Juvenile Salmonid Outmigration and Green Sturgeon Distribution in the San Francisco Estuary

Annual Report 2010

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~~To cite this document:~~

~~Hearn AR, Chapman ED, AP Klimley, PE LaCivita, & WN Brostoff (2010) Salmonid smolt outmigration and distribution in the San Francisco Estuary 2010. Interim Draft Report, University of California Davis and US Army Corp of Engineers. 90p.~~

EXECUTIVE SUMMARY

To reduce the impacts of dredging and in-bay placement of dredged materials the Long Term Management Strategy (LTMS) established environmental work windows for dredging. A Science Assessment and Data Gaps Work Group (Science Group) was created to coordinate scientific research that would provide better information to endangered species specialists at the National Marine Fisheries Service (NMFS). The purpose was to identify projects that would address data gaps and/or issues of concern to facilitate consultation under section 7 of the Endangered Species Act (ESA). The windows permit dredging in most areas from June through November when the majority of fish species of concern are not present. The windows were based on the best available science at the time but it was determined that the duration and/or locations of restrictions needed to be assessed by further research to decrease the potential for adverse effects on fish, mammal and bird species. It was determined that the original focus should be on out-migrating juvenile (smolt) late-fall run Chinook salmon (*Oncorhynchus tshawytscha*) and steelhead trout (*Oncorhynchus mykiss*). These might be used as surrogates for more vulnerable salmonid runs, for which there is little available data on their migration pattern, although surrogacy should always be applied with caution. The study was later extended to include the southern Distinct Population Segment (DPS) green sturgeon (*Acipenser medirostris*) population, currently listed as Threatened on the Endangered Species Act.

The objective of this study is to determine whether salmonid smolts may be exposed to dredged sites or dredged material placement sites during their outmigration through the San Francisco Bay Estuary. The study: 1) estimated transit times through various reaches of the San Francisco Estuary, 2) measured exposure times at dredged sites, and 3) identified the pathways of smolts as they migrate to the ocean. The study objective regarding green sturgeon concerns their general distribution and movements within the bay, including the identification of seasonal patterns of presence.

The first two years of the study (2006-2008) were performed by the San Francisco District of the United States Army Corps of Engineers (USACE) with oversight provided by the Science Group. During these two years the study closely matched the efforts of the California Fish Tracking Consortium (CAFTC) to study the migrations of smolts from the upper reaches of the Sacramento River. The first year served as a pilot study and the second improved study design and field methods. The third and fourth years, which this report is based on, were carried out by researchers at the Biotelemetry Laboratory (UC Davis).

Five hundred juvenile late-fall run Chinook salmon and five hundred juvenile steelhead trout were released at the end of January and early February 2010 at Elkhorn Landing at the northern end of the city of Sacramento, above any influence of the tides (river kilometer 209). The fish were tagged with individually coded ultrasonic beacons which can be detected by a watershed-wide array of underwater receivers. The receivers, placed at narrow stretches (bridges) to provide nearly complete coverage of the channel, made it possible to characterize both large scale movements through the estuary and migration trends related to water depths.

The overall success rate of the smolts from the release site to the start of the study area (Benicia Bridge) was 21% for steelhead trout and 41% for late-fall run Chinook salmon. Of these, approximately two thirds survived to the Golden Gate. This contrasted with 2009, when the overall success rate to Benicia was 48% for steelhead trout and 62% for late-fall run Chinook salmon, of which approximately one third survived to the Golden Gate.

The overall transit time, from Benicia Bridge to the last detection for those individuals which passed the Golden Gate (a distance of 50.69 km) was normally less than six days (median 2.7 days) and transit rates increased further downstream. Instantaneous rates of movement (measured as the time taken to transit between experimental receiver arrays deployed across the channel in San Pablo Bay) were significantly greater than the overall transit rate through San Pablo Bay, suggesting that fish either did not take the shortest route through the bay or were submitted to delays – probably related to the tides. Some individuals of both species displayed repeated upstream and downstream movements, which we related to the tidal state. Seventy percent of fish were subjected to at least one upstream movement. The number of upstream movements did not appear to influence successful migration to the Golden Gate. From the receiver detections we inferred that fish mostly travelled through the channel, with rare, short excursions to marina sites or up tributaries. Passage through the cross section arrays at the bridges was positively correlated with water depth.

Analysis of residency showed that fish do not reside at any of the sites, and that the term "exposure time" should be used instead. Exposure of smolts at marinas and dredged sites near shoals was variable – most fish were exposed for less than 30 minutes but a significant number were detected from 1-20 hours. The median exposure time through the San Pablo Placement Site SF10 was 5.3 minutes for late-fall run Chinook salmon and 6.5 minutes for steelhead trout, although the range of exposure times was great: up to 42 hours for late-fall run Chinook salmon and 13 hours for steelhead trout.

Green sturgeon were found in San Francisco Bay throughout the year, with more individuals detected in summer and fall around the Golden Gate and up to Carquinez Bridge. Fish were more evenly distributed throughout the system (from the Golden Gate to Freeport) in winter. Between May 2009 and August 2010, 47 green sturgeon were detected in the study area. Green sturgeon presence was positively correlated with depth at the cross section arrays. With the exception of Martinez Marina, which may have a detection range beyond the limits of the marina, green sturgeon were only detected briefly at Richmond Point and Vallejo Marina, and not in any of the other marina areas. Seven individuals were detected at SF9 and eight at SF11. At both placement sites, the median exposure time was under 20 minutes. Thirty five green sturgeon were detected at the SF 10 Placement Site in San Pablo Bay, for periods ranging from 5 to 1165 minutes. All the sturgeon were adults tagged in previous studies, undergoing seasonal migrations. These results cannot be generalized to include juveniles which may potentially inhabit the Bay year round or adults that may not be migrating. An ongoing study to tag and track juveniles in the Bay may shed more light on the spatial ecology of this key life stage. Adults that are potentially not migrating are currently being tagged in San Pablo and Suisun Bays.

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DRAFT -- NOT FOR ATTRIBUTION

1 Introduction

1.1 Study Objectives

The goal of this project is to provide endangered species specialists at the National Marine Fisheries Service (NMFS) with better information on which to perform consultations under section 7 of the Endangered Species Act. The research questions are as follows:

1. What are the general migratory patterns of outmigrating late-fall run Chinook salmon smolts (hereafter referred to as Chinook salmon) and steelhead trout smolts (hereafter referred to as steelhead) and to what extent does their spatial distribution coincide with the location of dredged material placement sites and dredging sites?
2. What is the residence time of outmigrating salmonid smolts in the various portions of the San Francisco Bay Estuary in and around the dredged material placement sites?
3. What are the spatio-temporal patterns of occurrence of green sturgeon in the San Francisco Bay Estuary, especially in relation to the location of dredging operations?

It is important to note that dredging operations did not generally take place during the periods when salmonids were migrating through San Francisco Bay. It is also important to mention that this study does not address the issue of dredging windows, as the migration timing of wild or hatchery fish cannot be inferred from the deliberate timed release of the experimental fish from Sacramento. This includes the other three runs of Chinook salmon which migrate through the estuary at all times of the year.

Green sturgeon are thought to inhabit the San Francisco Bay Estuary year-round although the tagged fish currently in the system are believed to be migrating through the estuary rather than resident fish. Studies have recently been undertaken at the UC Davis Biotelemetry Lab which focuses on these fish that are thought to reside in the estuary and will be reported on in the coming years.

1.2 Geography of San Francisco Bay Estuary

The San Francisco Bay Area is one of the most densely populated estuaries in the world. With a population of around 7.4 million (www.census.gov), three international airports and several major ports, (including the fourth busiest container port in the USA – the Port of Oakland), it is of vital importance to the economy of the nation. The Port of Oakland alone imported over $20 billion in commodities (mainly machinery, electric machinery and furniture) and exported over $10 billion (in edible fruit and nuts, meat and machinery) in 2009 (US Dept. of Commerce, Bureau of Census).

The Estuary can be subdivided into several regions (Fig. 1). At the head of the estuary, the Sacramento and San Joaquin rivers flow into Suisun Bay. Suisun is largely brackish, and is separated from the weakly saline San Pablo Bay by Carquinez Strait. At the end of Carquinez Strait, and the beginning of San Pablo bay is where the Napa River converges with these two larger rivers. South of the Richmond-San Rafael Bridge lies the Central Bay, bordered on the west by the Golden Gate Bridge, and to the south by the Bay Bridge and the South Bay. The Bay drains almost one-half of the land area of California (60,000 square miles) and the San Francisco Bay estuary contains 90 percent of California's remaining coastal wetlands.[1]

[1] http://mapping2.orr.noaa.gov/portal/sanfranciscobay/sfb_html/sfbenv.html

Figure 1. Satellite image of San Francisco Bay Estuary (from Google Earth) divided into sub-regions 1-5 and major bridges (A-E), named in inset (Photos: Alex Hearn).

1.3 Dredging Activities in the San Francisco Bay Area

1.3.1 Why Dredge

The depth profile for the San Francisco Bay has changed significantly through anthropogenic disturbance in the last 200 years. Beginning in the 1800s, sedimentation from mining practices in the upper Sacramento, American and Cosumnes rivers began to build up and fill in the bay. Dredging for navigational purposes, under the charge of the U.S. Army Corps of Engineers, began in the late 1800s and has continued non-stop, except for a brief interruption in the late 1980s (Dwinnell *et al*., 2003). Dredging is conducted to maintain shipping channels throughout the Bay Area and Delta, and to maintain access to ports and marinas for both commercial and recreational vessels.

Before 1850, the region sustained 1400 square kilometers of freshwater wetlands and 800 square kilometers of salt marshes; today, only 125 square kilometers of un-diked marshes remain of the original 2,200 square kilometers.[2] This equates to a 95 percent loss of crucial habitat. By the 1960s, one-third of the Bay was lost to filling and diking, and more than 80 percent of its tidal wetlands were converted to other uses. Dredged material has been used to reclaim wetlands and build Treasure Island or has been disposed of in the bay. San Francisco Bay depths range from 1 m (nearshore) to 53 m in the central part of the Bay and eventually to 115 meters depth just outside the Golden Gate Bridge (Chin *et al*., 2004).

[2] http://pubs.usgs.gov/fs/coastal-wetlands/index.html

1.3.2 How Dredging Occurs

The first dredged waterway in San Francisco Bay was created in 1868 and has been periodically dredged ever since. Today dredging is carried out by federal and non-federal entities and results in 2–10 million cubic yards of dredge spoils per year (USACE *et al.,* 1998). There are two types of dredging that occur in the San Francisco Bay Estuary – maintenance dredging (the removal of new sediments that have recently been deposited) and new work construction (dredging of sediments in their natural condition). Maintenance dredging is carried out by federal and private interests, new work is carried out mostly by private companies such as sand mining for construction material.

The excavation process commonly referred to as "dredging" involves the removal of sediment in its natural or recently deposited condition, using either mechanical or hydraulic equipment (Fig. 2). After the sediment has been excavated, it is transported from the dredging site to the placement site. This transport operation, in many cases, is accomplished by the dredge itself or by using additional equipment such as barges, scows, and pipelines with booster pumps.

Mechanical dredges remove bottom sediment through the direct application of mechanical force to dislodge and excavate the material at almost *in situ* densities. Backhoe, bucket (such as clamshell, orange-peel, and dragline), bucket ladder, bucket wheel, and dipper dredges are types of mechanical dredges. Sediments excavated with a mechanical dredge are generally placed into a barge or scow for transport to the placement site.

The hydraulic dredge uses water to remove and transport the material. This system has a pump for moving the water. The pump creates a vacuum or a pressure head, which moves water rapidly through the pipe. This system always has at least three components: dredging device, pump, and discharge system. There are many common hydraulic dredging systems: hopper dredges, sidecast dredges, cutterhead dredges, and dustpan dredges. Hydraulic dredges remove and transport sediment in liquid slurry form and are usually barge-mounted.

Figure 2. Top left: mechanical clam dredge (Photo: EIK Engineering), Bottom left: hydraulic dredge (Photo: Alibaba), Right: Dredging operation in SF Bay (Photo: Michael Slater).

1.3.3 Dredged Material Placement

Dredged materials were first placed at the Alcatraz Disposal site in 1894 because of a great depth that reached 50m (U.S. Environmental Protection Agency, 1996) and it was believed that strong tidal currents would disperse the dredged material from the site. In 1982 it was realized that the material was accumulating and resulting in a potential hazard to navigation. Subsequently, other placement sites were created to decrease the buildup of dredged materials at the Alcatraz site. Material is currently placed at three types of locations: other in-Bay sites; upland/wetland re-use placement sites; and in the ocean (Fig. 3).

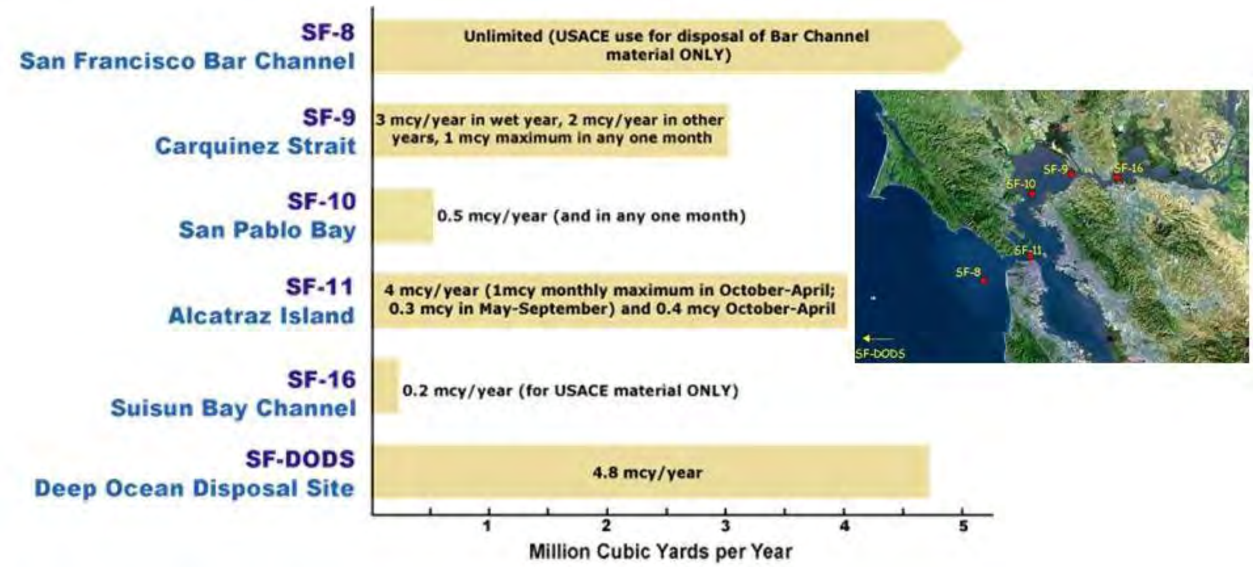

Figure 3. Permitted volumes of dredged material placement at sites in San Francisco Bay (Inset: location of placement sites). Source: LTMS.

1.3.4 Dredge management and issues

Potential impacts of dredging on fish in the Bay were described in the LFR 2004 report, which cited both the NMFS biological opinion (NMFS, 1999) and the LTMS EIS/EIR report (USACE *et al.,* 1998).

NMFS Biological Opinion Chinook salmon and steelhead trout:

- Redistribution of pollutants and/or release of contaminants which may result in chronic or acute toxicity, particularly those that rear for prolonged periods in affected areas, burial of bottom-dwelling organisms which may reduce feeding opportunities for rearing juvenile salmon.
- Re-suspension of sediment particles which could interfere with visual foraging, abrade gill tissues, or interfere with migration.
- Increased turbidity may interfere with primary productivity.
- Sediment alterations associated with in-Bay disposal.

EIS/EIR Chinook salmon and steelhead trout:

- Water quality degradation.
- Direct habitat loss or degradation.

- Interference with foraging or food resources.
- Entrainment by the dredge.

An important tool for the management of dredging activities is the use of work windows. These are based on the occurrence and distribution of listed species throughout the area, and are designed to minimize the impact of dredging activities on these species. During a work window, a dredging or placement activity is covered by the existing Biological Opinion and can take place with normal permits and condition. Activities to be carried out at other times require consultation. Work windows apply to both dredging and placement activities and are location-specific.

1.4 Threatened and Endangered Species in SF Bay

The San Francisco Bay Area is a prime nursery and foraging habitat for many fish species including Chinook salmon, steelhead and green sturgeon. Over 50 species of plants and wildlife in this region are on the threatened and endangered species list primarily due to habitat loss.

Those species listed as "Endangered" include the Central California Coast Coho salmon (*Onchorhynchus kisutch*) Evolutionary Significant Unit (ESU), the Sacramento River winter run Chinook salmon (*O. tshawytscha*) ESU and the green sturgeon (*Acipenser medirostris*) Southern Distinct Population Segment (DPS). The "Threatened" category includes the Central California Coast DPS of steelhead trout (*O. mykiss*) and spring run Chinook salmon. Fall run and late-fall run Chinook salmon are a "species of concern".

Chinook salmon (Fig. 4) were formerly abundant and widely distributed throughout rivers and streams of California's Central Valley. Chinook salmon occur in four distinct subpopulations, whose names are drawn from the seasons when most adults return to freshwater to spawn: winter, spring, fall, and late-fall (Stone, 1874; Fry, 1961). The fall and spring runs exhibit two types of juvenile life-history strategies: ocean-type and stream-type respectively. Winter run are somewhat anomalous in that they have characteristics of both ocean and stream-type. The juveniles spend four to seven months in fresh water (Healey, 1991). Late-fall run fish may also exhibit both types as they spend six to nine months if fresh water. The ocean-type juveniles spend relatively little time in streams and enter the ocean at a small size [80 mm fork length (FL)]. In contrast, the stream-type juveniles spend several months to over a year in streams and enter the ocean at a large size (120-180 mm FL) (Moyle 2002).

Steelhead (Fig. 4) are indigenous to the Pacific coast of Asia and western North America and are an anadromous (spend time in salt water and return to fresh water to spawn) and iteroparous (spawn more than once) form of rainbow trout (*Oncorhynchus mykiss*). Recent allozyme data show that samples of steelhead from Deer and Mill Creeks and Coleman National Fish Hatchery on the Sacramento River are well differentiated from all other samples of steelhead from California. The distance from the ocean to spawning streams can exceed 300 km, providing unique potential for reproductive isolation among steelhead in California (Busby *et al*., 1996). Only a winter run of Central Valley steelhead are currently recognized, although in the past there may have been a summer run of steelhead as well (Needham, 1941).Central valley steelhead were listed as threatened under the Endangered Species Act in 1998 and the status was reaffirmed in 2006. The central valley Evolutionary Significant Unit (ESU) occupies the Sacramento and San Joaquin Rivers and their tributaries. Steelhead in the Central Valley have been almost completely extirpated from their historical range mainly due to habitat loss by the construction of dams. There may have been more than one million adults returning to the Sacramento and San Joaquin drainages but by the 1960s that number had dwindled to 40,000.

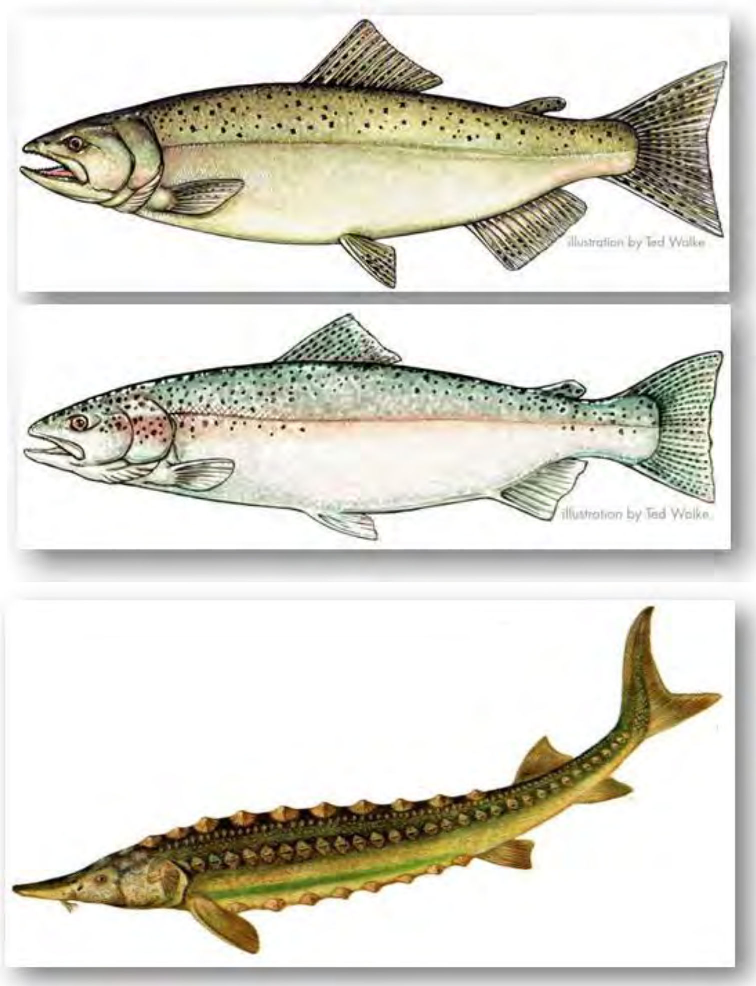

Figure 4. Target species of the current study. Above: late-fall run Chinook salmon (*Onchorynchus tshawytscha)*, Middle: steelhead (*Onchorynchus mykiss*), Below: green sturgeon *(Acipenser medirostris)* Photo from: www.zooschool.ru.

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Green sturgeon (Fig.4) are found in marine waters from Mexico to Alaska and make spawning and non-spawning movements into coastal lagoons and bays including the San Francisco Bay Estuary. It is believed that green sturgeon spawn in the Rogue River, Klamath River Basin and in the Sacramento River (Moyle, 2002). The sturgeon that spawn in the Sacramento River are part of the Southern DPS and are currently listed under the Endangered Species Act as a Threatened species. Juvenile green sturgeon spend 1-4 years in fresh and estuarine waters before dispersal to saltwater (Beamesderfer and Webb, 2002). Adults spawn when they are more than 15 years of age; males mature at a size ranging from 1.4 - 2m in fork length and females from 1.6 - 2.2m in fork length (VanEenennaam, 2002). Spawning is believed to occur every 2-5 years (Moyle *et al*., 1995) and females produce 60,000-140,000 eggs (Moyle *et al*., 1992).

1.5 The California Fish Tracking Consortium

The California Fish Tracking Consortium (CAFTC) was established in 2006, and maintains an array of receivers throughout the Sacramento River watershed, from the upper river (above Red Bluff Dam) to the ocean, including the delta and bay areas (www.californiafishtracking.ucdavis.edu/). The

Consortium is made up of a number of private and public institutions, such as the Biotelemetry Laboratory at the University of California, Davis, NOAA/UC Santa Cruz, the US Army Corps of Engineers, US Fish & Wildlife Service, California Department of Fish & Game, Bay Planning Coalition and others. Each institution carries out a series of research projects which utilize the receiver array. These include studies of the spawning migrations of green sturgeon (eg. see Heublein *et al.*, 2008), site fidelity of sevengill sharks, and several studies related to salmonid smolt movement patterns and survival in different river reaches, and comparisons between hatchery-reared and wild fish (eg. Johnson *et al.*, 2008).

1.6 Biotelemetry Studies

Biotelemetry is the science of tracking organisms. This can be complicated in aquatic environments where visibility is usually poor, organisms can move in three dimensions, and conventional tracking techniques such as radio telemetry perform poorly. Ultrasonic telemetry provides a solution to some of the technical difficulties presented by other technologies. Sound propagates better in water than it does in air, so fitting animals with tags which emit acoustic signals will allow them to be detected at distances by passive receiver stations (Fig. 5). VEMCO Ltd. (Halifax, Canada), manufactures a series of ultrasonic tags which emit unique coded pulses at a frequency of 69 KHz. When these pulses are detected by their VR2 receivers, they are logged and stored, and may be retrieved up to one year after deployment. To avoid signal collision by tags which are in the same place simultaneously, each tag is programmed with a random delay around a mean time interval between each pulse.

Several studies have examined the effect of radio or ultrasonic tags implanted within the body on swimming performance, growth, and vulnerability to predation of juvenile salmonids. Implanted tags weighing less than 8% of the fish's weight did not produce any significant difference in swimming performance of tagged fish from those having an operation but not carrying a tag, and those individuals that did not undergo an operation (Moore *et al*., 1990; Peake *et al*., 1997; Adams *et al*., 1998; Brown *et al*., 1999; Robertson *et al*., 2003; Anglea *et al*., 2004; Lacroix *et al*., 2004).

Figure 5. Underwater ultrasonic receiver (left), Vemco V7 and V9 tags (upper right), and deployment riggings with acoustic releases for deepwater deployment of receivers in San Francisco Bay (lower right).

