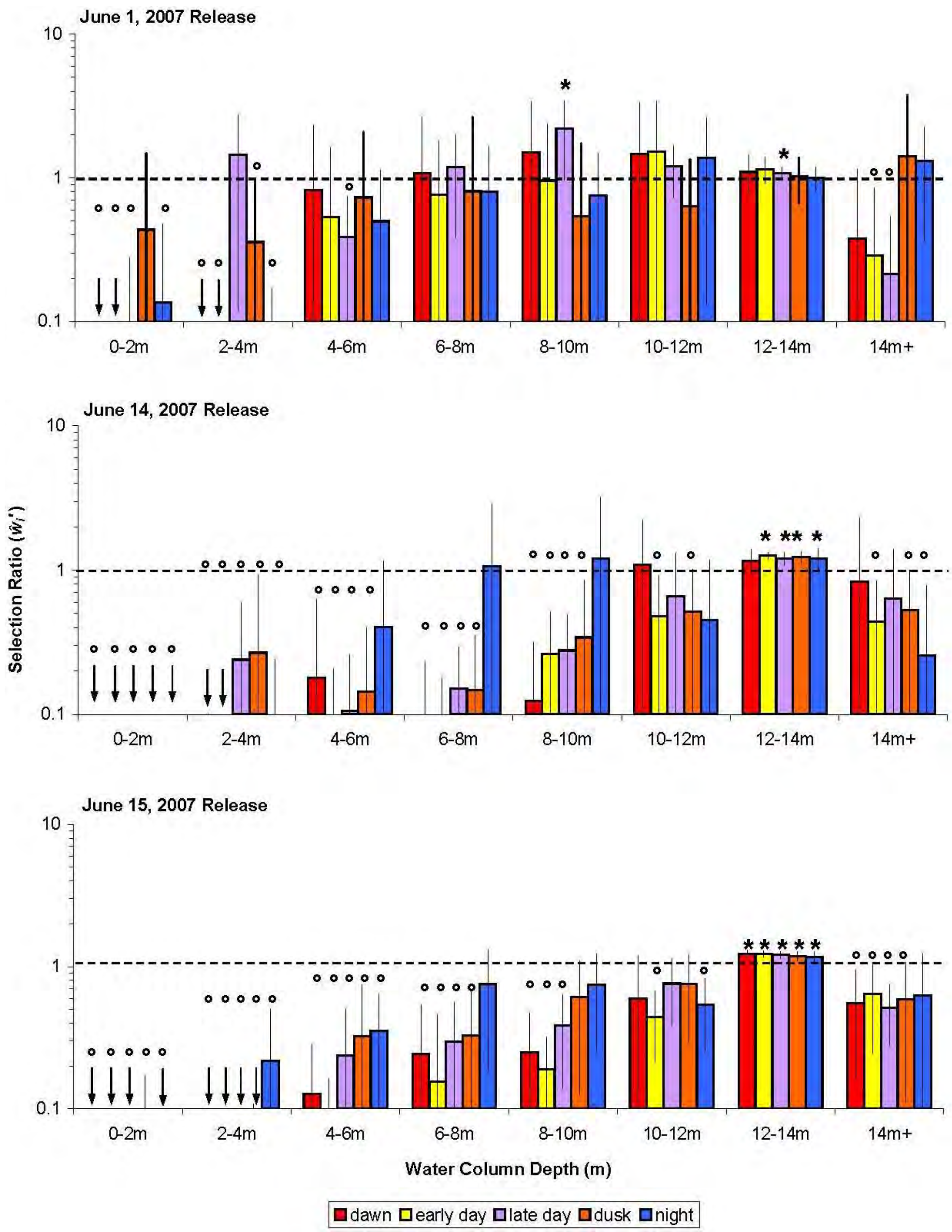
APPENDIX I. (cont.)



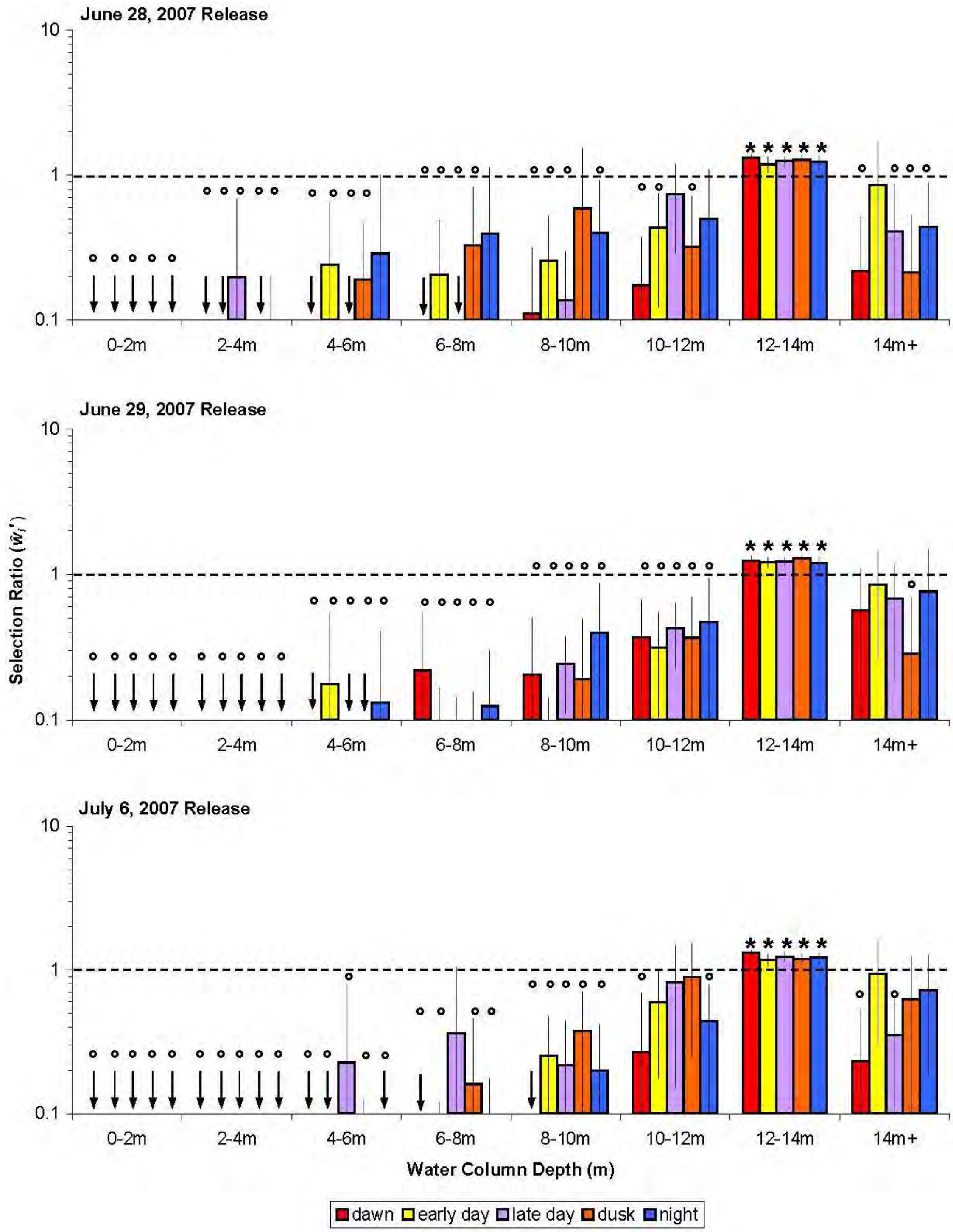
APPENDIX I. (cont.)