Listening stations can be deployed in arrays such as curtains, which might cover an entire cross-section of a channel, or to provide coverage at particular interest sites. Two receiver types are currently in use: VR2 and VR2W. The difference between the two receiver types lies in their communications systems – the latter uses Bluetooth technology to communicate with and transfer data to a computer, whereas the former uses a more traditional USB port. Both receivers use lithium batteries which must be replaced every 12 months, and passively record the code number, time and date of up to 300,000 tag pulses, whenever a tag comes within range. The detection range of a VR2 varies greatly depending on water turbidity, riverbed bathymetry, weather conditions, and ambient noise levels. VEMCO states that the detection range has a radius of 500 meters, but recommend that range testing be carried out for each individual study. Both types of receivers must be brought to the surface for data download.

1.7 Prior work

This report presents the results of the fourth year of a multi-year study which involves monitoring the migratory patterns of salmonids in the San Francisco Bay Estuary. The first two years of this study were carried out by the San Francisco District of the United States Army Corps of Engineers (USACE) with oversight by the LTMS Science and Data Gaps Work Group (Science Group) from late summer of 2006 to summer of 2008 (Klimley *et al.*, 2009). The USACE coordinated its effort with members of the California Fish Tracking Consortium to maximize the efficiency of data collection, analysis, and interpretation. The 2006-2007 study served as a pilot study, to determine the suitability of equipment and logistics, and the feasibility of addressing study questions. Improvements in field methods to more accurately record salmonid movements throughout the San Francisco Bay were reflected in subsequent years.

Juvenile Chinook salmon and steelhead smolts were released into the lower Sacramento River, near the Rio Vista Bridge. USACE released 49 Chinook salmon and 49 steelhead in 2006-2007 and 500 of each species in 2007-2008 were released in two batchers, separated by one week, further up river above Sacramento, CA. Individuals tagged with coded ultrasonic beacons were detected by an estuary-wide array of ultrasonic receivers. Each receiver records fish passage and the associated date and time for each detection. The receivers, placed at "choke points" and arranged in curtain arrays with overlapping ranges, made it possible to characterize both large scale movements through the estuary and migration trends related to water depths. Transit times were calculated between Rio Vista (the USACE release point) and the Richmond San Rafael Bridge as well as from the Richmond San Rafael Bridge to the Golden Gate Bridge. Migratory pathway trends were analyzed using data acquired from the Richmond San Rafael curtain array and its associated cross sectional depth profile.

This study passively detected salmonids to describe large-scale movements in and around dredge activity sites within the estuary. Based on tag-detection records for 2007-2008, the mean travel time between Rio Vista and Golden Gate Bridges was 10.2 days for Chinook salmon and 8.5 days for steelhead. The median residence time at SF10, the designated in-bay placement site for dredged material in San Pablo Bay, was 6.5 min for Chinook salmon and steelhead. Both species tended to use mid-channel waters around the Richmond San Rafael Bridge rather than the shallow flats on either side of the channel. Each exhibited a positive linear relationship, up to 11.3 m, between depth and frequency of detection. The analyses from both study years show a substantial proportion of both species utilized deeper dredged channels and/or passed at least one dredged material placement site. The analysis suggested that adjustments to this study were necessary to better obtain quantitative confirmation of the study objectives. Recommendations for the third year of study included: 1) a larger number of tagged fish, 2) a release location farther upstream, 3) spacing monitors based on current range tests, and 4) new monitor locations to better cover dredged material placement sites.

In 2009, several changes were made to the position of the array, the release site of the fish, and the analyses which were carried out. The results from 2009 are comparable with those obtained in the current year and are dealt with in more detail in the Results section – in some cases, data has been re-analyzed where new methods have been used.

Green sturgeon have been caught by various agencies and as part of various projects throughout the San Francisco Bay Estuary, including Suisun Bay and Grizzly Bay above Benicia Bridge. However, little can be inferred from this map, other than the presence of fish, as the lack of a directed search for fish over the entire area precludes making conclusions about absences.

Figure 6. Locations where green sturgeon were caught by research vessels in previous years

Green sturgeon have been caught in sizes ranging from 19-209 cm (Table 1), but using different methods and at different sites, so little can be inferred regarding the size structure of the population which utilizes the Bay, other than that all these sizes are present at least part of the time.

Table 1. Size range and number of green sturgeon caught in sampling nets in San Francisco Bay.

Program	Sampling Method	# Fish	Size Range (cm)
IEP Monitoring Program	Various	23	19-101
CDFG Trammel	Trammel Net	732	47-209
UC Davis	Gill Net	209	55-204

Kelly *et al*. (2007) provided the first fine-scale description of the daily estuarine movements and habitat use of green sturgeon, by tracking sub-adult and adult fish in the San Francisco Bay Estuary. They found that, although the fish tended to occupy the shallower parts of the estuary, sturgeon were apparently not limited by the broad range of environmental conditions in the region, making lengthy directional movements across large gradients.

Currently, over 400 green sturgeon have been fitted with V16 ultrasonic tags in the Sacramento River system, for studies which range from evaluating the impact of Red Bluff Diversion Dam in the upper Sacramento River on spawning migrations, habitat preference of adults and juveniles in the river and delta, and interannual spawning periodicity. A study funded by the United States Army Corps of Engineers Sacramento District to understand the movements of green and white sturgeon in relation to riverbank restoration attempts began in 2010, and will involve the placement of ultrasonic tags on at least 80 green sturgeon in the San Francisco Bay Estuary each year. These fish will also be analyzed with relation to the objectives of the current study.

2 Methods & Materials

2.1 Receiver locations

Receivers were placed at dredge and dredge placement sites throughout the San Francisco Bay Estuary (Table 2). Some were placed on bridges as arrays in order to detect passage through particular river reaches. Bridges are situated at narrow passes where fewer monitors are required to fully cover the expanse of the channel, and also provide the ease of attachment and highly successful recovery rates (monitors attached to bridges are far less likely to be lost and are easily interrogated by boat). We also placed monitors in marinas and channels throughout San Pablo and San Francisco Bay. These monitors were attached to US Coast Guard aids to navigation, marina docks, and other private and public channel markers. These were chosen so as to detect fish that ventured out of the main channels and into other dredged areas. The bridges are also situated at the logical beginning and end of each of the commonly referred to reaches of the San Francisco Bay Estuary: Suisun Bay, San Pablo Bay, Central Bay and South Bay. Several new locations were added to the existing array for this study: receivers were deployed at the SF 9 Placement Site and at Mare Island, and an array of eight receivers was deployed on the flats in San Pablo Bay (Fig. 7). The line of receivers at the Richmond Bridge was extended to provide shore to shore coverage.

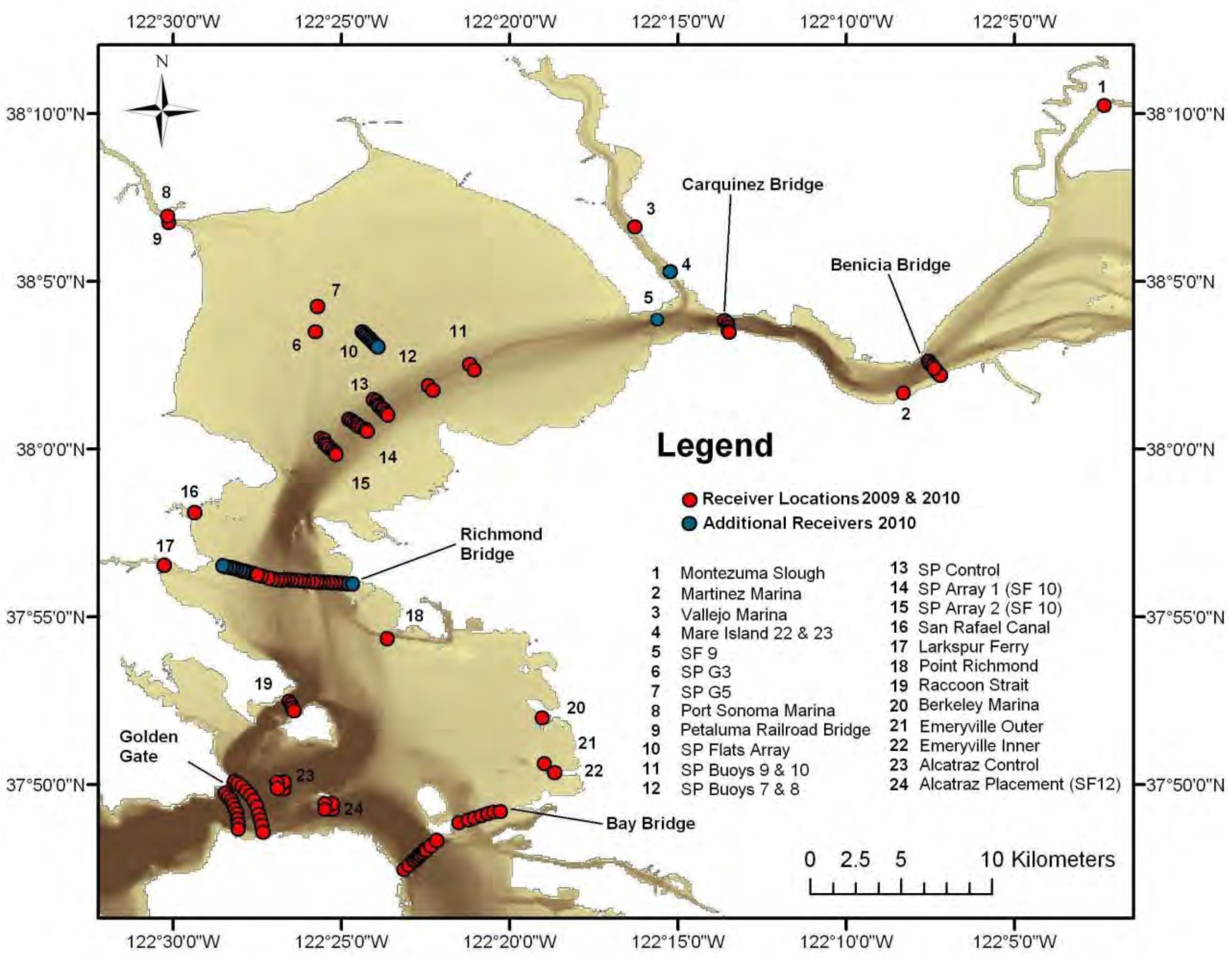

Figure 7. Map of study area showing receiver locations. Darker areas correspond to deeper channels.

Table 2. Name and location of underwater ultrasonic receiver stations used in study

Location	Lat	Long	Location	Lat	Long
Benicia_Bridge_01	38.043767	-122.12595	GoldenGate7.7	37.8221	-122.45841
Benicia_Bridge_02	38.042433	-122.12502	GoldenGate8.0	37.81856	-122.45764
Benicia_Bridge_03	38.041233	-122.12382	GoldenGate8.4	37.81696	-122.45953
Benicia_Bridge_04	38.03896	-122.12192	GoldenGate8.5	37.8159	-122.45675
Benicia_Bridge_05	38.037617	-122.12108	GoldenGate9.0	37.81305	-122.45598
Benicia_Bridge_06	38.03645	-122.1201	GoldenGate9.5	37.8094	-122.45549
Benicia_Bridge_Center	38.03994	-122.12301	RichBr_East_1_2009	37.933436	-122.417184
Carquinez_Bridge_01	38.063833	-122.22697	RichBr_East_2_2009	37.933237	-122.415209
Carquinez_Bridge_02	38.062333	-122.22525	RichBr_East_3_2009	37.933126	-122.413203
Carquinez_Bridge_03	38.060583	-122.22497	RichBr_East_4_2009	37.932977	-122.411154
Carquinez_Bridge_04	38.058667	-122.2251	RSRB_1_2009	37.93348	-122.41925
Carquinez_Bridge_05	38.05795	-122.22455	RSRB_2_2009	37.93361	-122.42132
SP_Bouy7_2009	38.03137	-122.37343	RSRB_3_2009	37.93376	-122.42332
SP_Bouy8_2009	38.02899	-122.37149	RSRB_4_2009	37.93392	-122.42501
SP_Buoy9_2009	38.04207	-122.35325	RSRB_East_Channel_2009	37.9339	-122.42706
SP_Buoy10_2009	38.03919	-122.35075	RSRB_5_2009	37.93418	-122.42887
SP_Flats_Array_1_2009	38.05819	-122.40629	RSRB_6_2009	37.93425	-122.43074
SP_Flats_Array_2_2009	38.05709	-122.40508	RSRB_7_2009	37.93439	-122.43282
SP_Flats_Array_3_2009	38.05607	-122.40405	RSRB_8_2009	37.93449	-122.43492
SP_Flats_Array_4_2009	38.05507	-122.40303	RSRB_9_2009	37.93458	-122.43699
SP_Flats_Array_5_2009	38.05397	-122.40186	RSRB_10_2009	37.93481	-122.43895
SP_Flats_Array_6_2009	38.05304	-122.40083	RSRB_11_2009	37.93494	-122.44098
SP_Flats_Array_7_2009	38.05195	-122.39972	RSRB_12_2009	37.9353	-122.4428
SP_Flats_Array_8_2009	38.05094	-122.39867	RSRB_West_Channel_2009	37.9352	-122.44465
SP_Array_1A_2009	38.01482	-122.41307	RSRB_13_2009	37.93495	-122.44659
SP_Array_1B_2009	38.01393	-122.41171	RSRB_14_2009	37.93522	-122.4484
SP_Array_1C_2009	38.01297	-122.41043	RSRB_15_2009	37.93553	-122.45043
SP_Array_1D_2009	38.01233	-122.10899	RSRB_16_2009	37.9359	-122.45251
SP_Array_1E_2009	38.011	-122.4081	RSRB_17_2009	37.9364	122.45444
SP_Array_1F_2009	38.01053	-122.40653	RSRB_18_2009	37.937	-122.4564
SP_Array_1G_2009	38.00991	-122.40483	RSRB_19_2009	37.93753	-122.45813
SP_Array_1H_2009	38.00867	-122.40402	RSRB_20_2009	37.938094	-122.460106
SP_Array_2A_2009	38.0053	-122.42673	RSRB_21_2009	37.93866	-122.46204
SP_Array_2B_2009	38.00461	-122.42513	RSRB_22_2009	37.93907	-122.46378
SP_Array_2C_2009	38.00276	-122.42491	RSRB_23_2009	37.93953	-122.46531
SP_Array_2D_2009	38.00193	-122.42368	RSRB_24_2009	37.94	-122.46677
SP_Array_2E_2009	38.00064	-122.42265	RSRB_25_2009	37.94052	-122.46863
SP_Array_2F_2009	37.99958	-122.42108	RSRB_26_2009	37.9409	-122.47033
SP_Array_2G_2009	37.99849	-122.42007	RSRB_27_2009	37.94127	-122.47196
SP_Array_2H_2009	37.99739	-122.41928	RSRB_28_2009	37.94161	-122.47368

Location	Lat	Long	Location	Lat	Long
SP_Control_1_2009	38.02457	-122.4009	RSRB_29_2009	37.942074	-122.475454
SP_Control_2_2009	38.02371	-122.3993	Bay_Bridge_E2_2009	37.81415	-122.35849
SP_Control_3_2009	38.02233	-122.39851	Bay_Bridge_E3_2009	37.815571	-122.35385
SP_Control_4_2009	38.02114	-122.39788	Bay_Bridge_E5_2009	37.816679	-122.35067
SP_Control_5_2009	38.02024	-122.3966	Bay_Bridge_E7_2009	37.817746	-122.34744
SP_Control_6_2009	38.0195	-122.39581	Bay_Bridge_E9_2009	37.81884	-122.34412
SP_Control_7_2009	38.0179	-122.39468	Bay_Bridge_E12_2009	37.819443	-122.34116
SP_Control_8_2009	38.01682	-122.3937	Bay_Bridge_E15_2009	37.819907	-122.33819
Aclatraz_SE_2009	37.82082	-122.42106	Bay_Bridge_18_2009	37.820376	-121.33522
Alcatraz_NE_2009	37.82385	-122.42153	Bay_Bridge_W1_2009	37.790891	-122.38563
Alcatraz_NW_2009	37.82385	-122.42474	Bay_Bridge_1.5_2009	37.79316	-122.38319
Alcatraz_SW_2009	37.82087	-122.41477	Bay_Bridge_W2A_2009	37.795616	-122.38091
Alcatraz_Control_1_2009	37.8313	-122.44522	Bay_Bridge_W2B_2009	37.795534	-122.38033
Alcatraz_Control_2_2009	37.83457	-122.44535	Bay_Bridge_2.5_2009	37.79682	-122.37914
Alcatraz_Control_3_2009	37.83449	-122.44876	Bay_Bridge_W3A_2009	37.798045	-122.37823
Alcatraz_Control_4_2009	37.83143	-122.44846	Bay_Bridge_W3B_2009	37.798341	-122.37742
Racoon_Lome_2009	37.86974	-122.44033	Bay_Bridge_3.5_2009	37.79949	-122.37656
Racoon_Middle_1_2009	37.87323	-122.44148	Bay_Bridge_W4A_2009	37.800855	-122.37531
Racoon_Middle_2_2009	37.87277	-122.44161	Bay_Bridge_W4B_2009	37.800717	-122.37471
Racoon_Lome_2009	37.86974	-122.44033	Bay_Bridge_4.5_2009	37.80299	-122.37252
GoldenGate1.0	37.82898	-122.4741	Bay_Bridge_W5_2009	37.805514	-122.36955
GoldenGate1.5	37.82737	-122.47266	Berkeley_Marina_2009	37.86649	-122.31712
GoldenGate2.0	37.82561	-122.47125	Emeryville_A_2009	37.8391	-122.3111
GoldenGate2.5	37.82344	-122.47022	Emeryville_B_2009	37.84355	-122.31609
GoldenGate3.0	37.82126	-122.46918	Vallejo_Marina_2009	38.11023	-122.27147
GoldenGate3.5	37.81877	-122.46816	Suisun_City_Marina_2009	38.2345	-122.03764
GoldenGate3.6	37.81958	-122.46544	Martinez_Marina_2009	38.02779	-122.13839
GoldenGate4.0	37.81615	-122.46799	Petaluma_RR_Bridge_2009	38.11248	-122.50219
GoldenGate4.1	37.81681	-122.46422	Port_Sonoma_Marina_2009	38.11558	-122.50263
GoldenGate4.5	37.81375	-122.46766	SP_G3_2009	38.05814	-122.42967
GoldenGate5.0	37.8112	-122.46778	SP_G5_2009	38.07095	-122.42856
GoldenGate5.5	37.83478	-122.46967	Montezuma West	38.17073	-122.03894
GoldenGate6.0	37.83393	-122.46794	Montetuma East	38.07187	-121.87507
GoldenGate6.5	37.83218	-122.4659	SanRafael_Canal_6_2009	37.96862	-122.48948
GoldenGate7.0	37.83025	-122.46376	Larkspur_Ferry_2009	37.94238	-122.50448
GoldenGate7.2	37.82794	-122.46168	Point_Richmond_6_2009	37.90573	-122.3938
GoldenGate7.5	37.82542	-122.45993			

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2.2 Receiver Deployment

The VR2 and VR2W underwater receivers were deployed in two fashions, depending on the deployment site. Receivers deployed at fixed stations (bridge abutments, docks, and channel markers) were attached to steel cables by means of two stainless steel clamps and one heavy duty cable tie (Fig. 8). The steel cable was weighted with up to 30 lb of iron plates, and attached to one of the bridge supports, so that the receiver was always below the surface but never touched the riverbed. To retrieve the monitors, each site was visited every three months by boat, the steel cable was hauled by hand, and the monitor interrogated. Receiver batteries were changed after 12 months. A similar procedure was used for deploying receivers at marina piers and channel marker buoys.

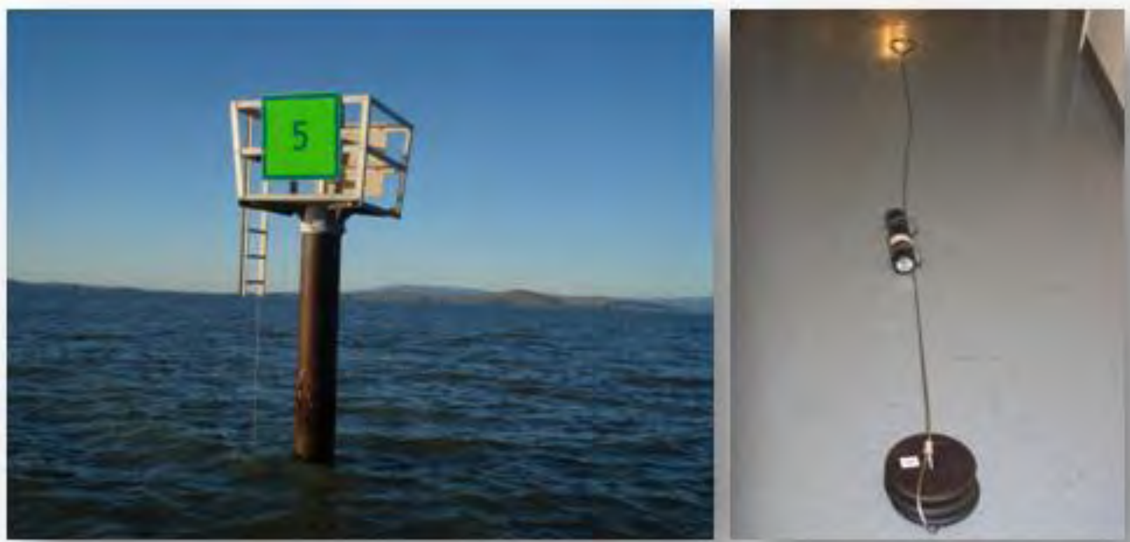

Figure 8. Left: VR2/VR2W ultrasonic receiver rigging from a channel marker in San Pablo Bay Right: VR2W mooring design for fixed stations (Photos: Eric Chapman).

For open water deployments, the monitor was fitted with an acoustic release system (Fig. 9). The rigging was weighted with 90 lb of iron plates and was deployed from a vessel. Deployment was assisted by use of a hydraulic winch and ramp. In order to retrieve the monitors, each site was visited every three months. Each acoustic release responded to a unique acoustic pulse generated at the surface by an acoustic release interrogator which triggers the release to send an electrical current over the release mechanism. The mechanism is a small wire that corrodes when the current is sent through salt water, releasing the monitor, acoustic release and floats. The system was then retrieved when the floats surfaced with the monitor and acoustical release attached. The monitor was then interrogated and placed back in the same location.

Figure 9. Left: VR2/VR2W ultrasonic receiver rigging with acoustic release, attached to steel weights (Photo: Alex Hearn). Right: Retrieval of receiver – the buoys float to the surface with the receiver and acoustic release still attached. (Photo: Michele Buckhorn).

2.3 Range Testing

Range testing was performed in November 2008, by deploying a line of receivers, each spaced 30 meters apart, at the SF 10 placement site in San Pablo Bay (Fig. 10). Range testing tags with the same power output to those used on the experimental fish, were deployed at the first receiver and left for 24 hours, after which the entire array was recovered and the data processed.

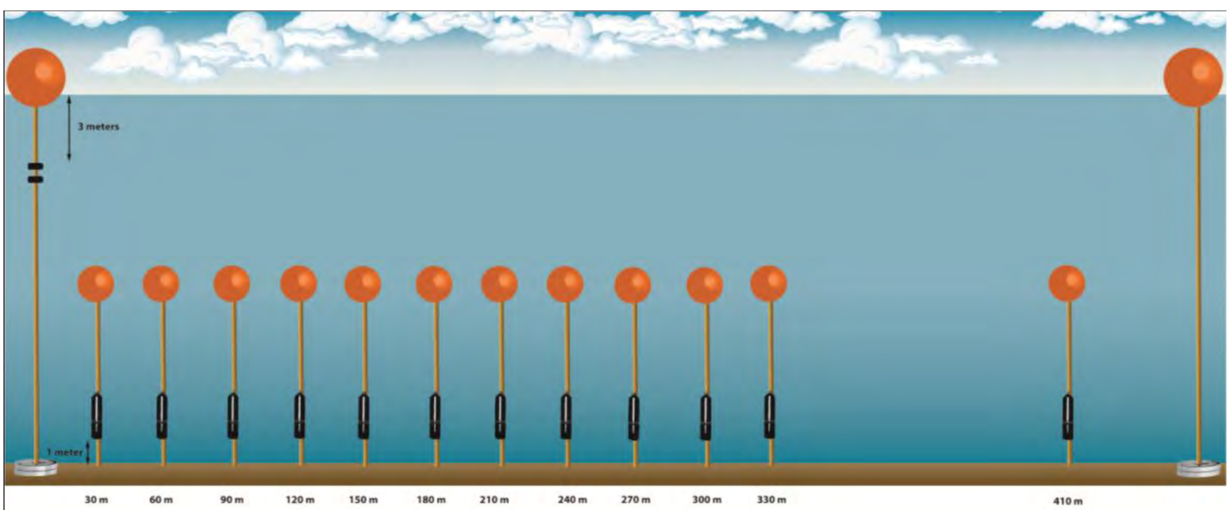

Figure 10. Range test experimental design at SF10 placement site. Receivers are attached to moorings that are weighted down with 4 x 10 lb. weight plates. Receivers are spaced every 30 meters up to 330 meters and then a last receiver at 410 meters. Not to scale.

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As a result of range testing the monitor spacing was determined to be 150 meters (Fig. 11). A detection efficiency of 75% was achieved at a distance of 70-75 meters from the location of the tester tags. The monitor placed at 150 meters malfunctioned and produced no data, indicated by the dashed line. The monitors were spaced every 30 meters extending to 330 meters and one was placed at 410 meters.