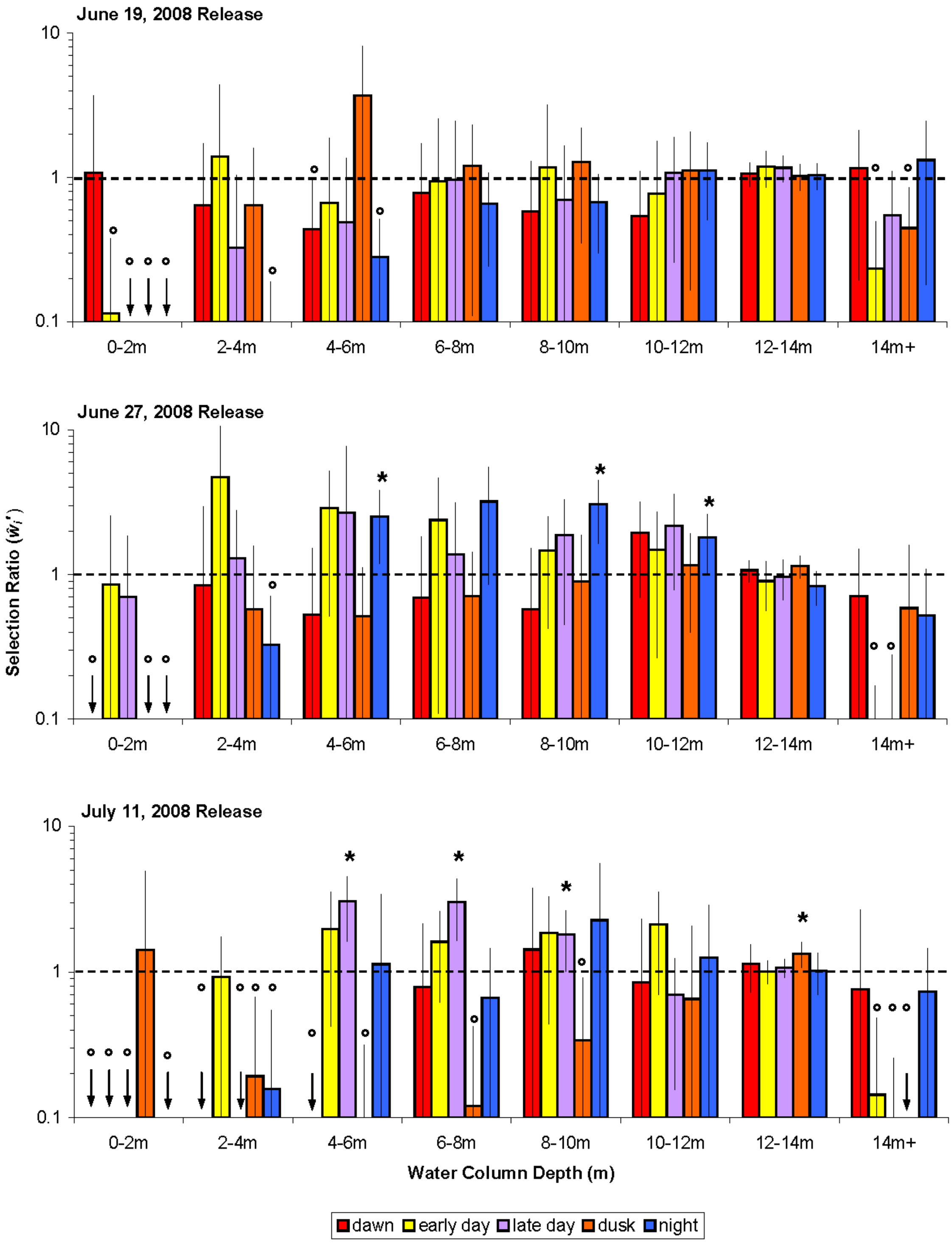
APPENDIX J. Diel bottom depth (water column depth) selection ($\hat{w}_i$', selection ratio; log scale) of Chinook salmon at the Gas Works Park study site, June-July, 2007-2008. Error bars represent Bonferroni-adjusted 90% confidence