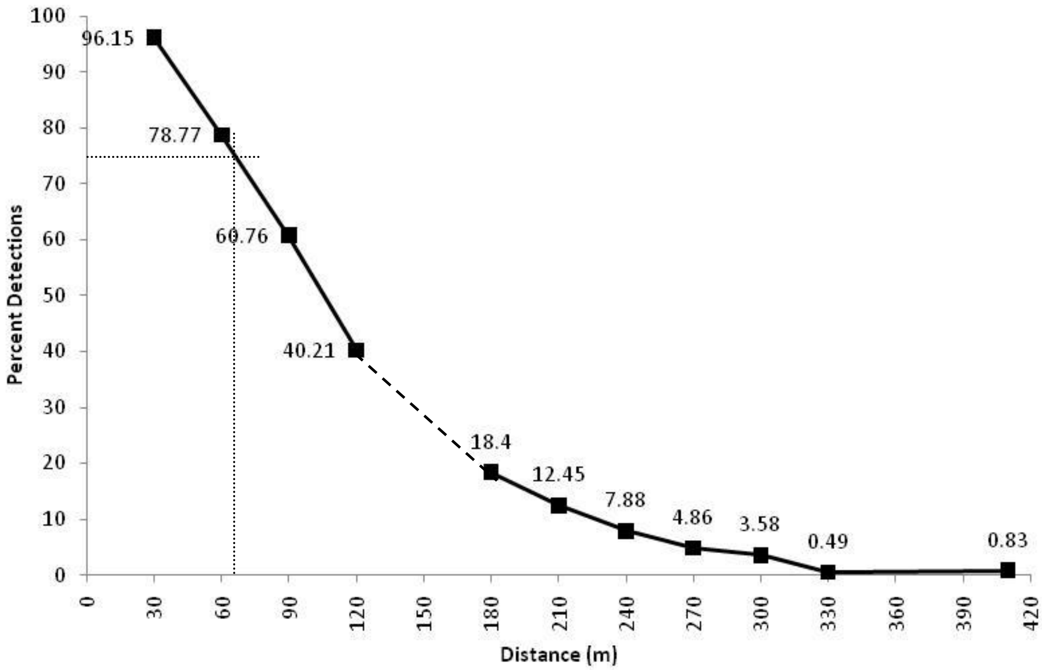

Figure 11. Detection efficiency of VR2W receivers during range tests in San Pablo Bay, November 2008.

2.4 Tagging procedure

A sample size of 500 individuals for each species was determined by using the program MARK to simulate the mortality of batches of fish released at different sites along the Sacramento River, with the objective of obtaining a success rate of 75-100 fish arriving at the Golden Gate (Table 3). Inputs to the model were based on studies of hatchery released smolts from Coleman National Fish Hatchery.

Table 3. Predicted survival (n=100, 500) of salmonid smolts through reaches of the Sacramento River.

Reach	Survival Prob.	n=100	n=500
Feather River to Sacramento	0.9565	96	478
Sacramento to Freeport	1	96	478
Freeport to Rio Vista	0.7273	70	348
Rio Vista to Benicia	0.5	35	174
Benicia to Richmond	0.625	22	109
Richmond to Golden Gate	0.8	17	87

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We obtained 500 steelhead and 500 late-fall run Chinook salmon smolts (Fig. 12) from the US Fish & Wildlife Service, Coleman National Fish Hatchery (Anderson, CA). We chose to conservatively tag fish whose tag-to-body weight was 5% or less, so a cut-off weight was imposed for each species based on the weight of the tag (V7-2L = 1.6 g, V7-4L = 1.84 g), implying that only Chinook salmon greater than 32 g, and steelhead greater than 94 g were tagged.

Figure 12. Late-fall run Chinook salmon smolt (above) and steelhead smolt (below) used in this study in 2010 (Photos: Alex Hearn).

The average tag-to-body weight of Chinook salmon smolts was 2.5% and was 1.5% for steelhead. Fig. 13 shows the size distribution of the salmonids tagged during this study. Steelhead were larger than Chinook salmon but there was no significant different between the two batches for each species (Mann-Whitney Rank Sum Test $P_{LFC} = 0.8$, $P_{STH} = 0.1$; Fig. 12). However, the overall size distribution for each species was significantly larger than that for 2009 (Mann-Whitney Rank Sum Test $P_{LFC} = 0.002$, P_{STH} <0.001).

The fish were anaesthetized with 90 mg/L tricaine methanesulphonate (MS222) in accordance with UC Davis Animal Care Protocol 15486. Once anesthetized, each individual was removed from the solution, photographed, and length, weight and condition were recorded. Fish were then placed ventral-side up on a surgery cradle and kept sedated by flushing a lower concentration of MS222 (30 mg/L) over the gills. A 10-mm incision was made beside the mid-ventral line, ending 3 mm anterior to the pelvic girdle. A sterilized, individually-coded, cylindrical ultrasonic tag was inserted into the peritoneal cavity of the fish and positioned so as to lay just under the incision (Fig. 14). The incision was then closed using two simple interrupted sutures (Supramid, 3-0 extra nylon cable). All fish were placed into a 75 gallon tank to recover from the anesthetic before being moved outside to larger holding tanks, where they were kept under observation before release. No mortalities or tag shedding were observed during this period.

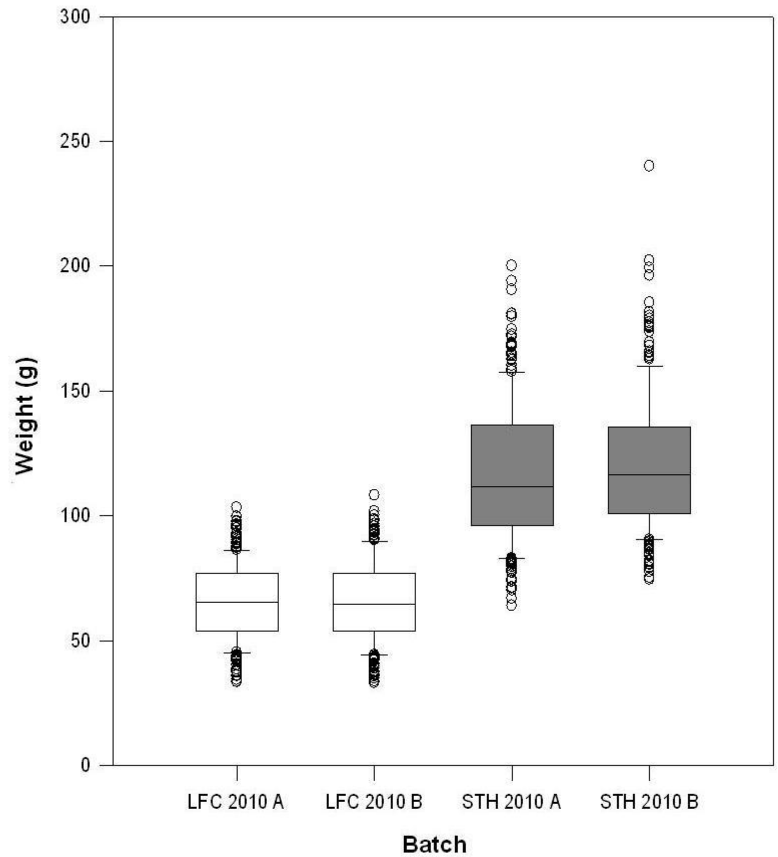

Figure 13. Boxplots (median, quartiles and outliers) of fish weight for each batch of Chinook salmon (LFC) and steelhead (STH) smolts tagged in spring 2010.

The surgeries (defined as the time from which the fish was removed from the anesthetic to the time which it was placed in the recovery tank) averaged 5.5 minutes for Chinook salmon and ranged from 3.0 to 9.6 minutes. The average surgery time for steelhead was 4.8 minutes and ranged from 1.4 to 9.4 minutes. This procedure was repeated so that a total of five hundred Chinook salmon smolts and five hundred steelhead smolts were tagged over a period of two weeks. The vital statistics for each fish such as time and date of tagging and its body mass and fork length were provided to researchers at the Southwest Fisheries Science Center of NMFS in Santa Cruz, California for entry into the CAFTC database.

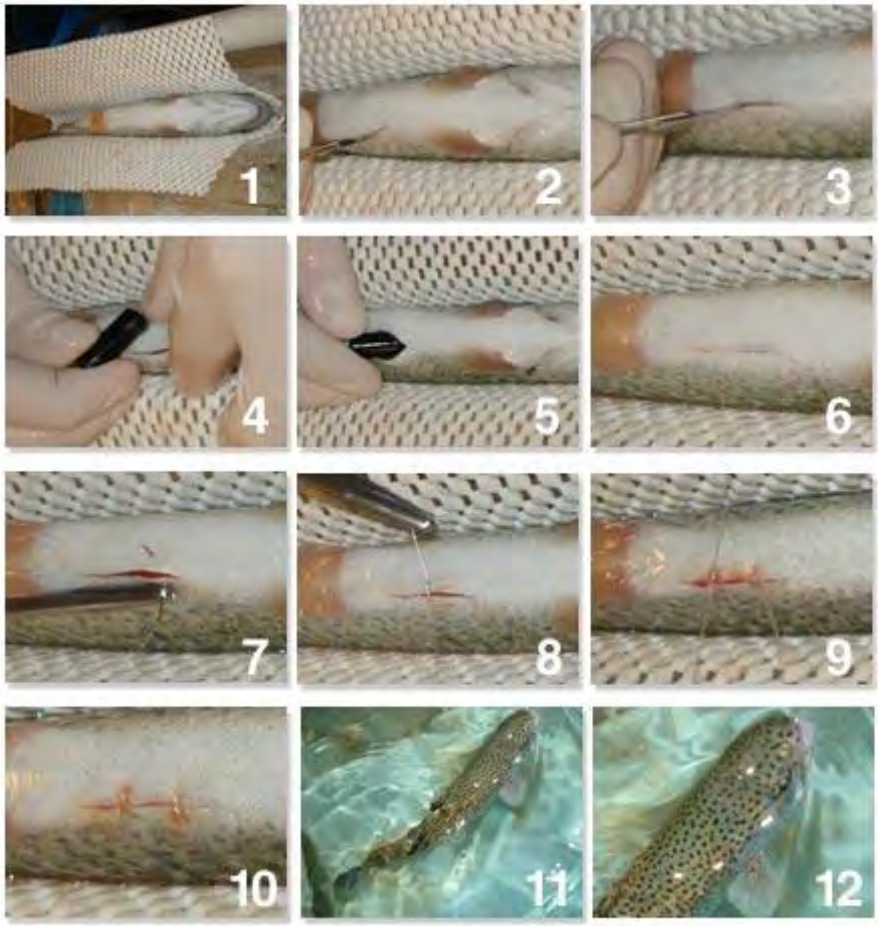

Figure 14. Stages during surgical implantation of tags in salmonid smolts.

2.5 Release Site and Procedure

Fish were released in two batches of 500 fish (250 STH and 250 LFC) on January 30th and on February 5th 2010. Two fish transport tanks, one for each species, were used for transport from UC Davis to the release site at Elkhorn Landing (Fig. 15) on the river above Sacramento (transport time was approximately 30 minutes). Oxygen was pumped from tanks mounted on the truck through hoses to oxygen diffusers placed in the bottom of each tank. Dissolved oxygen and temperature were recorded throughout transport to ensure the fish were healthy upon release. Upon arrival at the release site, the river temperature was taken to ensure the fish were not stressed by a large temperature fluctuation. On both occasions the river temperature was within 2°C of the hauling tanks. The fish were then released into the river after dark to provide relief from predators within the first few hours of acclimatization.

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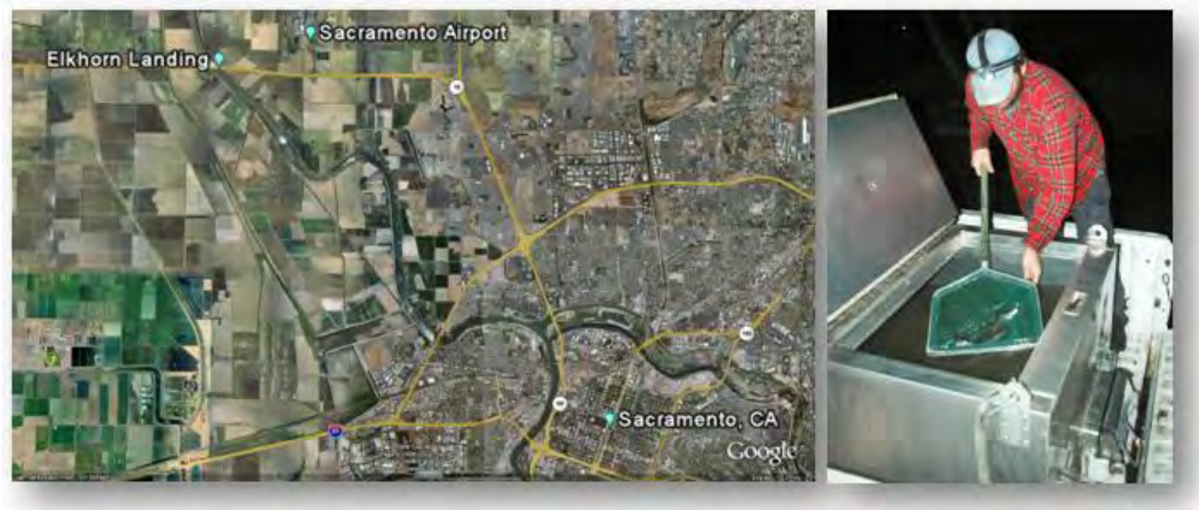

Figure 15. Left: Elkhorn release site in relation to Sacramento Latitude: 36.62266 Longitude:-121.62479 (Image from Google Earth). Right: Fish were released from the transport tanks into the river at night at Elkhorn Boat Landing (Photo: Alex Hearn).

2.6 Environmental Data

We obtained river discharge data (in cubic feet per second [cfs]) at Rio Vista from the California Data Exchange Center website (http://cdec.water.ca.gov/cgi-progs/staSearch). We obtained tidal height (in meters) data at Richmond Station (37.9283, -122.4) in one-hour intervals, from the NOAA website http://tidesandcurrents.noaa.gov/geo.shtml?location=9414863.

Monthly precipitation values were obtained for San Francisco International Airport and Fairfield via the National Climatic Data Center (NCDC) portal at; http://www.ncdc.noaa.gov/oa/ncdc.html. These two sites were chosen as representative examples of precipitation levels throughout coastal and central northern California.

2.7 Data Analysis

2.7.1 Data Quality

We ran several filtering processes on our dataset as a quality control. False detections may occur at receiver sites due to collisions of several tags or interference with real tag detection by ambient processes. We ran a rapid filter for each detection to determine the movement rate between two detections. Where this was greater than 3 ms^{-1} we zoomed in on the tag and examined the entire record for that fish.
We found that the receiver at Richmond 14 displayed a periodic presence of Tag # 33775 throughout the study period and beyond. There is a fallen tag close to this receiver which may be causing it to generate this number on a frequent basis. We found that if we removed all detections of Tag #33775 at this receiver, then the movement patterns of the corresponding fish conformed to the general pattern we have observed in the past for outmigrating salmonid smolts.

We performed a probability analysis, using detection efficiencies from 2009, to determine whether a single detection at Raccoon Strait was false. Tag #34313 was recorded once at Raccoon Strait (Raccoon Middle1), then subsequently at Benicia Bridge. For this to have occurred, the fish must not have been detected at Benicia, Carquinez, the SP Arrays or Richmond Bridge on the way down to Raccoon, then must have not been detected again on the way back up until Benicia. The probability of non-detection (or avoidance) at all these sites was less than 0.0002% so we assumed this to be a false detection.

2.7.2 Successful Migration Rates

We recorded the number of individuals detected at each of the four cross-section arrays throughout the study system – Benicia Bridge represented the start of the study area, Carquinez Bridge represented entry to San Pablo Bay, Richmond Bridge represented entry to Central San Francisco Bay, and the Golden Gate represented exit of the study area into the marine environment. The proportion of smolts surviving to a particular cross section array was calculated as *the sum of all individuals detected at that array or below*. The detection efficiency of each array was calculated by *dividing the number of individuals detected at that array by the number of individuals detected at that array or below*. Successful migration was expressed as the numbers of individuals surviving through each cross-section array as a proportion of the number originally released at Elkhorn Landing, and also as a proportion of those entering the study system at Benicia. The migration success through each particular reach was expressed as a function of the migration success through the previous reach.

2.7.3 Dispersal Patterns

We analyzed how the release batches became dispersed throughout the watershed as they moved downstream. We used the first detection of fish at each of the following cross-section bridge arrays: Benicia, Carquinez, Richmond-San Rafael and the Golden Gate. We plotted the cumulative number of fish which passed through each array each day.

We calculated a group cohesion index at each cross section array by calculating the straight line slope of the cumulative percentage (using the 25-75 % quartiles) of fish reaching the array by day since release. Thus, were the entire batch of fish to reach Benicia Bridge in the same day, the group cohesion index would be 100, and the greater number of days over which the batch arrived, the lower the value would be.

2.7.4 Transit Times and Rates

The transit rate (expressed as "meters per second") of a fish through a particular reach was estimated to be the time elapsed from the first detection at the start of a reach, to the last detection at the end of the reach (the "transit time"), divided by the distance covered and expressed in meters per second. As this definition was different from the analysis carried out in previous years (Chapman *et al.,* 2009), we also re-analyzed the data from 2009 for reasons of comparison.

For overall transit times over the study area, we used all fish which were detected at both Benicia Bridge and the Golden Gate. Transit time was calculated as the time interval between the first detection at Benicia and the last detection at the Golden Gate. Rates were tested for normality and compared using appropriate statistical methods (Mann-Whitney Rank Sum Tests were used where data was non-normal) and post-hoc testing.

We compared the transit times (and rates) for each river reach between the two species, using all individuals which were detected at the start and end array of each reach. We used non-parametric statistical methods to compare between years.

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We selected all those fish which were detected at each of the cross section arrays to determine whether the transit rates of individuals changed as they moved downstream. A pairwise Kruskal-Wallis test with post-hoc was carried out to determine whether differences were significant.

The instantaneous rate of transit through San Pablo Bay was estimated for those fish which made a single downstream movement through the study array. We used the time elapsed between the last detection at SP Control Array and the first detection at SP Array 1, and that between the last detection at SP Array 1 and the first detection at SP Array 2, to determine instant transit rates, assuming a distance of 1500 m between each detection array. These rates were then compared to the overall rate of transit through San Pablo Bay, assuming a distance of 26751 m, and using the time elapsed between the last detection at Carquinez Bridge and the first detection at Richmond Bridge. Each dataset was tested for normality using the Komolgorov-Smirnov test. Where datasets were found to be normally distributed, a One Way Repeated Measures ANOVA was used with the Holm-Sidak post-hoc test to determine differences between overall transit rates and instantaneous rates through the two array sections. Where data was non-normal, the Friedman Repeated Measures Analysis of Variance on Ranks was carried out.

2.7.5 Migratory Pathways

We compiled a list of the number of fish detected at each site and determined potential pathways through the system based on their presence or absence at specific areas. This was carried out separately for each species and repeated for the data in 2009.

We analyzed the extent of upstream movements, or "tidal sloshing" by determining the number of occasions that each individual increased its distance from the Golden Gate. The data were analyzed in terms of overall upstream movements, number of upstream movements in each particular reach, and by receiver site.

Each species was grouped by whether or not they successfully migrated to the Golden Gate Bridge. The number of upstream movements to which each fish was subjected was tested for normality and subsequently compared using a Mann Whitney Rank Sum Test to determine whether successful outmigration was affected by the number of upstream movements.

Tidal height information for Mare Island, Richmond Point and the Golden Gate was compared with the number of fish completing an upstream or downstream movement in Carquinez Strait, San Pablo Bay and Central San Francisco Bay respectively. We presented examples of individual movements of successful and unsuccessful fish in conjunction with tidal height.

2.7.6 Habitat Preference

We deployed an array of eight receivers on the flats in San Pablo Bay, and another similar array across the channel upstream from the SF10 Placement Site, to compare the use of the channel with that of the flats. We compared the number of fish detected at each site using a T-test (Chinook salmon) and a Mann-Whitney Rank Sum Test (steelhead). We also showed the number of fish detected at each array by day throughout the study period. Circular statistics (Rao's spacing Test) were used to determine whether there was a diel pattern to the use of each array.

To determine whether there was a relationship between the depth of the water column and the number of fish passing through each receiver station, we measured the water depth at each receiver station at the Bay Bridge and Richmond Bridge. We plotted the number of fish detected across each cross-section array. A linear regression was fitted to the number of fish detected for each depth and tested for significance.

2.7.7 Residency and Exposure Times

We calculated the number of fish detected at each potentially dredged site (marinas and channels). As an initial measure of use, we also present the total number of detections at each site. We carried out this analysis for both 2009 and 2010 data, for comparison.

Exposure time at each site was defined as the sum of all the visit times. Each visit time was calculated as the time period between the first and the last detection for that visit. Based on our knowledge of movement and detection rates, we assigned a *cut-off time interval of five minutes* between detections. Any detection at a given site which occurred more than five minutes after the previous detection at that site was considered to be the start of a new visit. Single detections at a site were assigned a *nominal exposure time of one minute*. We plotted the total exposure time at all dredged sites for each individual.

At the Alcatraz sites, we applied the same rules to determine exposure time for individuals at Alcatraz Control Site and Alcatraz SF11. Data were tested for normality, and analyzed using non-parametric statistical methods (Mann-Whitney Rank Sum Test).

At the San Pablo dredge material placement site, we compared the exposure time of fish over the area potentially influenced by dredged material placement activities with that of an adjacent control area (Fig. 16).

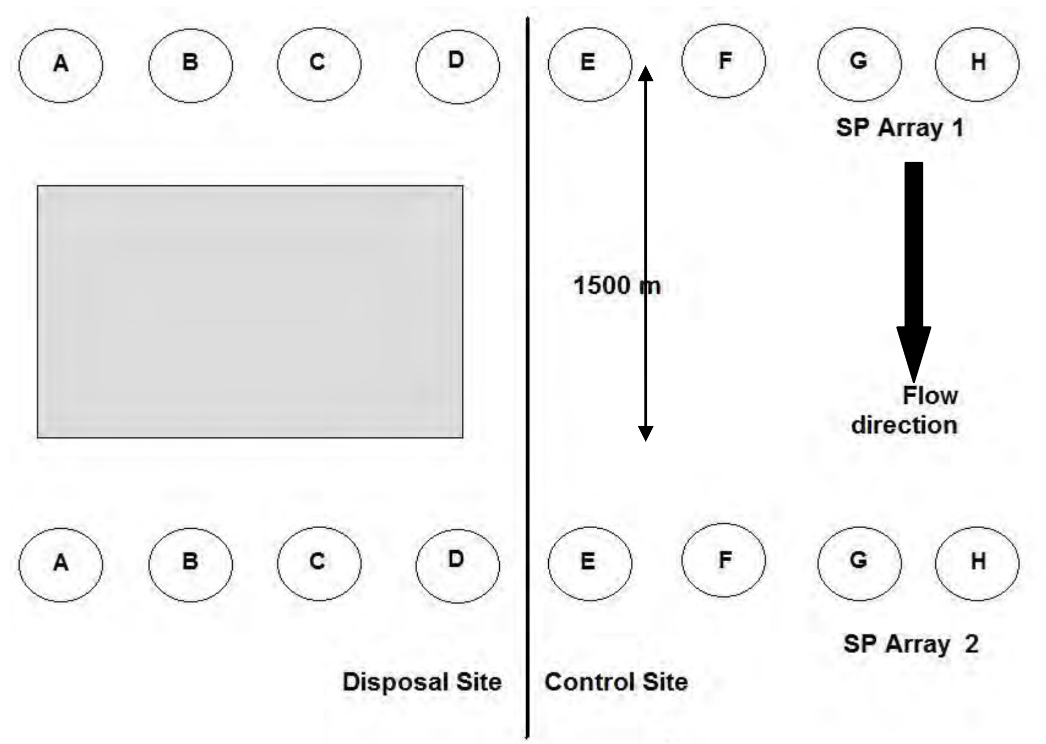

Figure 16. Receivers used to determine exposure time of salmonids smolts to San Pablo Bay Disposal Site (SP Array 1 & 2, receivers A-D) and adjacent control site (SP Array 1 & 2, receivers E-H).

We grouped all the detections of fish at SP Array 1 and 2, receivers A-D into one site (Disposal Site) and all the detections of fish at SP Array 1 and 2, receivers E-H into another site (Control Site). As the sites of interest in this case are surrounded by receivers rather than being point sites (see prior analysis of dredge sites), we calculated exposure time as the sum of consecutive detections at each of the two sites, *regardless of the interval between successive detections.* This was based on the precautionary assumption that any period of time between consecutive detections was spent within the area of influence of the Disposal or Control site. Where single detections occurred, we assigned a value equal to the mean blanking interval for the tag in question (for Chinook salmon: 30 seconds; for steelhead: one minute). We used a test of matched pairs to determine whether the salmonid smolts spent more time at one of the sites. To compare exposure time between species and years we used a Friedman Repeated Measures Analysis of Variance on Ranks Test.