intervals. Error bars indicate if selection for (> 1) or against (< 1) a habitat type occurred. An asterisk (*) denotes selection for a bottom depth category and a circle (o) denotes selection against.



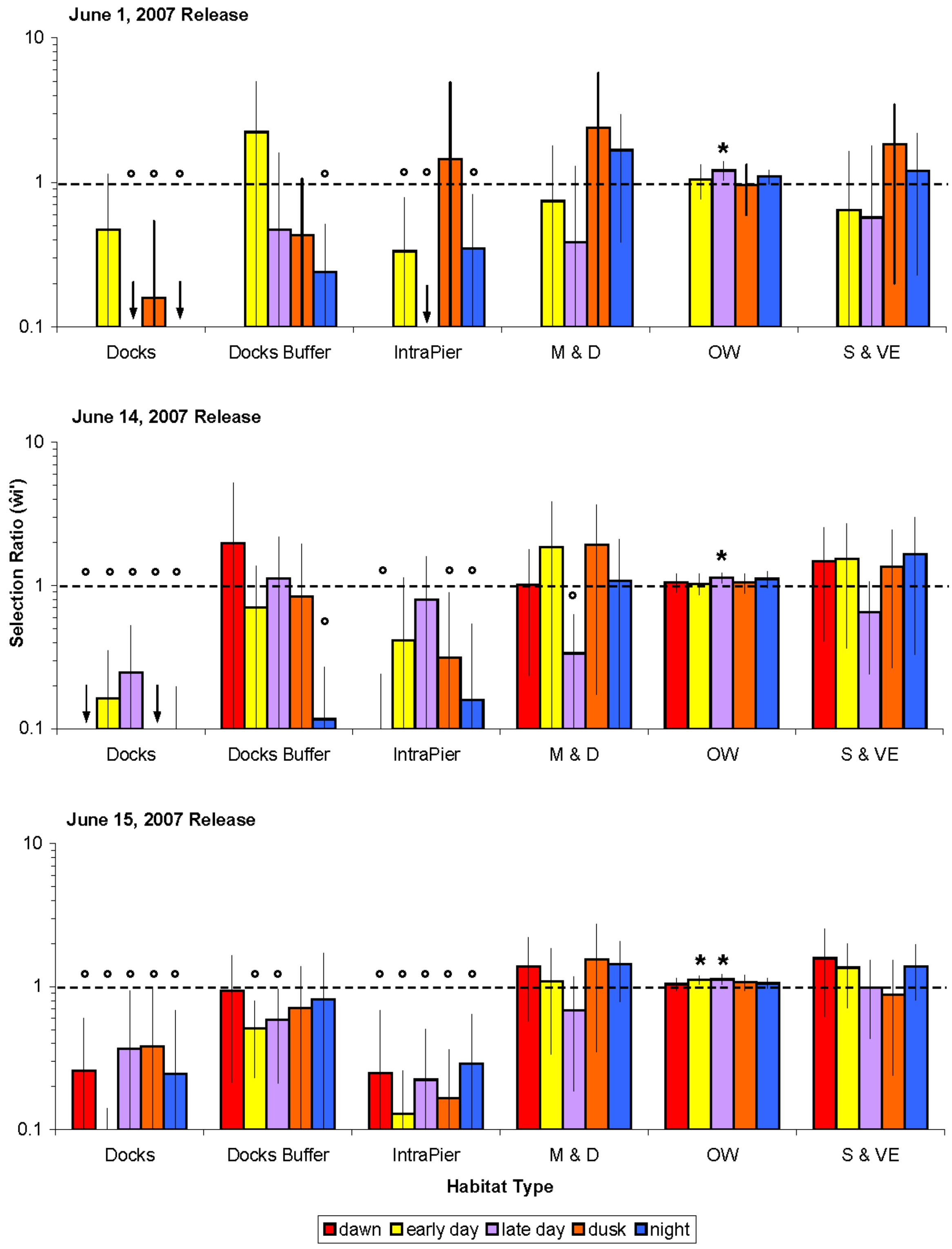
APPENDIX J. (cont.)



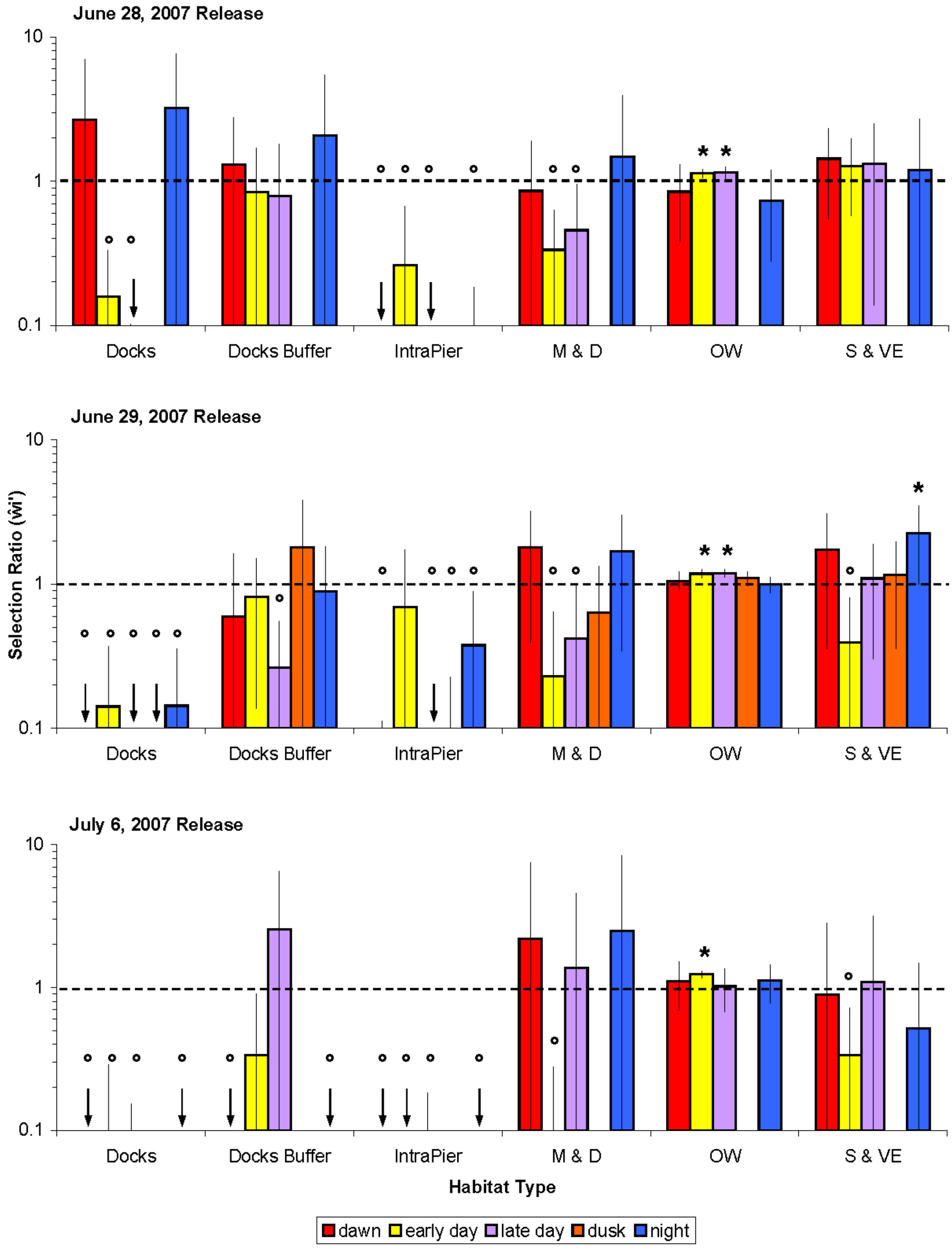