2.7.8 Green Sturgeon Movements

The California Fish Tracking Consortium database provided information on the presence of green sturgeon throughout the Bay Area in 2009/10 and for the period of time coinciding with the movement of the salmonid smolts from this study through the area (March to June 2009). We determined the relationship between channel depth and the number of fish at the Bay Bridge and Richmond Bridge cross section arrays as described in section 2.7.6. We calculated the proportion of these which were detected at dredged sites and dredge placement sites, and estimated the exposure time at these sites using the same methods outlined in section 2.7.7. In addition, we grouped all green sturgeon detections at key sites between the Golden Gate Bridge and Freeport (near Sacramento) from 2005-2009 and plotted the number of fish present at each site during each season (spring, summer, fall and winter).

3 Results

3.1 The Physical Environment

The precipitation amounts between this study year and that of the previous year vary considerably (Fig. 17). Whereas the winter rains (January and February) were of similar amounts in both years, the fall 2009 and spring 2010 rains more than doubled the amounts for the previous years. The dry season has remained similar over the past three summers, with little to no precipitation between the months of June through September.

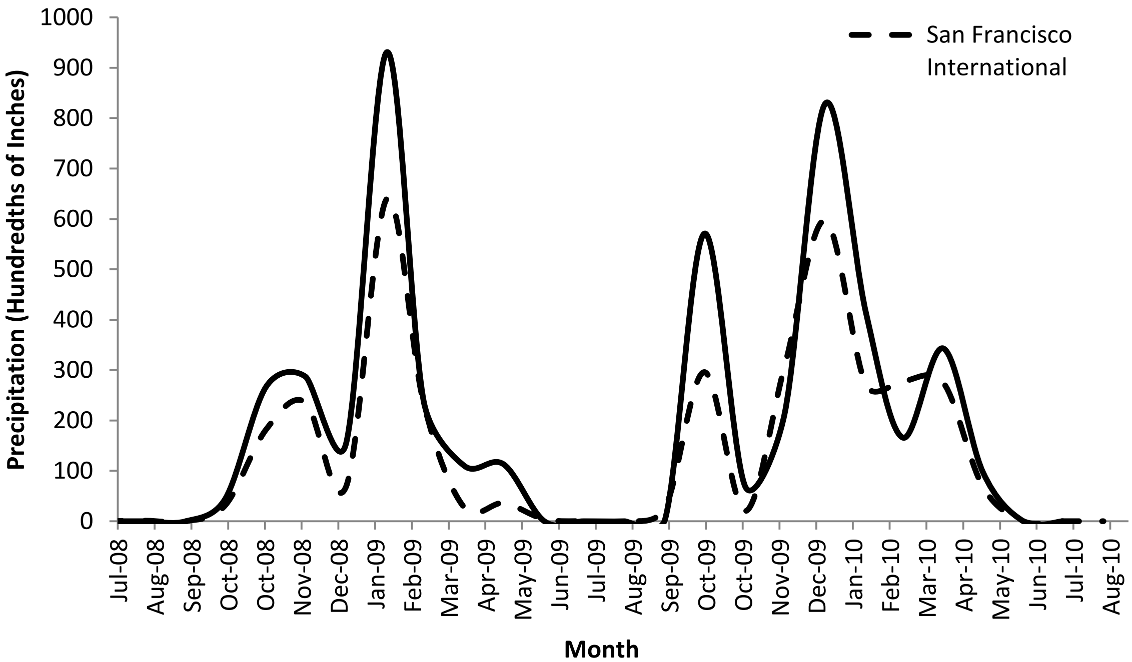

Figure 17. Total monthly precipitation (in hundredths of inches) for San Francisco and Fairfield (Sacramento River Delta) from January 2009 to July 2010 (Source: http://www.ncdc.noaa.gov/oa/ncdc.html).

3.2 Salmonid Smolt Migration Success

Fewer fish of either species successfully migrated to Benicia Bridge (the start of the study area) in 2010, compared with 2009 (Table 4). However, more individuals of each species actually migrated successfully to the Golden Gate in 2010. This implies that, assuming that detection rates remained constant, the reach-specific mortality was inverted between years: low above Benicia Bridge yet high below in 2009, and high above Benicia Bridge yet lower below in 2010. Mortality in San Pablo Bay was particularly low for steelhead, with only eight individuals not reaching the Richmond Bridge in 2010, compared to 61 in 2009. Similarly, 106 Chinook salmon disappeared in San Pablo Bay in 2009, compared to only half that number in 2010.

Table 4. Numbers of salmonid smolts detected at each bridge array and estimated detection efficiencies, compared with data from 2009 (in grey). Figures for Golden Gate in italics are estimates based on fish detected at Point Reyes.

	Success to Site 2010	Success 2009	Actual Detections	From Benicia %	From Release Site %	Reach Specific %	Reach Specific % 2009	Detection Prob. %
Steelhead								
Benicia	107	238	97		21.4	21.4	47.4	90.7
Carquinez	99	213	63	92.5	19.8	92.5	89.5	63.6
Richmond	91	152	84	85.0	18.2	91.9	71.4	92.3
Golden Gate	69	64	65	64.5	13.8	75.8	42.1	94.2
Chinook salmon								
Benicia	204	309	185		40.8	40.8	61.8	90.7
Carquinez	193	270	116	94.6	38.6	94.6	87.4	60.1
Richmond	151	164	126	74.0	30.2	78.2	60.7	83.4
Golden Gate	118	89	108	57.8	23.6	78.1	54.3	91.5

3.3 Dispersal Patterns

The cohesion of the release groups was similar between batches but varied between species (Figure 18). Chinook salmon moved through the river and delta with a cohesion index (CI), which refers to the number of fish reaching a point per day, of 6.7 and 6.1 for each batch respectively, and generally maintained a similar level of group cohesion until the Golden Gate. In contrast, steelhead behaved less as a group (CI = 1.3 and 1.6 for each batch), and maintained a similar CI throughout the system.

In comparison with 2009, the first batch of Chinook salmon behaved in a similar fashion to the two batches of fish released in 2010, however the second batch was more cohesive (CI = 10.6 at Benicia Bridge, and consistently higher than the other batches throughout). In contrast, the first batch of steelhead in 2009 was more cohesive (CI = 4.1) than the second (CI = 2.1), and both batches were more cohesive than those of 2010 (Figure 19).

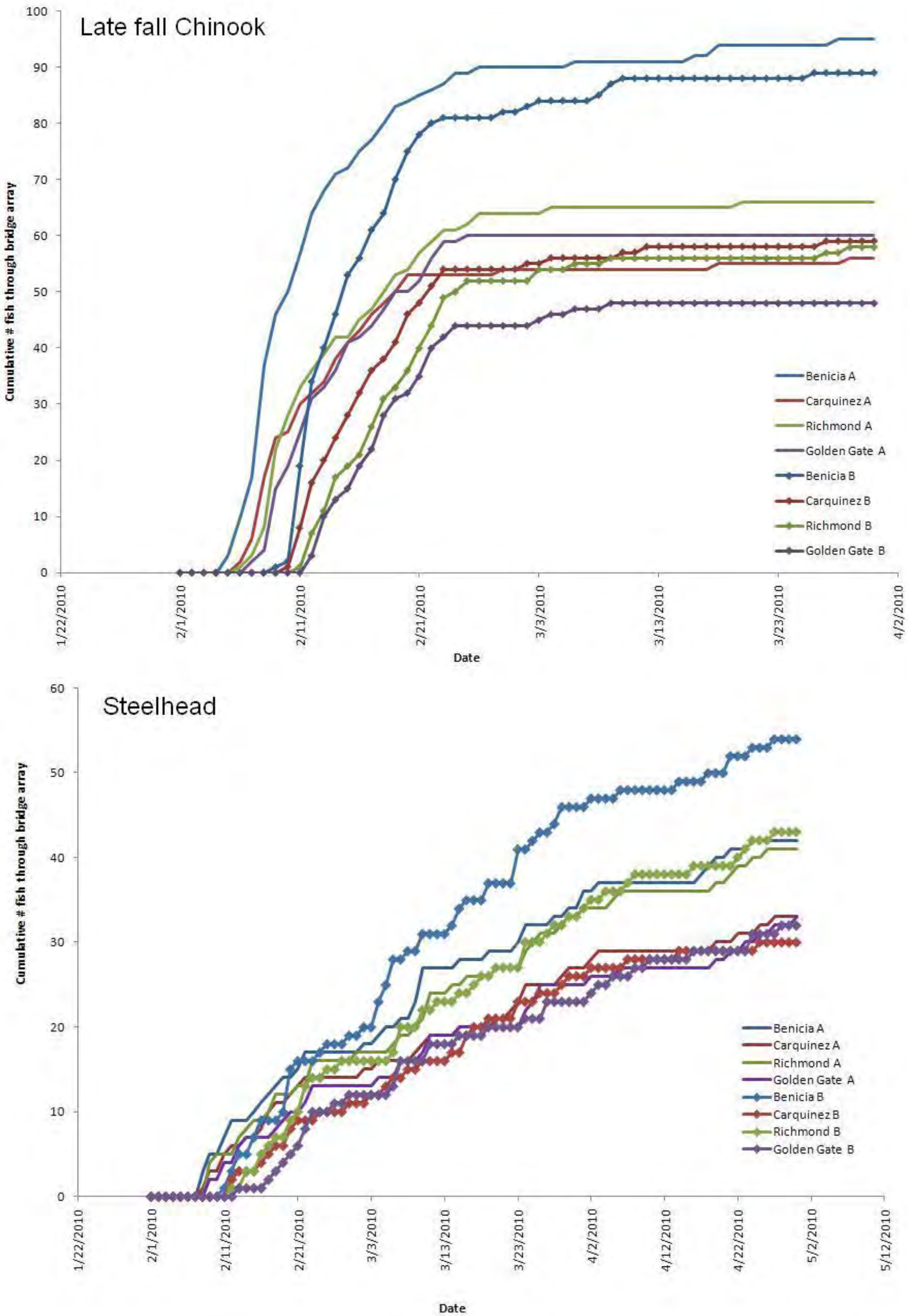

Figure 18. Plots of the cumulative number of fish by date, detected at each major cross section array (Benicia, Carquinez, Richmond and Golden Gate Bridges) for each batch of Chinook salmon (above) and steelhead (below).

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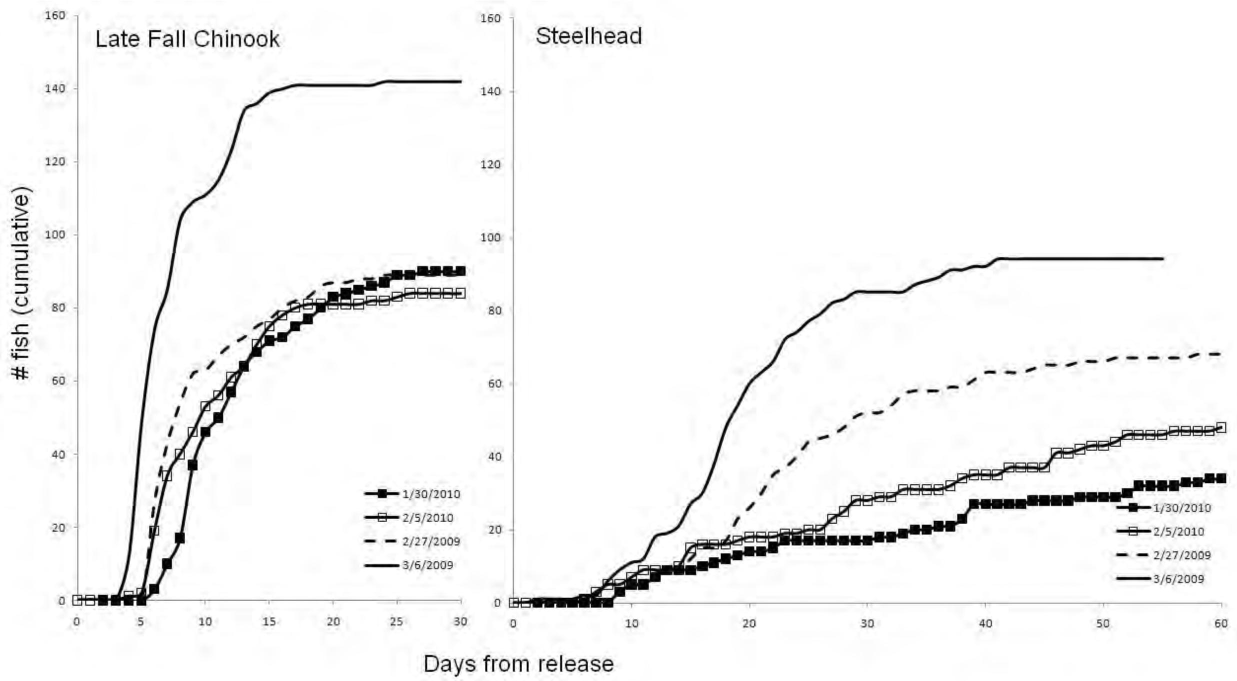

Figure 19. Plots of the cumulative number of fish detected at the start of the study area (Benicia Bridge) as a function of the number of days since release, for each batch of Chinook salmon (left) and steelhead (right) in 2009 and 2010. Legend displays actual release date.

3.4 Salmonid Smolt Transit Time

3.4.1 Reach Specific Transit Time

The total transit time through the study area, from the first detection at Benicia Bridge to the last detection at the Golden Gate, was estimated for all those fish which were detected at both these locations (n = 98 LFC, 59 STH). No significant differences were found between species or in comparison with the behavior displayed by fish released in 2009 (Figure 20). Most fish had arrived at the Golden Gate less than 6 days after entering the study area (median = 2.7 days).

For both species, there was a tendency for transit rates to increase downstream (Figure 21) yet in the case of Steelhead, transit rate changed significantly only between the Ben-Car and Rich-GG reaches (Mann Whitney Rank Sum Test, P = 0.009). Steelhead moved through the study area in a similar fashion in both years, despite the different environmental conditions between years, the only significant difference in reaches was that fish moved faster through Central San Francisco Bay in 2009 (median: 0.379 ms^{-1}) as opposed to 2010 (median: 0.25 ms^{-1}) (Mann Whitney Rank Sum Test, P=0.092). In the case of Chinook salmon, transit rate increased significantly between each successive reach (Mann Whitney Rank Sum Test, P <0.001), and in each reach was similar to rates displayed in 2009 (Mann Whitney Rank Sum Test, Ben-Car: P = 0.239, Car-Rich: P=0.689, Rich-GG: P=0.138). Transit rates through each reach were non-normally distributed and, with few exceptions, for both species, were less than 0.5 ms^{-1} (Figures 22-24).

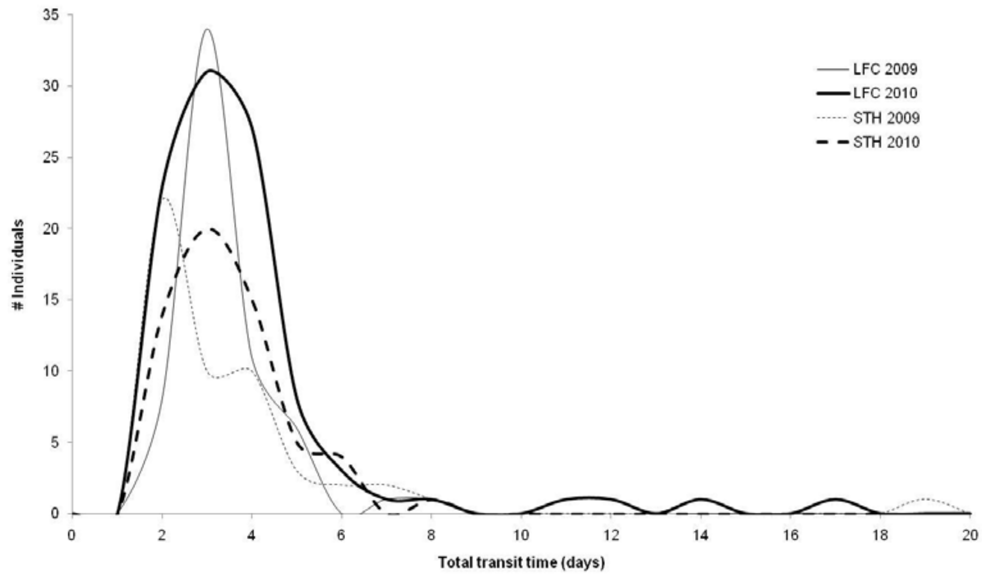

Figure 20. Total transit time (in days) for Chinook salmon (LFC) and steelhead (STH) from Benicia Bridge to the Golden Gate in 2009 and 2010.

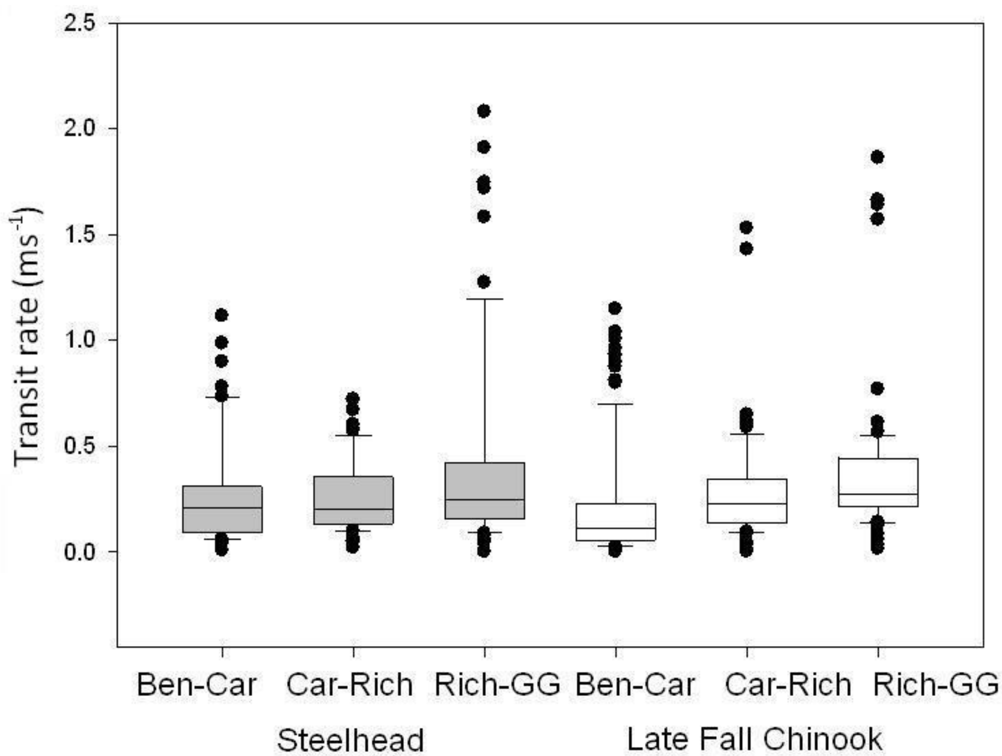

Figure 21. Transit rate of steelhead (grey) and Chinook salmon (white) in three sections of the Sacramento River system: Benicia (BEN) –Carquinez (CAR), Carquinez (CAR)–Richmond (Rich), Richmond (Rich) –Golden Gate (GG). The boxes display the upper and lower quartiles, the line denotes the median, caps at each end of the box delimit extreme values; outliers are displayed as "●".

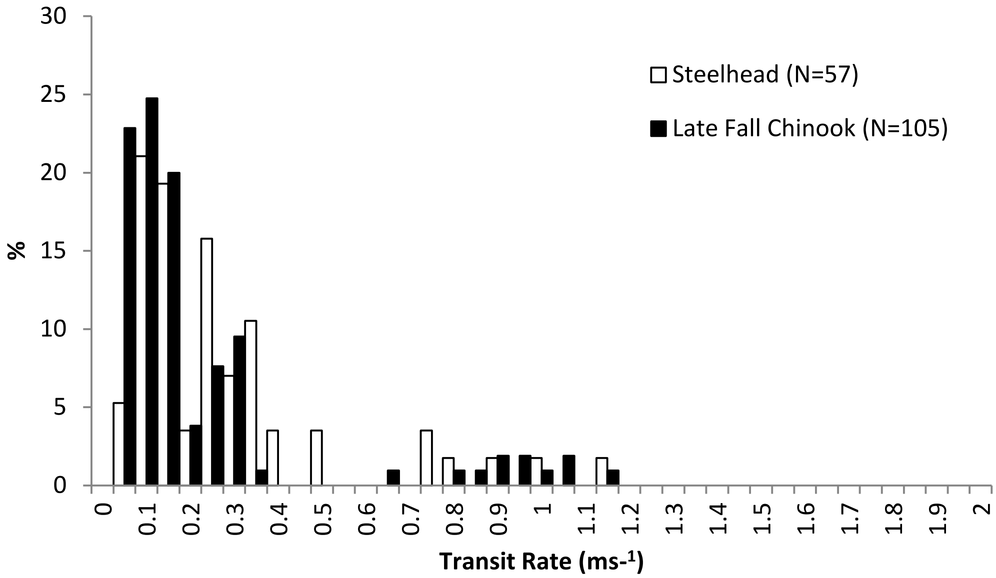

Figure 22. Transit rates (ms^{-1}) for Chinook salmon (filled bars) and steelhead (white bars) from Benicia Bridge to Carquinez Bridge, 2010.

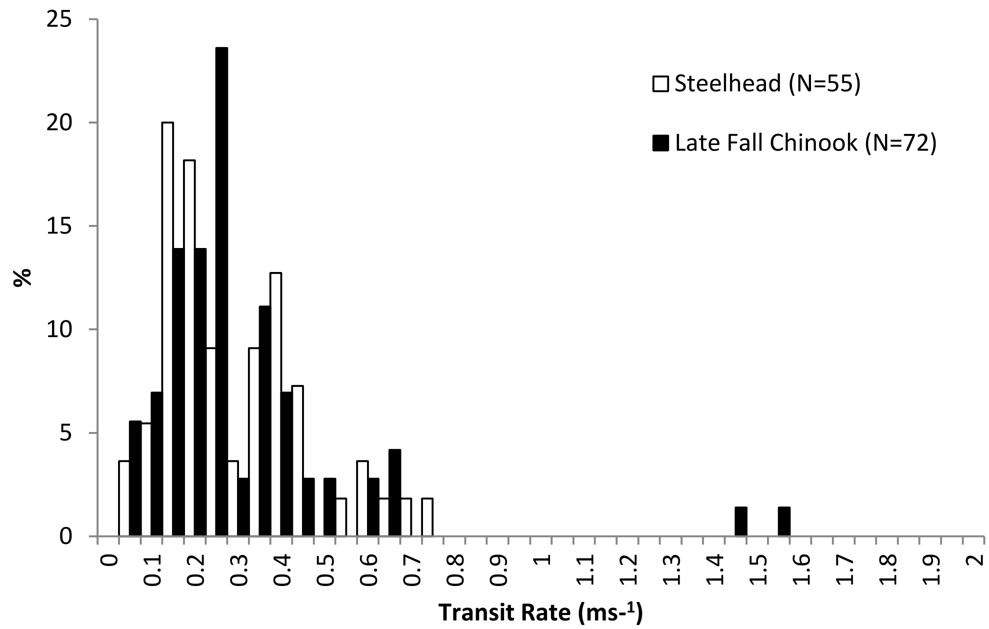

Figure 23. Transit rates (ms^{-1}) for Chinook salmon (filled bars) and steelhead (white bars) from Carquinez Bridge to Richmond Bridge, 2010.

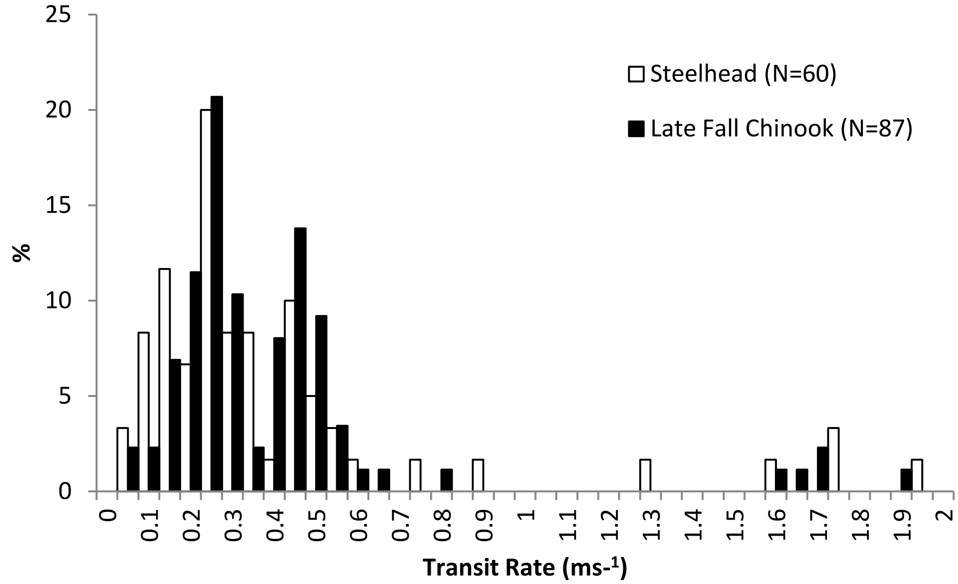

Figure 24. Transit rates (ms-1) for Chinook salmon (filled bars) and steelhead (white bars) from Richmond Bridge to the Golden Gate, 2010.

Forty five Chinook salmon and 33 steelhead were detected at each of the four cross section bridge arrays, and these were analyzed to determine whether individual fish changed their rate of movement as they moved downstream (Tables 5 and 6). The transit rates were non-normally distributed, with the exception of the Chinook salmon transiting through the Central San Francisco Bay (Kolmogorov-Smirnov, P=0.06). In the case of Chinook salmon (Table 5), the change in speed was more evident, with significant increases between Ben-Car and the lower two reaches, but not between Car-Rich and Rich-GG (pairwise Kruskal-Wallis, H=31.997, 2 df, P=<0.001, Posthoc Tukey: P<0.05). In the case of steelhead (Table 6), a significant increase in speed was found between the Ben-Car and the Rich-GG reaches (pairwise Kruskal-Wallis, H=8.011, 2 df, P=0.018, Posthoc Tukey: P<0.05) but not between other reaches, suggesting that the increase in speed is gradual.

Table 5. Transit time (in days) and rate (ms^{-1}) of individual Chinook salmon which were detected through each section of the river system.

Tag ID	Benicia-Carquinez 10.4 km		Carquinez-Richmond 26.6 km		Richmond-Golden Gate 17.72 km	
	Transit (days)	Transit rate (ms^{-1})	Transit (days)	Transit rate (ms^{-1})	Transit (days)	Transit rate (ms^{-1})
33775	1.53	0.08	1.24	0.25	1.46	0.14
33802	1.51	0.08	0.86	0.36	0.95	0.22
33805	1.73	0.07	0.75	0.41	0.41	0.51
33815	0.96	0.13	1.82	0.17	0.50	0.41
33834	0.85	0.14	0.20	1.53	0.73	0.28
33835	0.13	0.93	0.85	0.36	12.90	0.02
33865	4.44	0.03	3.28	0.09	0.50	0.41

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Table 5 cont.

33867	0.12	1.04	2.41	0.13	0.49	0.42
33869	0.86	0.14	0.22	1.43	1.31	0.16
33879	0.54	0.22	0.64	0.48	0.90	0.23
33891	3.03	0.04	2.00	0.15	1.04	0.20
33895	0.92	0.13	1.47	0.21	1.28	0.16
33896	1.59	0.08	1.58	0.20	1.26	0.16
33906	4.59	0.03	3.39	0.09	0.55	0.37
33930	6.06	0.02	0.97	0.32	0.53	0.39
33939	0.53	0.23	0.89	0.34	0.46	0.44
33941	0.47	0.26	0.51	0.61	3.49	0.06
33955	0.58	0.21	0.87	0.35	0.83	0.25
33956	1.62	0.07	1.50	0.21	0.33	0.61
33963	9.85	0.01	1.88	0.16	5.78	0.04
33965	1.81	0.07	1.00	0.31	0.72	0.29
33969	1.08	0.11	0.90	0.34	0.43	0.48
33973	0.41	0.29	0.52	0.59	0.43	0.47
33991	0.41	0.30	9.08	0.03	1.06	0.19
33995	0.15	0.80	2.88	0.11	0.43	0.47
34003	0.88	0.14	3.12	0.10	0.52	0.39
34005	1.94	0.06	2.33	0.13	0.89	0.23
34012	1.96	0.06	1.49	0.21	0.45	0.46
34016	3.44	0.03	1.45	0.21	0.36	0.57
34017	1.23	0.10	1.36	0.23	0.49	0.42
34037	1.93	0.06	0.92	0.33	0.85	0.24
34044	9.40	0.01	1.36	0.23	0.81	0.25
34049	1.38	0.09	1.24	0.25	0.75	0.27
34061	2.44	0.05	2.80	0.11	0.73	0.28
34091	1.70	0.07	1.32	0.23	0.53	0.39
34094	0.41	0.29	0.63	0.49	0.76	0.27
34112	0.84	0.14	0.99	0.31	1.36	0.15
34117	1.86	0.06	1.95	0.16	0.89	0.23
34119	1.62	0.07	0.68	0.45	1.34	0.15
34127	0.57	0.21	1.71	0.18	1.34	0.15
34150	2.45	0.05	0.47	0.65	0.59	0.35
34167	0.80	0.15	1.85	0.17	0.88	0.23
34176	1.20	0.10	0.50	0.62	0.84	0.24
34179	0.36	0.33	1.32	0.23	0.85	0.24
34259	2.03	0.06	0.83	0.37	0.51	0.40
Median	**1.38**	**0.09**	**1.32**	**0.23**	**0.76**	**0.27**

Table 6. Transit time (in days) and rate (ms^{-1}) of individual steelhead which were detected through each section of the river system.

Tag ID	Benicia-Carquinez 10.4 km		Carquinez-Richmond 26.6 km		Richmond-Golden Gate 17.72 km	
	Transit (days)	Transit rate (ms^{-1})	Transit (days)	Transit rate (ms^{-1})	Transit (days)	Transit rate (ms^{-1})
34262	0.50	0.24	0.53	0.58	0.85	0.24
34280	1.75	0.07	3.09	0.10	0.90	0.23
34282	0.95	0.13	0.88	0.35	1.63	0.13
34313	1.37	0.09	0.97	0.32	0.49	0.42
34318	0.49	0.25	0.86	0.36	0.48	0.43
34370	0.86	0.14	2.30	0.13	1.02	0.20
34373	0.83	0.14	1.83	0.17	0.81	0.25
34377	0.89	0.14	1.56	0.20	0.38	0.54
34386	2.80	0.04	1.71	0.18	0.59	0.35
34390	0.58	0.21	2.02	0.15	1.31	0.16
34394	0.55	0.22	1.21	0.25	0.93	0.22
34406	0.90	0.13	2.00	0.15	4.53	0.05
34413	0.70	0.17	1.64	0.19	0.57	0.36
34435	0.33	0.37	4.57	0.07	0.38	0.54
34445	0.47	0.26	1.44	0.21	0.94	0.22
34461	0.56	0.22	2.50	0.12	0.87	0.24
34490	0.16	0.73	2.93	0.11	0.50	0.41
34503	1.46	0.08	0.92	0.33	2.60	0.08
34514	0.39	0.31	1.99	0.15	0.79	0.26
34516	0.53	0.23	0.46	0.67	1.41	0.14
34570	0.11	1.12	0.87	0.35	0.96	0.21
34584	1.68	0.07	2.12	0.14	1.41	0.15
34585	2.81	0.04	1.68	0.18	1.14	0.18
34595	1.26	0.10	2.01	0.15	1.47	0.14
34613	1.56	0.08	0.77	0.40	0.49	0.42
34638	1.97	0.06	1.40	0.22	0.29	0.70
34646	0.93	0.13	2.56	0.12	2.35	0.09
34658	0.84	0.14	6.22	0.05	1.74	0.12
34669	0.43	0.28	0.43	0.72	0.86	0.24
34673	0.56	0.21	1.50	0.21	0.41	0.50
34717	1.88	0.06	1.27	0.24	0.65	0.32
34739	0.89	0.14	0.98	0.32	0.64	0.32
34762	2.01	0.06	3.03	0.10	0.93	0.22
Median	**0.86**	**0.14**	**1.64**	**0.19**	**0.87**	**0.24**

3.4.1 Instantaneous Rates of Transit

Twenty six Chinook salmon and 14 steelhead were detected at both Carquinez and Richmond Bridges, and also detected going through each line (Control, 1 and 2) of the study array. The average transit rate through the study area was roughly four times faster than the overall rate through San Pablo Bay, for both species (Tables 7 and 8). Significant differences were found in the rates for both species (Chinook salmon, Friedman Repeated Measures ANOVA on Ranks P < 0.001; steelhead: One Way Repeated ANOVA P <0.001). Post hoc testing determined that the differences were between the Carquinez-Richmond reach and the two arrays, but that there were not significant differences among the two arrays.

Table 7. Instantaneous transit rates (ms^{-1}) of Chinook salmon through sections of the San Pablo Array compared with overall transit times from Carquinez to Richmond Bridge

Tag ID	Carquinez-Richmond	SP Control - SP Array 1	SP Array 1- SP Array 2
33791	0.363	1.674	1.911
33805	1.236	2.322	2.267
33815	0.172	1.665	1.685
33834	1.742	2.642	2.352
33891	0.218	1.134	0.364
33895	0.261	1.773	2.273
33943	0.317	2.226	2.542
33906	0.233	1.814	2.776
33939	0.348	1.856	1.974
33969	0.350	2.174	1.949
33991	0.034	1.151	1.324
34012	0.208	0.944	1.417
34016	0.302	1.884	0.439
34028	0.242	2.298	0.265
34049	1.341	2.134	1.829
34061	0.451	1.288	1.569
34070	0.152	1.979	1.634
34112	1.895	2.988	2.287
34117	0.271	1.791	1.453
34150	0.687	1.667	0.736
34214	0.171	2.216	0.827
34235	0.230	1.682	0.837
34259	0.385	3.755	1.293
34017	0.286	0.763	0.499
34109	0.204	0.758	1.115
34119	0.478	0.866	1.382
Average transit rate	**0.484**	**1.825**	**1.500**

Table 8. Instantaneous transit rates (ms^{-1}) of steelhead through sections of the San Pablo Array compared with overall transit times from Carquinez to Richmond Bridge

Tag ID	Carquinez-Richmond	SP Control - SP Array 1	SP Array 1-SP Array 2
34300	0.245	1.899	0.371
34313	0.725	2.773	1.499
34318	0.659	1.665	2.595
34370	0.186	1.636	1.667
34373	0.242	1.330	1.328
34396	0.497	2.269	3.550
34445	0.217	1.515	1.193
34595	0.789	1.816	2.836
34613	0.418	1.342	1.379
34625	0.789	2.370	2.419
34675	0.313	1.728	1.652
34709	0.700	2.183	1.953
34717	0.345	1.953	3.589
34739	1.636	2.742	2.385
Average transit rate	**0.554**	**1.944**	**2.030**

3.5 Migratory Pathways

3.5.1 Potential Routes

In 2009, 14% of the Chinook salmon (LFC) reaching the start of the study area at Benicia Bridge, did not subsequently reach Carquinez Bridge, compared to only 5% in 2010. The majority of fish in the study areas moved through the system without straying up tributaries or into marinas along the shores. Those fish which did move up the Petaluma River or Mare Island Strait in most cases subsequently returned to the main estuary and did not appear to be affected in terms of their likelihood of successfully reaching the Golden Gate. In 2009, 12 LFC moved up Mare Island Strait, eight of which returned downstream and were detected at the San Pablo Bay study arrays, and one eventually reached the Golden Gate (Fig. 26). In 2010, 26 LFC moved up Mare Island Strait, all but one of which returned to the main estuary (Fig. 27). Eighteen of these fish were later detected at the Golden Gate. In 2009, five LFC moved up the Petaluma River, of which three returned and one arrived at the Golden Gate. In 2010 only one LFC was detected here, but it also migrated successfully to the Golden Gate and was subsequently detected at the ocean array at Point Reyes.

In 2009, 45 LFC (17% of the fish present) migrated successfully through San Pablo Bay without swimming through the buoys or study arrays, and a similar proportion (12%, 24 individuals) behaved similarly in 2010. The presence of the Flats Array in 2010 helps elucidate some of the pathways of fish outside the main channel, and shows how fish detected at this array were often also detected at the G3 and G5 channel markers but that in most cases they returned to the main channel.

No LFC were detected at marina sites bordering San Pablo Bay (San Rafael Canal and Larkspur Ferry Terminal), and only one fish was detected at a marina site in the central bay. This fish was detected in 2009 at Emeryville and later at the Bay Bridge where its signal was lost.

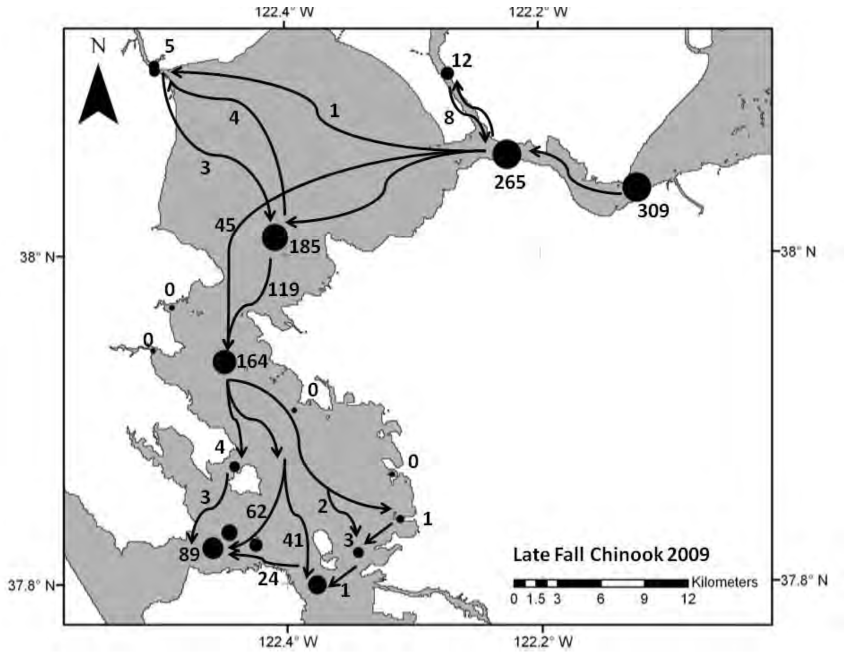

Figure 26. Movement patterns by outmigrating Chinook salmon in San Francisco Bay Estuary in 2009. Black dots refer to receiver sites or arrays, and are sized relative to the number of fish detected at each site (numbers also shown). Note that the lines portray movements between sites, not actual pathways.

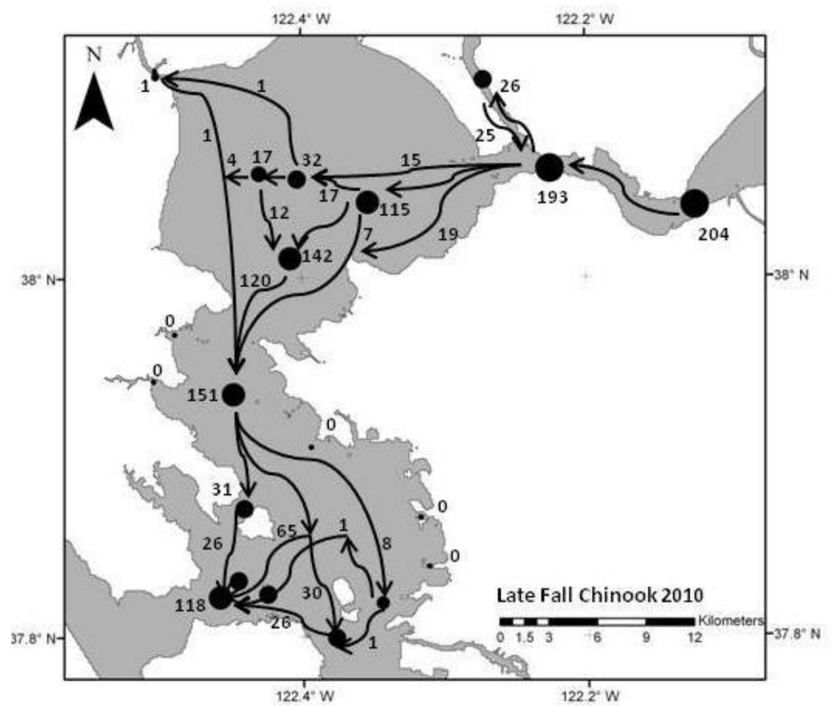

Figure 27. Movement patterns by outmigrating Chinook salmon in San Francisco Bay Estuary in 2010. Black dots refer to receiver sites or arrays, and are sized relative to the number of fish detected at each site (numbers also shown). Note that the lines portray movements between sites, not actual pathways.

The majority of detections of LFC at the Bay Bridge occurred along the western stretch, between Treasure Island and San Francisco. In 2009, only three LFC were detected at the eastern stretch, whereas 42 fish (including one from the eastern stretch) were detected along the western stretch, 24 of which reached the Golden Gate. Presence at the Bay Bridge was generally short in duration. In 2010, only eight LFC were detected along the eastern stretch, while 31 were detected along the western reach, 26 of which arrived at the Golden Gate.

The number of LFC moving through Raccoon Strait increased from four in 2009 to 31 in 2010. Similarly, fewer fish were detected at Alcatraz in 2009 – 9 individuals, all of which had been previously detected at the Golden Gate. In 2009, 12 LFC were later detected at the offshore array at Point Reyes, approximately 60 km to the north of San Francisco Bay, whereas in 2010 this number increased to 61.

In 2009, 10% of the steelhead (STH) reaching the start of the study area at Benicia Bridge, did not subsequently reach Carquinez Bridge, compared to 7% in 2010. The majority of fish in the study areas moved through the system without straying up tributaries or into marinas along the shores. Those fish which did move up the Petaluma River or Mare Island Strait in most cases subsequently returned to the main estuary and did not appear to be affected in terms of their likelihood of successfully reaching the Golden Gate. In 2009, no STH moved up Mare Island Strait (Fig. 28). In 2010, seven STH moved up Mare Island Strait, all but one of which returned to the main estuary and five were later detected at the Golden Gate (Fig. 29). In 2009, five STH moved up the Petaluma River, of which four returned to San Pablo Bay and all arrived at the Golden Gate. In 2010 only one STH was detected here, but it was not detected anywhere else subsequently.

In 2009, 48 STH (23% of the fish present) migrated successfully through San Pablo Bay without swimming through the buoys or study arrays, and the same proportion (23%, 23 individuals) behaved similarly in 2010. The presence of the Flats Array in 2010 helps elucidate some of the pathways of fish outside the main channel, and shows how fish detected at this array returned to the study array or downstream to Richmond Bridge.

Five STH in 2009 and one STH in 2010 were detected at a marina site bordering San Pablo Bay (Larkspur Ferry Terminal). Of the former, two were subsequently detected at the Golden Gate. The latter fish returned to the Richmond Bridge but was not detected further. Two STH were detected at Point Richmond in 2009 and a further one fish was detected in 2010. All three fish were subsequently detected at the Golden Gate.

The majority of detections of STH at the Bay Bridge occurred along the western stretch, between Treasure Island and San Francisco. In 2009, only nine STH were detected at the eastern stretch, whereas 34 fish (including one from the eastern stretch) were detected along the western stretch, seven of which reached the Golden Gate, implying a loss of 26 fish at this site. In 2010, only eight STH were detected along the eastern stretch, six of which moved to the western stretch. A total of 24 STH were detected along the western reach, 20 of which arrived at the Golden Gate.

The number of STH moving through Raccoon Strait increased from 15 in 2009 to 21 in 2010. A similar number of fish were detected at Alcatraz in both years, and detections at these sites were often preceded and followed by detections at the Golden Gate. In 2009, two STH were later detected at the offshore array at Point Reyes, approximately 60 km to the north of San Francisco Bay, whereas in 2010 this number increased to 17.

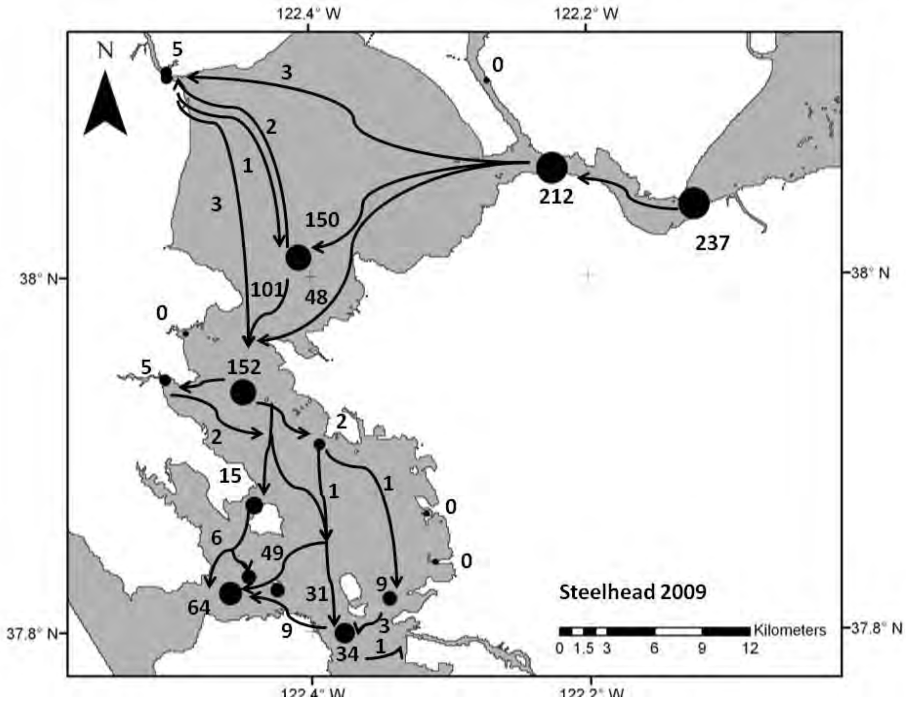

Figure 28. Movement patterns by outmigrating steelhead in San Francisco Bay Estuary in 2009. Black dots refer to receiver sites or arrays, and are sized relative to the number of fish detected at each site (numbers also shown). Note that the lines portray movements between sites, not actual pathways.

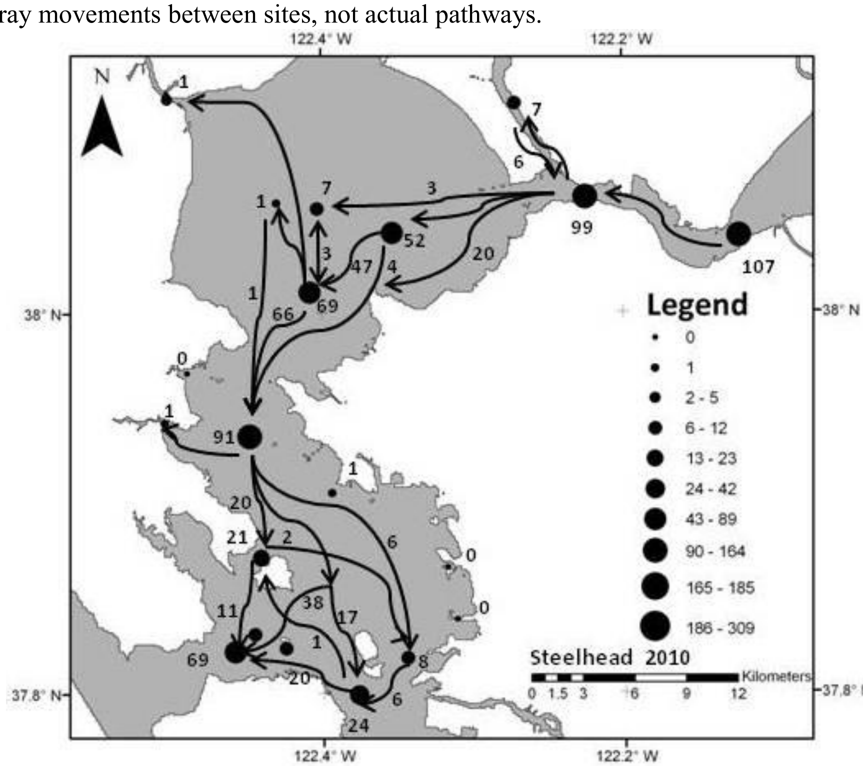

Figure 29. Movement patterns by outmigrating steelhead in San Francisco Bay Estuary in 2010. Black dots refer to receiver sites or arrays, and are sized relative to the number of fish detected at each site (numbers also shown). Note that the lines portray movements between sites, not actual pathways.

3.5.2 Tidal Sloshing

One hundred and thirty five Chinook salmon (66 % of the fish in the system) and 57 steelhead (53 % of the fish in system) made at least one upstream movement during the study period, with up to 5 movements quite common (Fig 30). Upstream movements were also common in 2009, when 152 Chinook salmon (49 % of the fish) and 77 steelhead (32 %) made at least one upstream movement (Fig. 31). The number of upstream movements varied significantly between species in both study years (Mann-Whitney Rank Sum Test, P_{2010} <0.001, P_{2009} = 0.006), and for both species was higher in 2009 (Mann-Whitney Rank Sum Test, P <0.001).

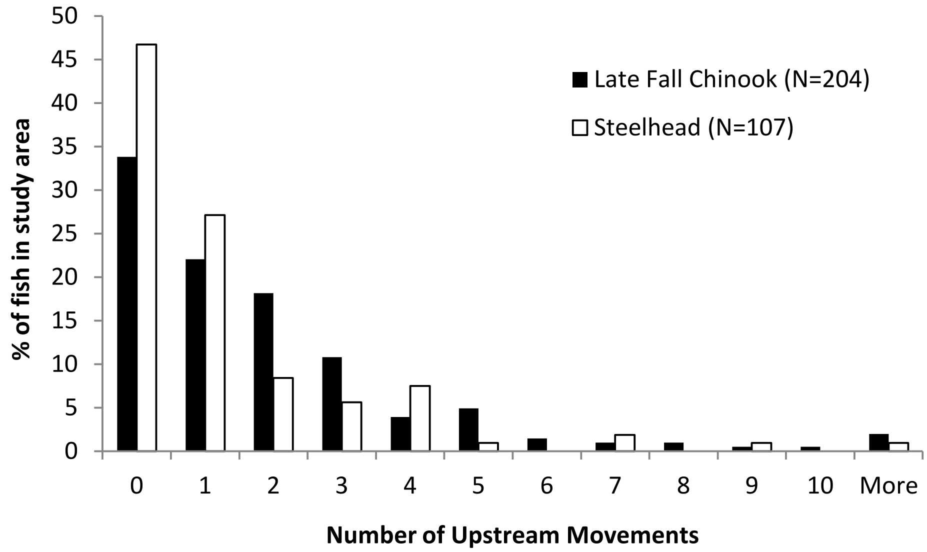

Figure 30. Percentage of individuals making upstream movements during their outmigration from San Francisco Bay in 2010.