APPENDIX J. (cont.)



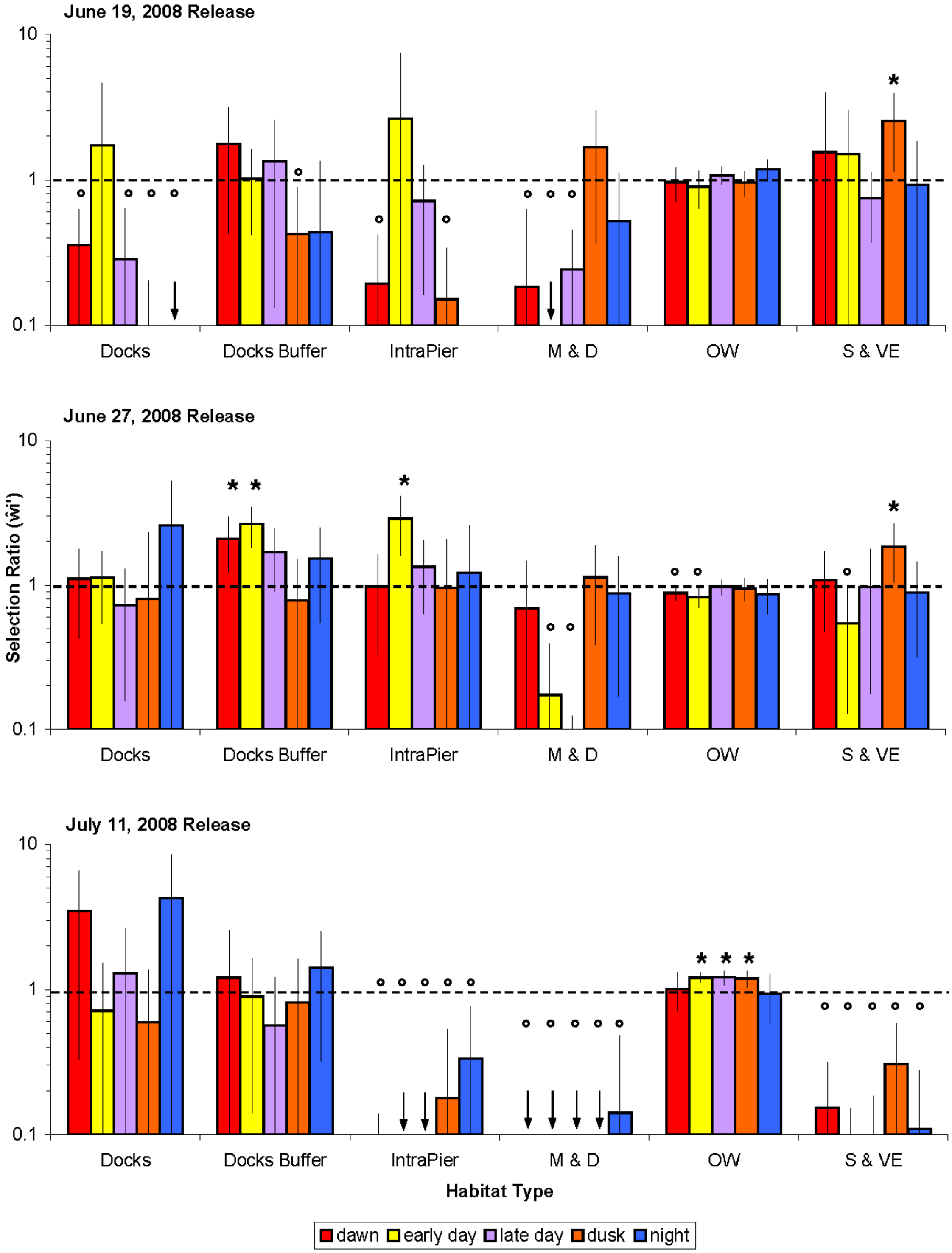
APPENDIX K. Diel habitat selection ($\hat{w}_i$', selection ratio; log scale) of Chinook salmon at the South Lake Union study site, June-July, 2007-2008. Error bars represent Bonferroni-adjusted 90% confidence intervals. Error bars indicate if selection for (> 1) or against (< 1) a habitat type occurred. An asterisk (*) denotes selection for a habitat and a circle (o) denotes selection against. See Table 2 for habitat types.



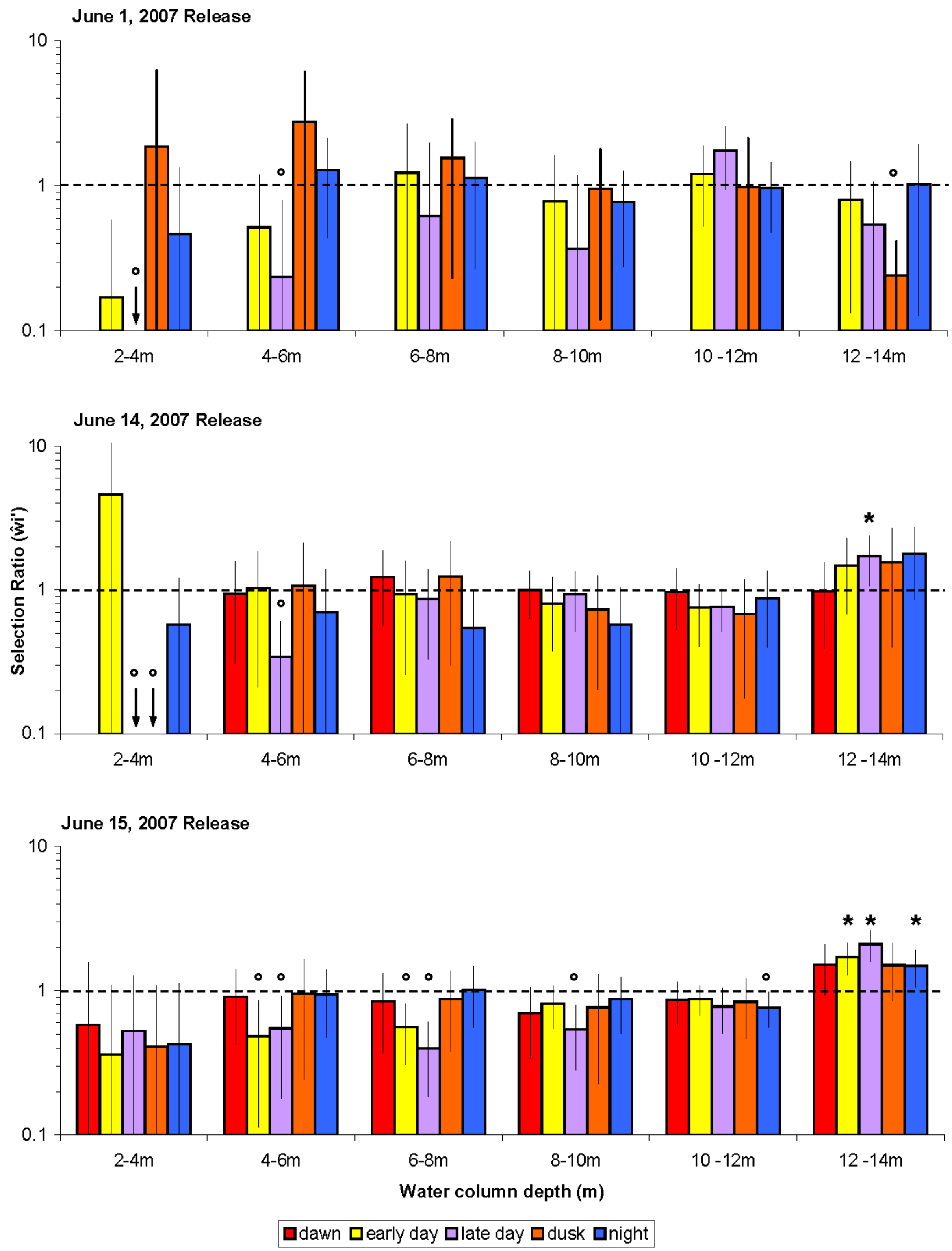
APPENDIX K. (cont.)