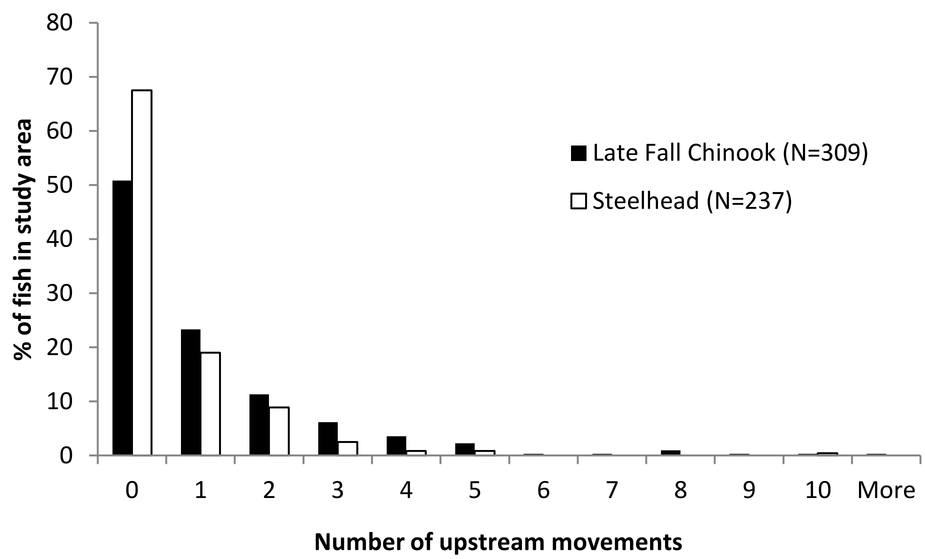

Figure 31. Percentage of individuals making upstream movements during their outmigration from San Francisco Bay in 2009.

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Upstream movements occurred in all sections of the study area (Table 9), and in general Chinook salmon were more susceptible to this phenomenon than steelhead – in San Pablo Bay in 2010, the average upstream moves for a Chinook salmon was 1.56, compared to 0.89 for steelhead.

Table 9. Number of upstream moves made by fish in each river section in 2009 and 2010, normalized by the number of fish in each section.

Year	Section	Chinook salmon			Steelhead		
		# moves up	# fish	Per fish	# moves up	# fish	Per fish
2010	Carquinez Strait	70	204	0.34	36	107	0.34
	San Pablo Bay	301	193	1.56	88	99	0.89
	Central SF Bay	38	151	0.25	14	91	0.15
2009	Carquinez Strait	147	309	0.48	46	237	0.19
	San Pablo Bay	187	265	0.71	77	212	0.36
	Central SF Bay	11	161	0.07	10	152	0.07

The direction of movements was associated with the direction of the tides – examination of the number of fish completing an upstream or downstream movement in both Carquinez Strait and Central San Francisco Bay (Figs 32 and 33) showed that these upstream movements were commonly completed at high tides, whereas downstream movements were completed at low tides.

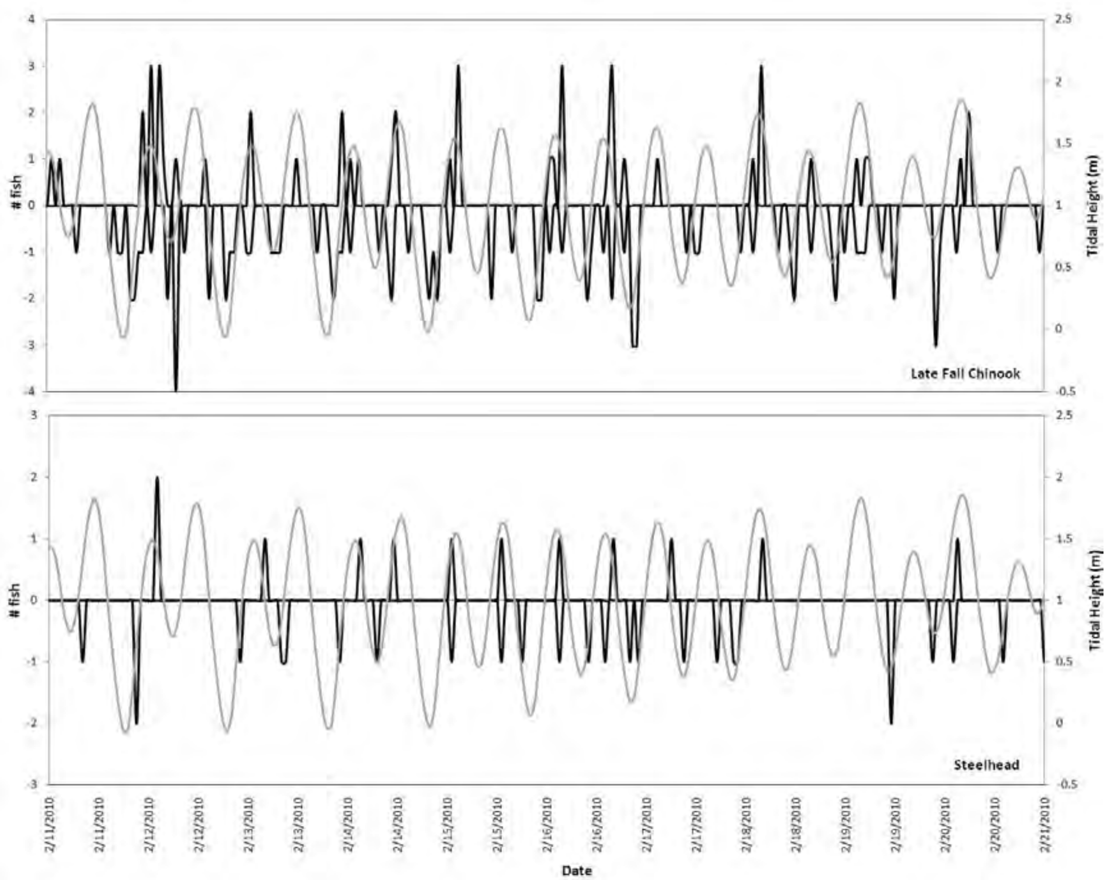


Figure 32. Number of fish making upstream and downstream movements in Carquinez Strait over time (black lines) compared with tidal height at Mare Island (grey lines).

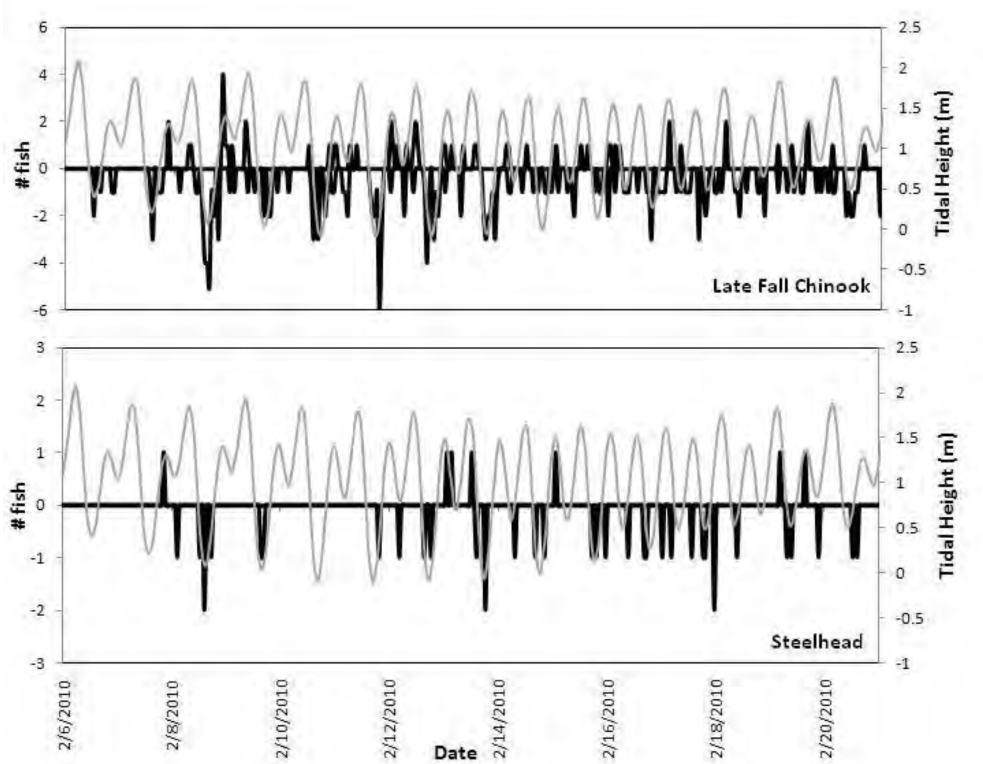


Figure 33. Number of fish making upstream and downstream movements in Central San Francisco Bay over time (black lines) compared with tidal height at the Golden Gate (grey lines).

Chinook salmon which were subjected to more than five events of tidal sloshing did not successfully reach the Golden Gate (Figs. 34 and 36), yet overall, there was no significant difference in the number of tidal sloshing movements between those fish which reached the Golden Gate and those which did not (Mann-Whitney Rank Test P=0.121).

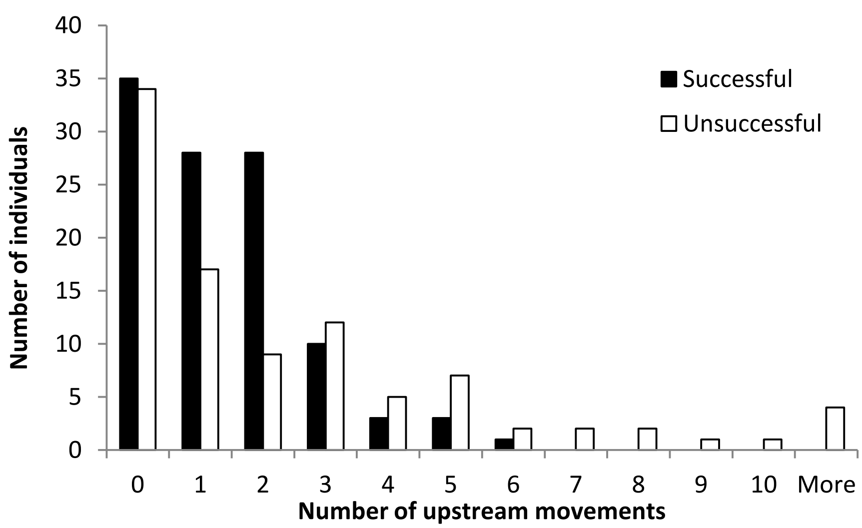


Figure 34. Comparison of the number of upstream movements made by Chinook salmon which successfully outmigrated and those which did not.

Steelhead were not subjected to as much tidal sloshing (Figs. 35 amd 36), however, in contrast to Chinook salmon, those fish which successfully migrated to the Golden Gate made significantly more upstream movements than those which did not (Mann-Whitney Rank Test, P = 0.042).

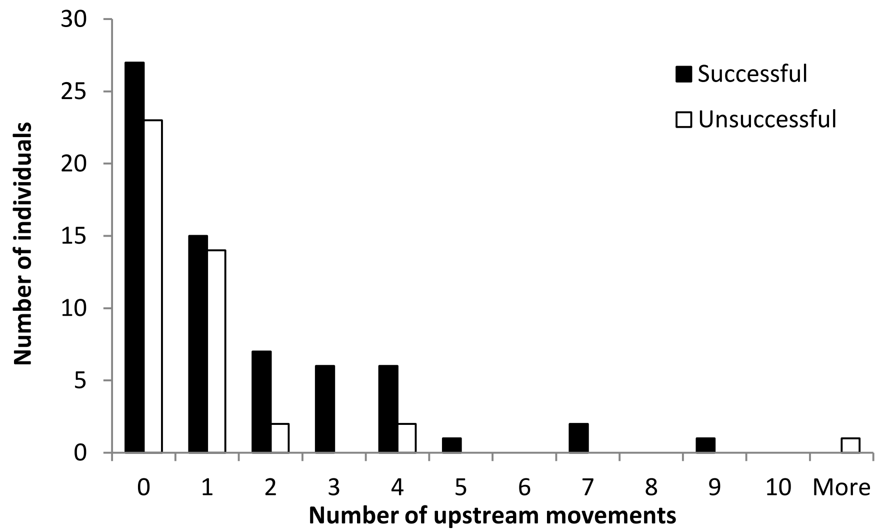


Figure 35. Comparison of the number of upstream movements made by steelhead which successfully outmigrated and those which did not.

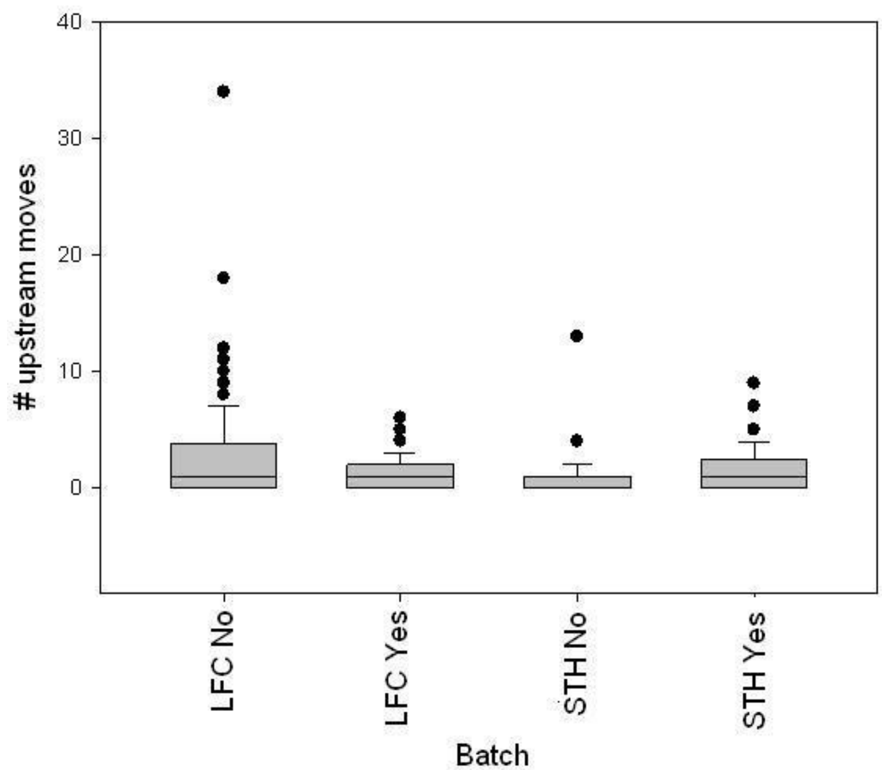


Figure 36. Number of upstream moves made by steelhead and Chinook salmon, grouped by successful migration to the Golden Gate.

Figures 37 and 38 describe some of the movements made by individual fish during their outmigration in relation to tidal height, grouped by whether or not they reached the Golden Gate.

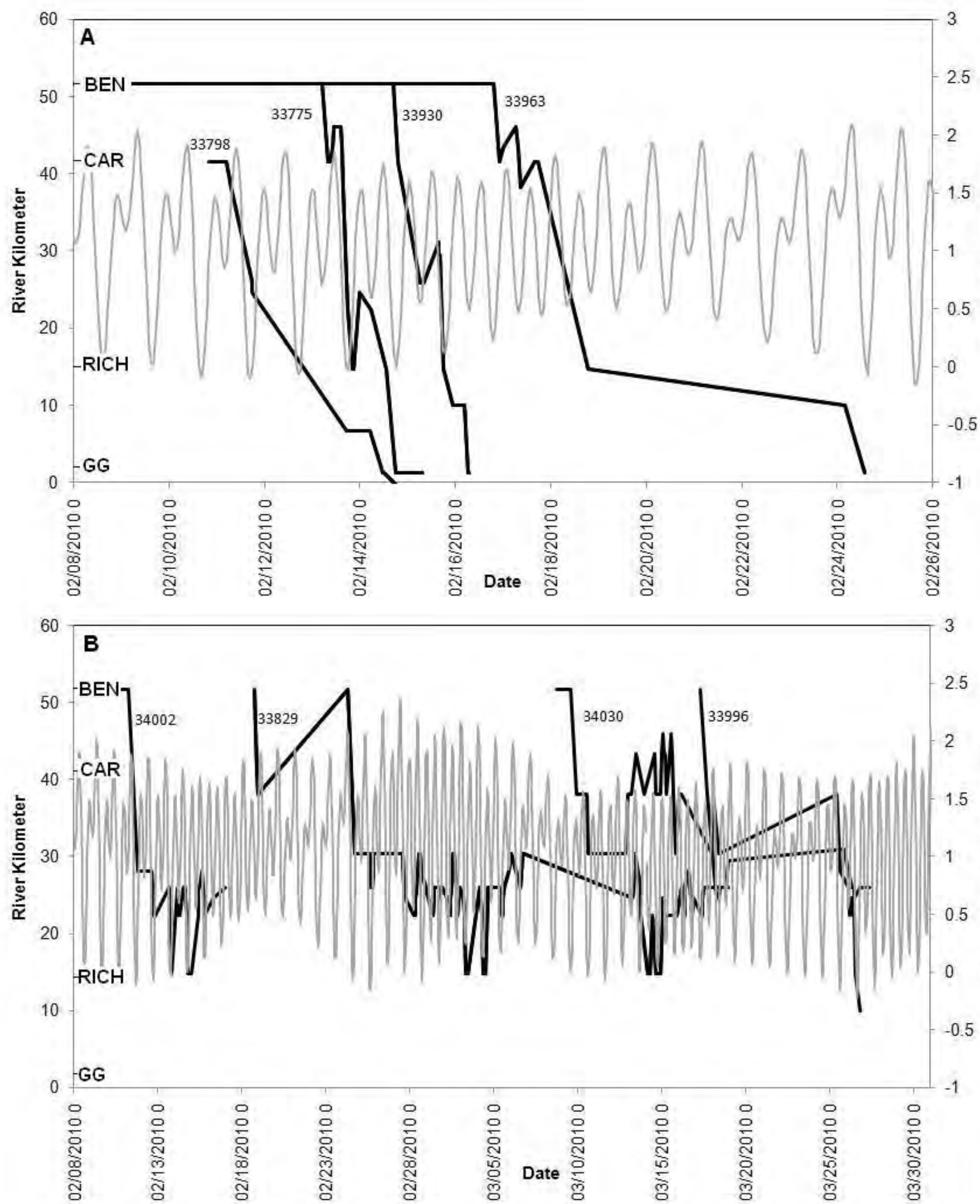


Figure 37. Examples of downstream movements with tidal sloshing for Chinook salmon which successfully reached the Golden Gate (A), and those which did not (B).

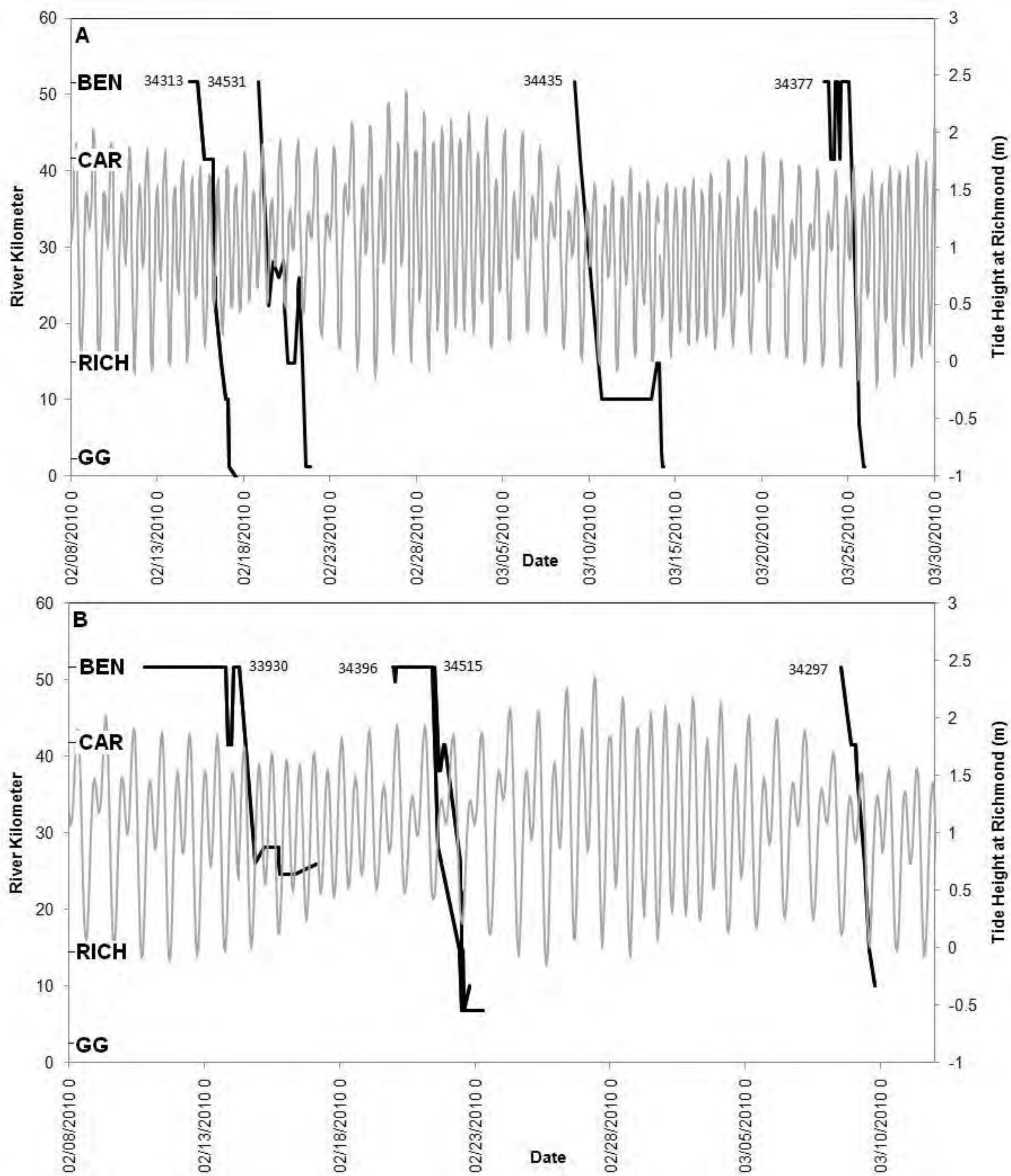


Figure 38. Examples of downstream movements with tidal sloshing for steelhead which successfully reached the Golden Gate (A), and those which did not (B).

3.6 Habitat Preference

3.6.1 The Flats Array

Thirty two Chinook salmon were detected at the Flats Array (Table 10), 18 of which were also detected at the SP Control Array, which in turn was visited by 123 individuals (T-test, $P < 0.001$). Nineteen of the fish were subsequently detected at the Golden Gate, although one of these returned upstream and was last detected at Raccoon Strait. For five individuals, their last detection was at the Flats Array.

Only seven steelhead were detected at the Flats Array (Table 10), four of which eventually arrived at the Golden Gate, one was last detected at the Bay Bridge, and one at Richmond Bridge. The remaining individual (Tag ID 34397) made four separate visits to the Flats Array, the last of which included its final detection. In contrast, significantly more steelhead were detected at the Control Array (Mann-Whitney Rank Test $P < 0.001$). Of these 58 fish, 42 were subsequently detected at the Golden Gate.

As a proportion of the number of fish known to have reached San Pablo Bay, 16% of Chinook salmon and 6.5% of steelhead utilized the Flats Array whereas over 50% of both species utilized the channel-based Control Array. Exposure time at the Flats array ranged from one minute to 313 minutes (median: 21 minutes) for Chinook salmon, and from one minute to 212 minutes (median: 2.8 minutes) for steelhead.

Table 10. Number of fish detected at each 8-receiver array in the Flats and in the channel (Control) in San Pablo Bay.

	Chinook salmon		Steelhead	
Receiver #	**Flats**	**Control**	**Flats**	**Control**
1	21	68	3	26
2	20	61	3	24
3	18	50	2	26
4	21	55	1	29
5	17	44	1	19
6	16	57	1	33
7	17	53	2	28
8	17	54	3	30
Total	**32**	**123**	**7**	**58**

Chinook salmon mostly utilized the Control and Flats Array from February 10^{th}-16^{th}, whereas steelhead were more dispersed, in the manner of their overall movements downstream. Besides the actual numbers of fish at each site, there was no difference in their timing at the sites (Fig. 39).

Diel analysis of fish presence at both the Flats and Control Arrays showed that use of both sites was significantly different from even spacing (Rao's Spacing Test <0.001). Mean vectors were always at night (LFC Flats: 07:55, LFC Control: 21:56, STH Control: 11:14, STH Flats: 04:38). The length of mean vector (concentration of times) was greatest for steelhead at the flats (0.558), but the sample size was very small. Overall, there was no clear diel pattern of use for either site (Fig. 40).

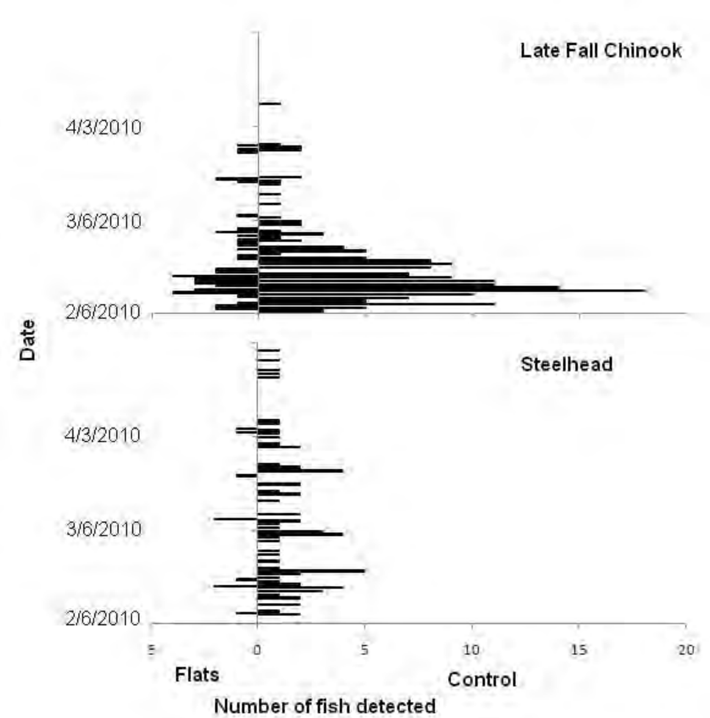


Figure 39. Numbers of fish detected at Flats and Control Arrays in San Pablo Bay, by date.

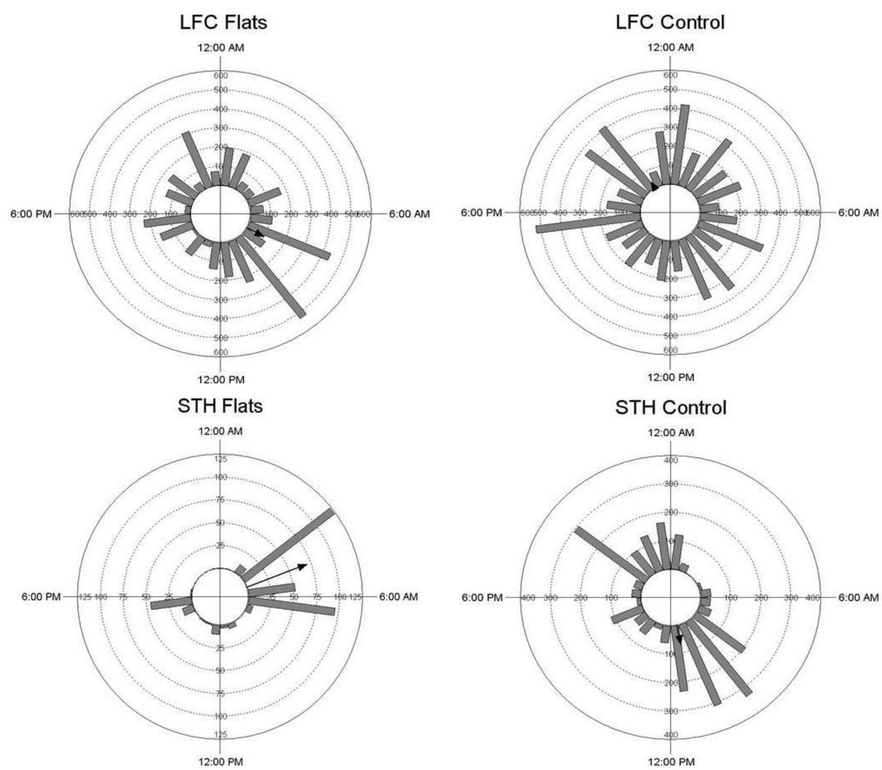


Figure 40. Diel presence of Chinook salmon (LFC) and steelhead (STH) smolts at the Flats and Control Arrays in San Pablo Bay. Direction of arrows show mean time of presence, length of arrows shows strength of relationship.

3.6.2 Cross-Section Arrays

Fewer fish of both species were detected along the shallower, eastern portion of the Bay Bridge than along the deeper western portion (Fig. 41). At the Richmond San Rafael Bridge (Fig. 42), more fish were detected towards the center of the bridge and along the deepest part of the channel.

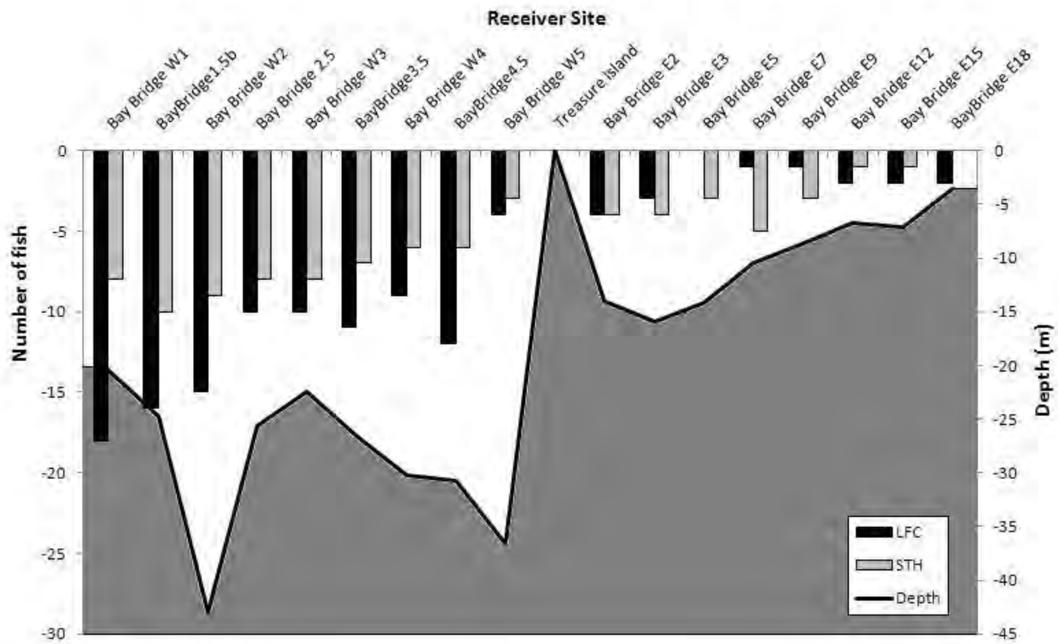


Figure 41. Cross section of the Bay Bridge showing water depth and number of Chinook salmon (LFC, N=37) and steelhead (STH, N=26) at each receiver site.

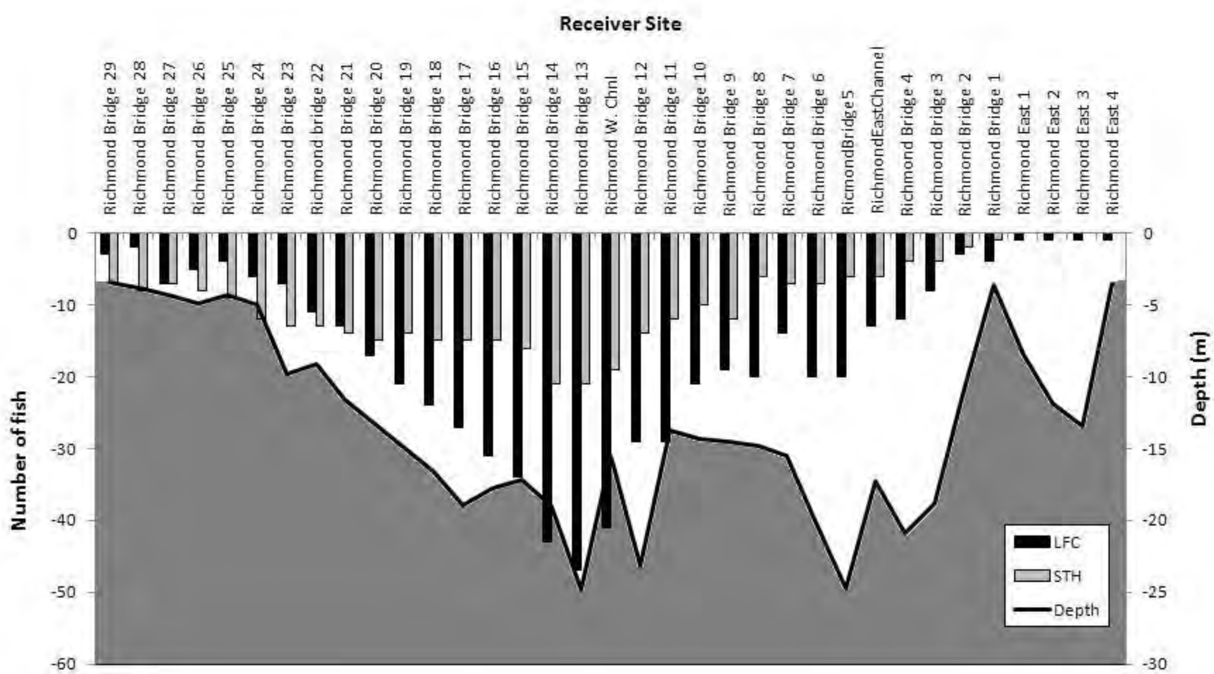


Figure 42. Cross section of the Richmond Bridge showing water depth and number of Chinook salmon (LFC, N=126) and steelhead (STH, N=84) at each receiver site.

The number of Chinook salmon detected at each abutment increased with increasing depth at both the Richmond Bridge ($F_{0.05,1,32}$= 30.79, P <0.001), and at the Bay Bridge ($F_{0.05,1,14}$= 19.15, P <0.001) (Fig. 43). The number of steelhead detected at each abutment increased with increasing depth at both the Richmond Bridge ($F_{0.05,1,32}$= 13.89, P= 0.002), and at the Bay Bridge ($F_{0.05,1,14}$= 5.19, P= 0.03) (Fig. 44).

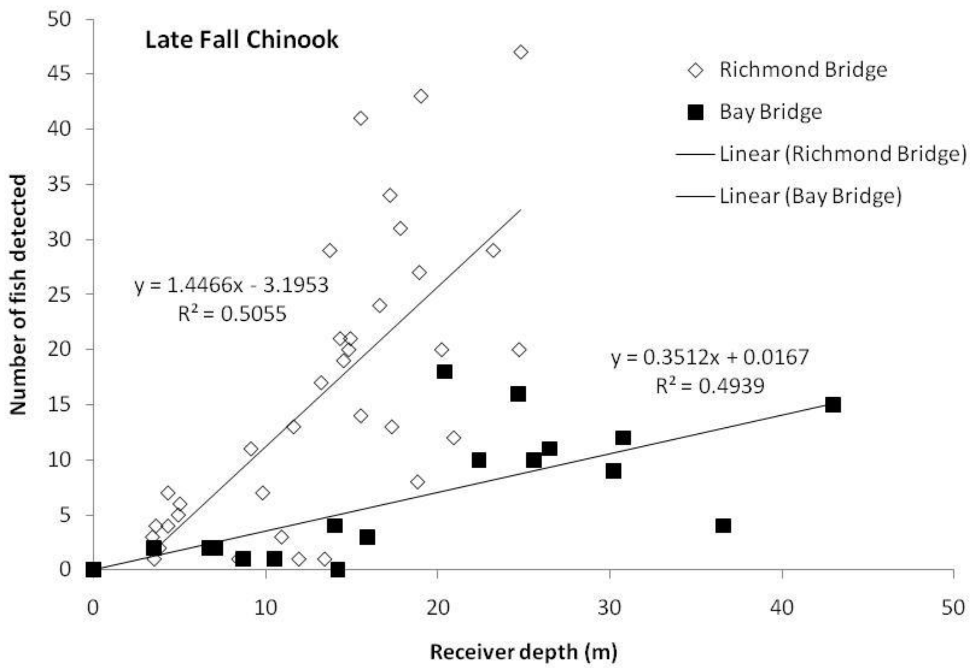


Figure 43. Number of Chinook salmon smolts detected at receiver sites by depth, for Richmond and Bay Bridges.

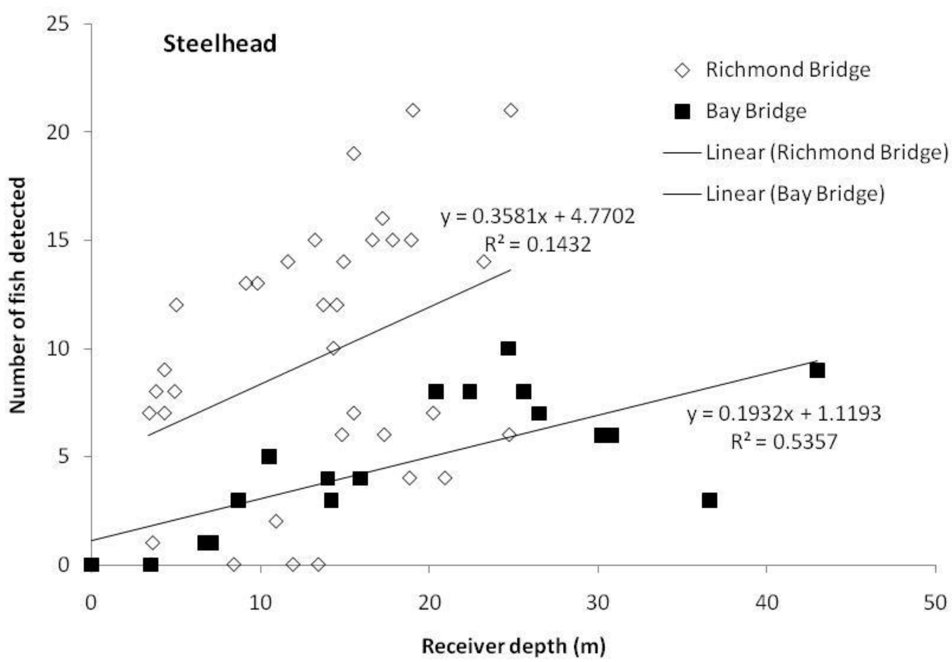


Figure 44. Number of steelhead smolts detected at receiver sites by depth, for Richmond and Bay Bridges.

3.7 Residency and exposure times

3.7.1 Dredged Sites

Of the 193 Chinook salmon smolts which entered San Pablo Bay, 73 % (141 individuals) were detected at a dredged marina/shoal or channel site (Table 11). Similarly, of 99 steelhead smolts which entered San Pablo Bay, 60 % (60 individuals) were detected at one or more of these sites. For both species, the majority of these detections took place around the channel buoys. Of the shoal/marina sites, Martinez Marina detected the largest number of individuals (31 Chinook salmon and 7 steelhead), whereas several sites (Berkley Marina, Emeryville, San Rafael Can6, Suisun City Marina) were not visited by any individual of either species.

Table 11. Number of fish detected at marinas and channel sites (where dredging occurs).

		Chinook salmon				Steelhead			
		2009		2010		2009		2010	
Station Type	**Station Name**	**# Fish**	**# Detections**	**# Fish**	**# Detections**	**# Fish**	**# Detections**	**# Fish**	**# Detections**
Marina/ Shoal	Berkley Marina	0	0	0	0	0	0	0	0
	EmeryvilleA	0	0	0	0	0	0	0	0
	EmeryvilleB	1	2	0	0	0	0	0	0
	G3	5	160	15	231	2	22	1	5
	G5	0	0	7	67	1	1	0	0
	Larkspur Ferry 15	0	0	0	0	5	112	1	52
	MartinezMarina	156	1152	31	74	64	162	7	15
	MontezumaEast	4	308	NA	NA	4	149	NA	NA
	MontezumaWest	4	103	NA	NA	2	22	NA	NA
	PetalumaRRBridge	5	192	1	2	5	206	1	56
	Point Richmond	0	0	0	0	2	30	1	2
	PortSonomaMarina	4	50	0	0	3	7	1	22
	San Rafael Can 6	0	0	0	0	0	0	0	0
	Suisun City Marina		0	0	0	0	0	0	0
	Vallejo Marina C	12	36	26	185	0	0	7	14
	Total	**168**	**2003**	**65**	**559**	**77**	**711**	**18**	**166**
Channel	SPBuoy7	NA	NA	49	507	NA	NA	24	127
	SPBuoy8	50	331	54	1023	38	163	34	261
	SPBuoy9	NA	NA	69	1731	NA	NA	21	170
	SPBuoy10	38	240	54	469	2	5	17	56
	Total	**80**	**571**	**115**	**3730**	**40**	**168**	**52**	**614**

The total exposure time for individuals at these potentially dredged sites was in most cases less than 30 minutes but for some fish ranged to 1050 minutes in the case of Chinook salmon (Fig. 45) and 990 minutes in the case of steelhead (Fig.46).

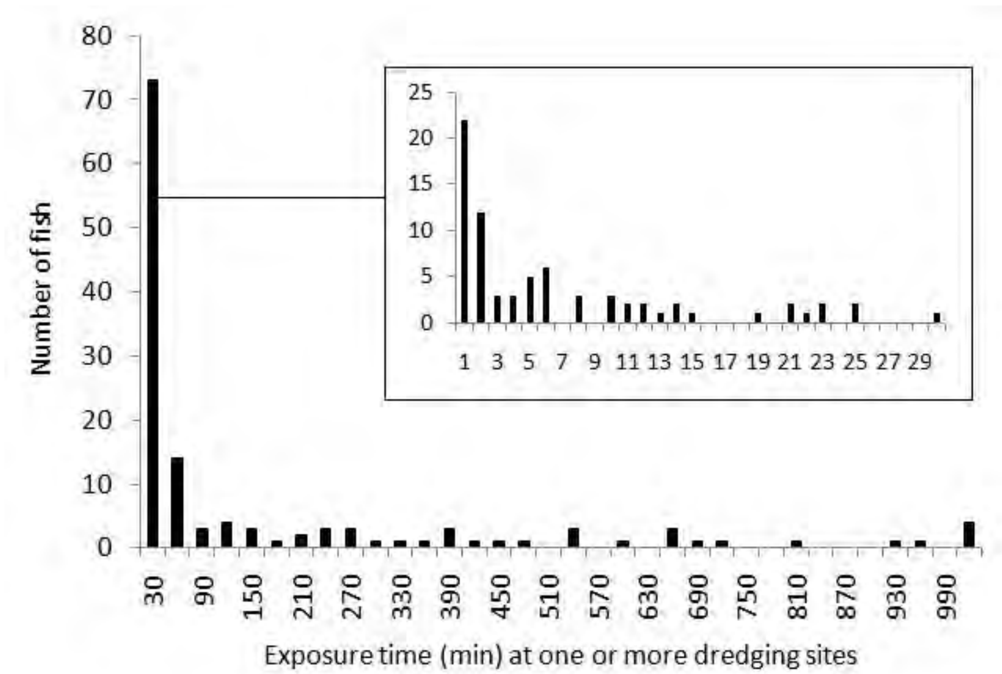


Figure 45. Total exposure time of Chinook salmon at all dredging sites.

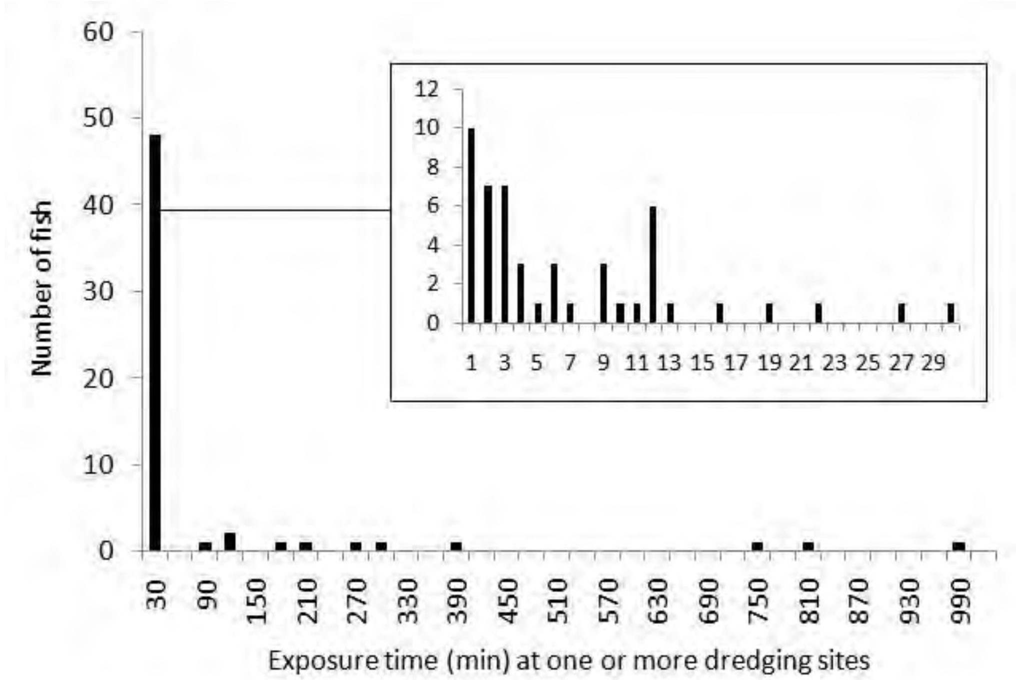


Figure 46. Total exposure time of steelhead at all dredging sites.

3.7.2 Exposure at Alcatraz SF11

Using the cut-off interval of five minutes to determine the start of a new visit to each site, we compared the total period of time each fish spent at the four receiver sites at Alcatraz Placement Site (SF11) with the Alcatraz Control Site (see points 23 and 24 on Figure 7). For single detections we assigned a nominal exposure time of one minute.

Table 12. Exposure time at receiver stations placed in Alcatraz SF11 and Alcatraz Control, for Chinook salmon and steelhead in 2010.

Chinook salmon			**Exposure Time (minutes)**			**Steelhead**	**Exposure Time (minutes)**	
Tag ID	Alcatraz Control	Alcatraz SF11	Tag ID	Alcatraz Control	Alcatraz SF11	Tag ID	Alcatraz Control	Alcatraz SF11
33762	13.7		**34003**		85.7	**34262**	1.3	
33764		0.8	**34005**		7.6	**34282**		1.0
33772		3.6	**34028**	1.0	43.7	**34300**	4.2	
33774	14.9		**34047**	15.6		**34316**	11.8	6.7
33776	23.0		**34049**	68.1		**34394**		1.1
33815	41.3		**34061**		6.3	**34434**	2.9	
33816		2.4	**34087**	4.7		**34435**	1.0	
33818	6.7		**34094**		37.2	**34445**	1.0	1.5
33839	2.4		**34097**	1.2	0.8	**34503**		10.6
33849	18.9	5.9	**34105**		7.6	**34516**	4.8	
33855	3.8	3.1	**34117**	7.3		**34570**	20.5	
33861		3.2	**34119**		23.5	**34584**		14.6
33865	3.2		**34123**	59.3		**34602**	1.0	
33869		1.2	**34130**	14.2		**34607**	58.0	
33875	8.6		**34134**	1.0		**34658**		1.0
33879	52.8	4.5	**34138**	14.9	3.5	**34727**	3.6	
33883		25.7	**34141**		1.2	**34739**	29.5	
33885		8.6	**34150**	6.4				
33895		4.9	**34157**	41.0				
33896	13.7		**34160**	4.1				
33898		11.3	**34176**		1.2			
33936	1.0		**34177**	26.1				
33939		1.0	**34193**		7.3			
33946		0.4	**34203**	6.2	1.0			
33965	22.4		**34204**		1.0			
33968	7.3		**34214**		3.7			
33969		2.9	**34235**	1.0				
33973		39.5	**34237**		8.6			

Thirty-one Chinook salmon were detected at the Control Site, whereas 32 individuals were detected at the Placement site (Table 12). Only seven fish were detected at both sites. For both sites, the distribution of exposure times was non-normal (Kolmogorov-Smirnov, $P < 0.001$). The median exposure time at the Control site was 8.6 minutes, whereas that of the Placement site was 4.1 minutes, although there was no significant difference overall between the sites (Mann-Whitney Rank Test, $P = 0.053$). Twelve steelhead were detected at the Control Site, whereas only seven were detected at the Placement Site (Table 12). Only two fish were detected at both sites. For both sites, the distribution of exposure times was non-normal (Kolmogorov-Smirnov, $P_{Control} = 0.001$, $P_{SF12} = 0.029$). The median exposure time at the Control site was 3.9 minutes, whereas that of the Placement site was 1.4 minutes, although there was no significant difference overall between the sites (Mann-Whitney Rank Test, P = 0.579).