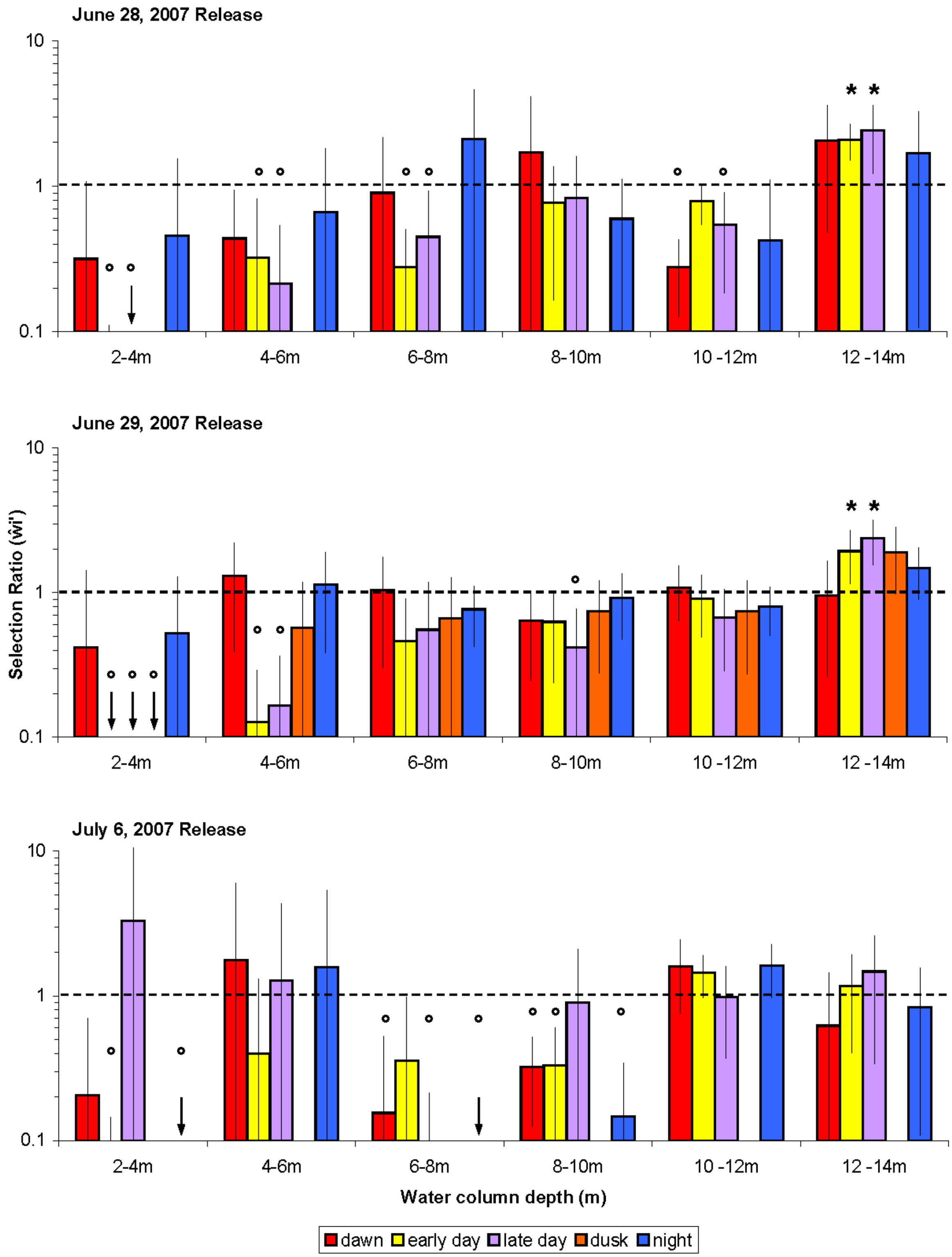
APPENDIX K. (cont.)



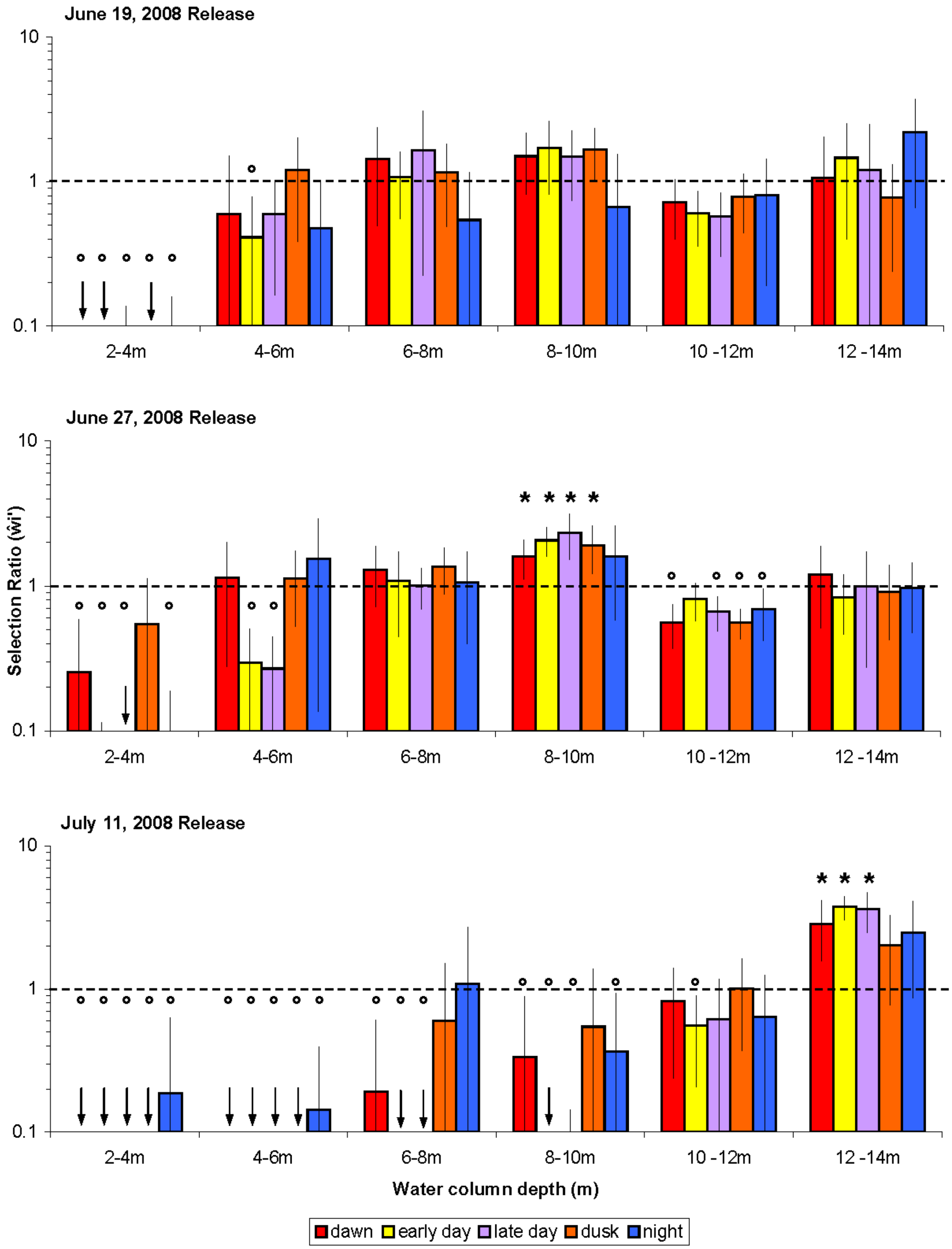
APPENDIX L. Diel bottom depth (water column depth) selection ($\hat{w}_i$', selection ratio; log scale) of Chinook salmon at the South Lake Union study site, June-July, 2007-2008. Error bars represent Bonferroni-adjusted 90% confidence intervals. Error bars indicate if selection for (> 1) or against (< 1) a habitat type occurred. An asterisk (*) denotes selection for a bottom depth category and a circle (o) denotes selection against.



APPENDIX L. (cont.)



APPENDIX L. (cont.)



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