If the Alcatraz Placement site SF11 covers an area of approximately 292,000 m^2, and we assume that each VR2 receiver has a detection range of 70 meters, then these results correspond to a coverage of 21 % of the available area, so that estimations of median total exposure time might be scaled up to 19.5 minutes for Chinook salmon and 6.7 minutes for steelhead.

3.7.3 Exposure at SF 9

One hundred and seventeen Chinook salmon and 42 steelhead were detected by the single receiver deployed at SF9. The exposure time at the receiver for both species was non-normal (Komolgorov-Smirnov, P < 0.001). The median time spent at the site was 3.25 minutes for Chinook salmon and 2.8 minutes for steelhead. There was no significant difference in exposure time between the species (Mann-Whitney Rank Test, P = 0.772).

If the area of SF9 is approximately 186,000 m^2, and the single receiver covers 15,390 m^2, then this corresponds to a coverage of 8.3 %, so the median exposure time might be scaled up to 39 minutes for Chinook salmon and 33 minutes for steelhead.

3.7.4 Exposure at SF 10

Eighty six Chinook salmon and forty one steelhead were detected at the SF 10 Placement Site (SP Array 1A-D, 2A-D), corresponding to 44.6% and 41.4% of the fish which survived to Carquinez Bridge and beyond. In contrast, 112 Chinook salmon and 48 steelhead were detected at the adjacent control site (SP Array 1E-H, 2E-H). The exposure times varied from a single detection to 42 hours (32 hours at the control site) for Chinook salmon (Fig. 47) and 13 hours (36 hours at the control site) for steelhead (Fig. 48). The exposure time at the SF10 Placement Site did not vary between species (U = 1868, P = 0.590). Steelhead had a longer exposure time at the Control Site (median = 19.8 min), than at the Placement Site (median = 6.5 minutes) (Friedman Repeated Measures ANOVA, P = 0.005), as did Chinook salmon (Control Site median = 13.5 minutes, Placement Site median = 5.3 minutes, Friedman Repeated Measures ANOVA, P = 0.027).

Exposure time was longer in 2010 than in 2009 for steelhead at the Control Site (U = 1437, P < 0.001) and the Placement Site (U = 699, P < 0.001). Similarly, exposure time was greater for Chinook salmon at the Placement Site (U = 2497.5, P < 0.001), but not at the Control Site (U = 7113, P = 0.083) (Fig. 49).

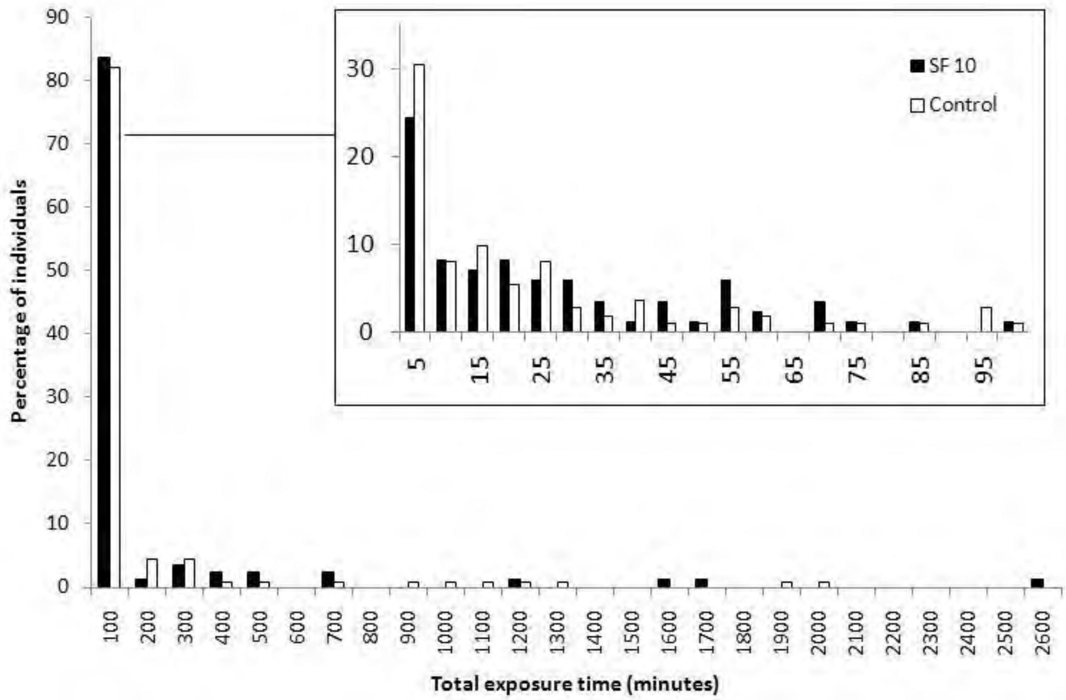


Figure 47. Frequency distribution of exposure time of Chinook salmon at SF10 Placement Site and an adjacent Control Site. Note that the 0-100 minute exposure time bin has been expanded (inset graph).

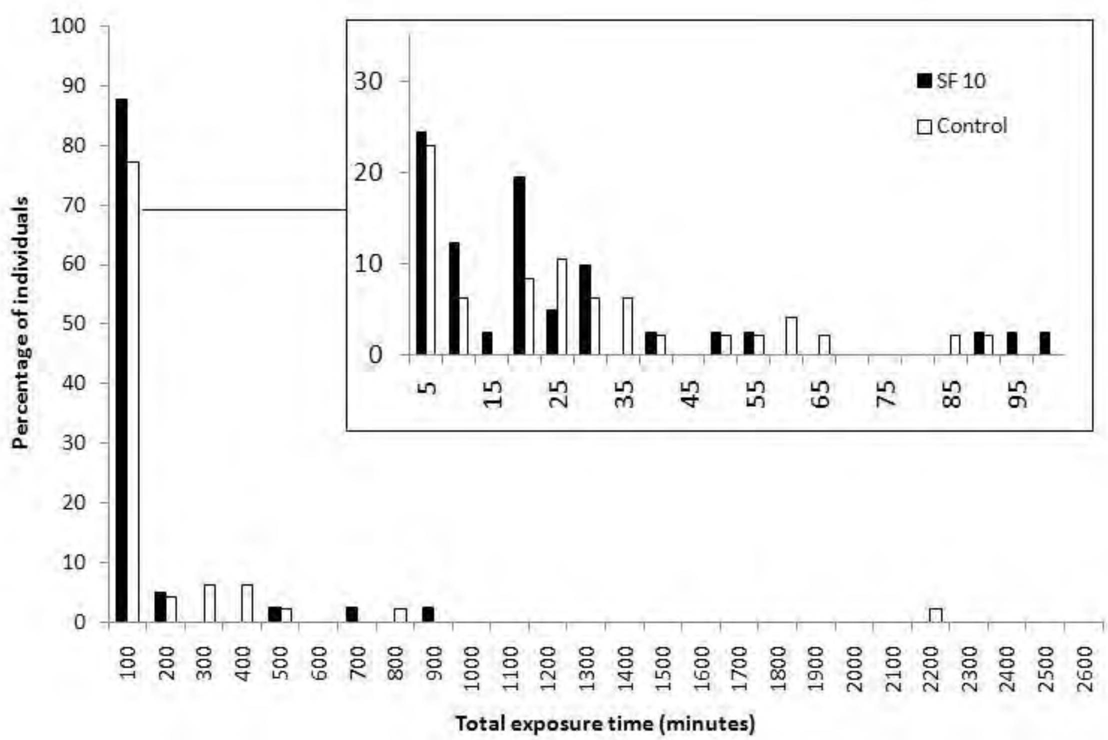


Figure 48. Frequency distribution of exposure time of Chinook salmon at SF10 Placement Site and an adjacent Control Site. Note that the 0-100 minute exposure time bin has been expanded (inset graph).

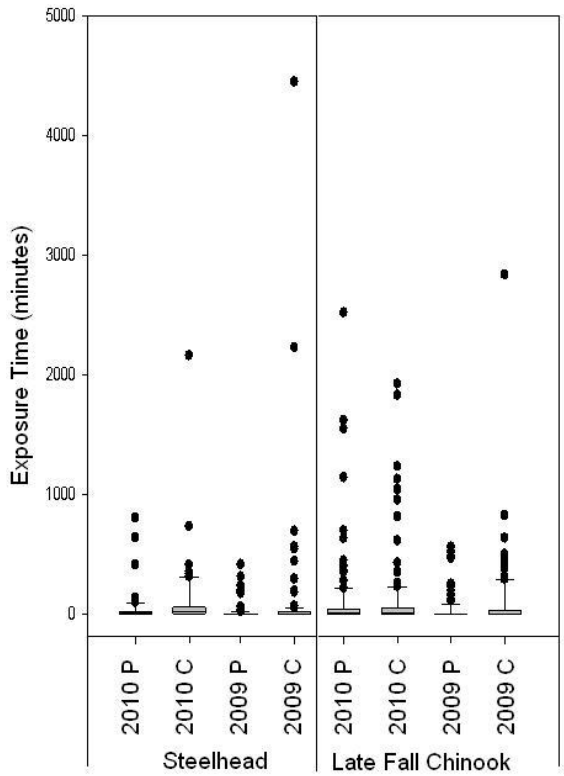


Figure 49. Boxplots (medians, quartiles and outliers) of exposure time of steelhead and Chinook salmon at the SF 10 Placement Site (P), and the adjacent control site (C) in 2009 and 2010.

3.8 Green sturgeon movement patterns

Green sturgeon were found to occur in San Francisco Bay throughout the year, with more individuals detected in summer and fall around the Golden Gate and up to Carquinez Bridge (Fig. 50). Fish were found to be more evenly distributed throughout the system (from the Golden Gate to Freeport) in winter.

Between May 2009 and August 2010, 47 green sturgeon were detected in the study area (appendix 1). Most of these exhibited a rapid, highly directional transit through the area (Fig. 51), spending only 2-4 days in the Bay. We identified two main periods of outmigration movements – October and January, while incoming movements were clustered around February. None of the fish which left the system to the ocean were subsequently detected returning to the Bay. In addition to the five sturgeon which made a single upstream migration (Fig. 51), a small number of sturgeon made the following movements:

- Three individuals made a rapid upstream movement in early summer of 2009, and returned downstream and to the ocean between early fall and early winter. These fish subsequently returned to the Bay in February 2010 and made a further rapid transit upstream (Fig. 52 top). Although they migrated above Benicia Bridge, they did not make spawning runs to the upper river.
- Three individuals made brief incursions into the Bay over the summer 2009 period, but did not migrate above Benicia Bridge into the delta and river, but rather left the Bay at the end of summer (Fig. 52 bottom).
- One individual was only detected for a brief period at the Golden Gate and no further upstream.

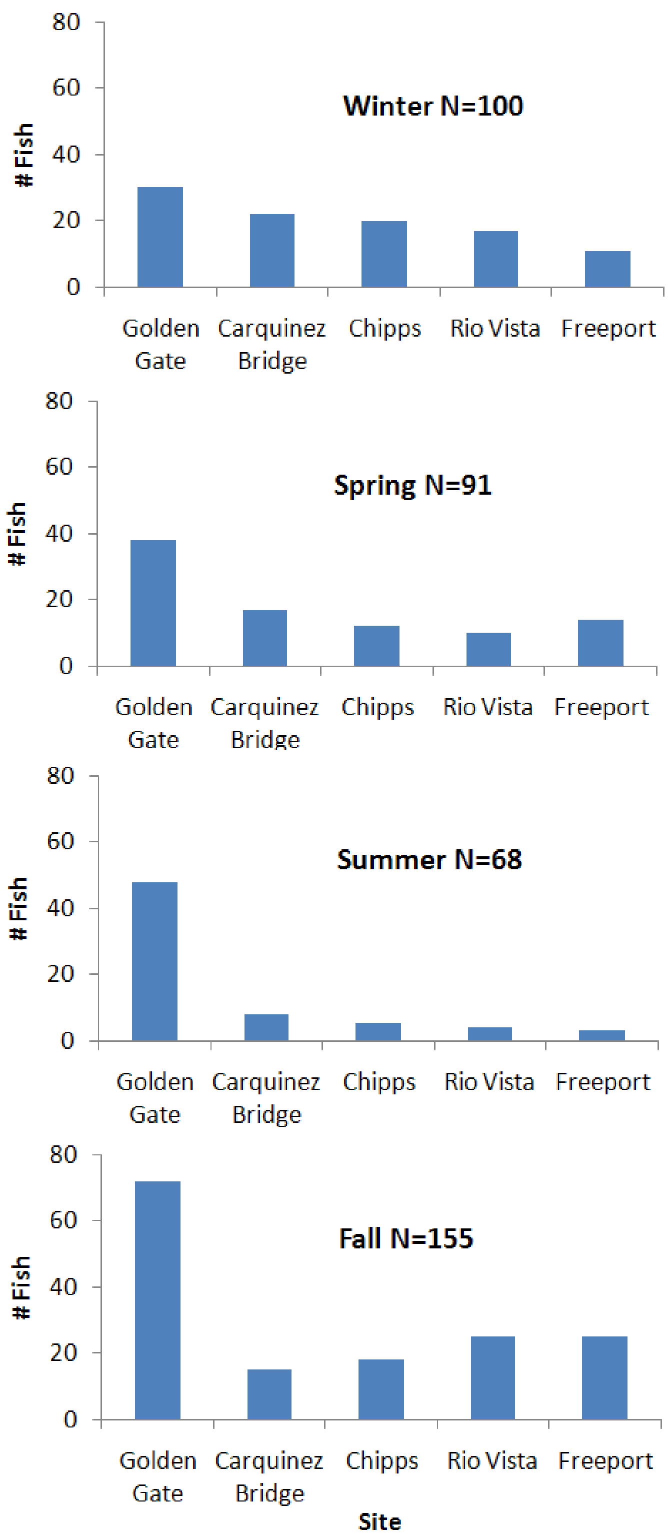


Figure 50. Seasonal distribution of green sturgeon at sites from the Golden Gate moving upstream to Freeport. Data is grouped over several years (2005-2009).

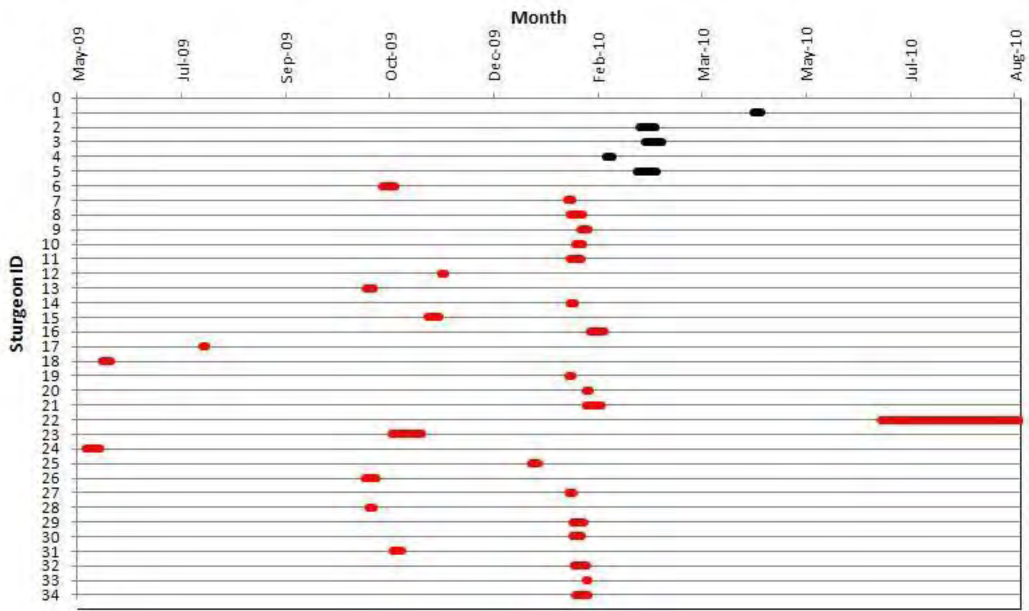


Figure 51. Days spent in the San Francisco Bay Area (Golden Gate to Benicia Bridge) by green sturgeon making directional upstream (black markers) or downstream (red markers) movements.

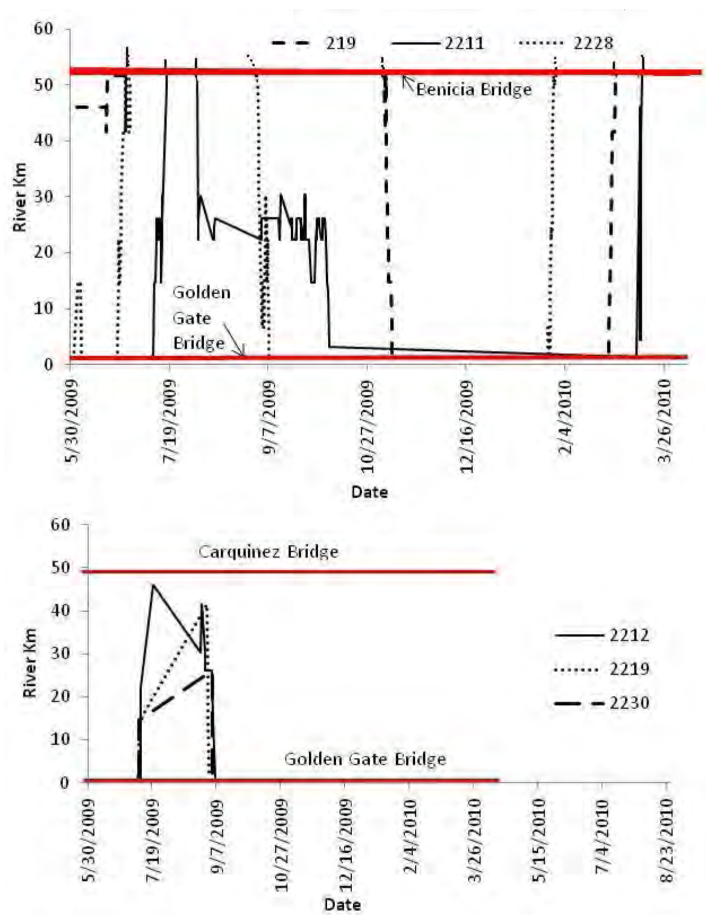


Figure 52. Upstream and downstream directional movements by three green sturgeon making repeated movements (above), and three green sturgeon not migrating beyond the Bay Area (below).

Green sturgeon displayed a positive relationship with depth at the Bay Bridge ($F_{0.05,1,33} = 61.99$, $P < 0.001$) and Richmond Bridge ($F_{0.05,1,16} = 22.2$, $P < 0.001$) cross-section arrays (Figs. 53 and 54).

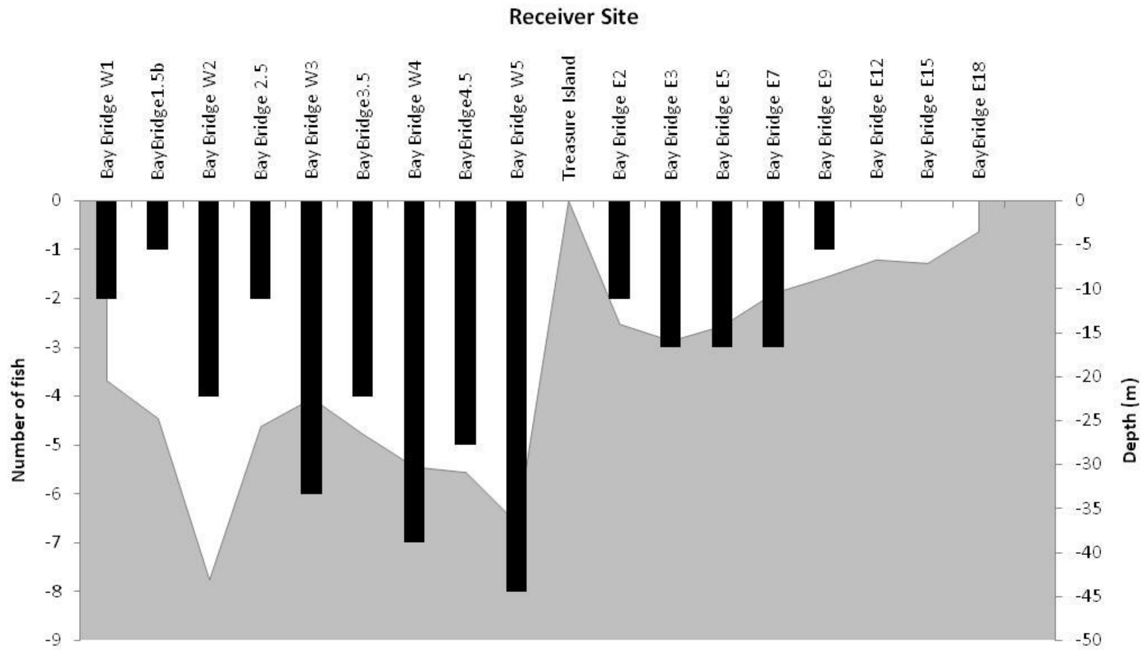


Figure 53. Number of green sturgeon detected at receivers deployed across the Bay Bridge. Shading indicates depth.

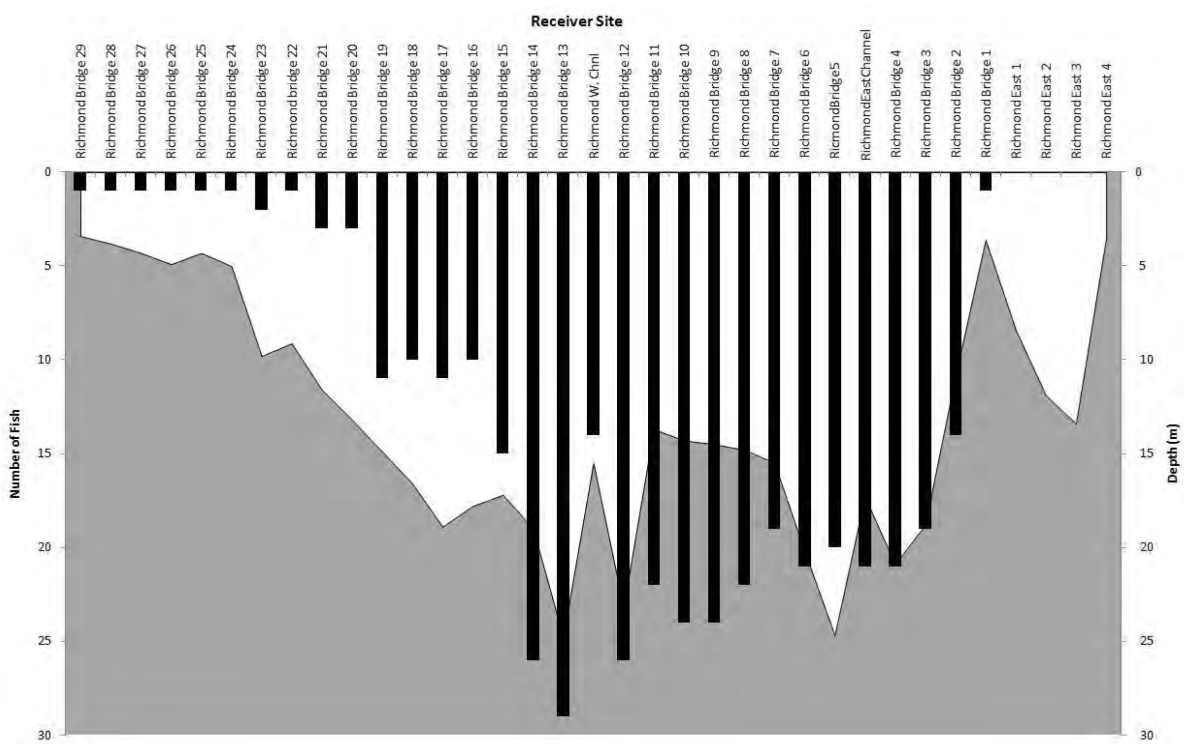


Figure 54. Number of green sturgeon detected at receivers deployed across the Richmond Bridge. Shading indicates depth.

No green sturgeon were detected at most of the marina sites (Berkley, Larkpur, San Rafael Canal, Port Sonoma, Emeryville). One fish was detected at Richmond Point for 22 minutes, while five fish were detected at Vallejo Marina (Table 13). Most of the fish in the system were detected by the receiver at Martinez Marina (median exposure time = 20 minutes), although it must be taken into account that this receiver probably detects fish out into the channel. The median exposure time and number of fish detected were both greatest in the San Pablo Bay Channel (SP Buoys 7-10).

Table 13. Exposure time (in minutes) of green sturgeon at marina and channel sites in San Francisco Bay between May 2009 and August 2010.

Tag ID	Martinez Marina	Richmond Point	Vallejo Marina	G3 Channel	SP Channel	Total
217	15.7				10	25.7
219	30.3		2713.6		51.5	2795.4
221	0.4				6.1	6.5
223					34.9	34.9
224	0.8				18.4	19.2
1132	5.1				4.6	9.7
2211	0.4		8.3	13.6	40.9	63.2
2212			1.1		53.8	54.9
2222	5.2				77.7	82.9
2228	14.4				19.5	33.9
2230		22.1				22.1
2236			0.8			0.8
2237					20.7	20.7
4325	73.9				238.2	312.1
4330	12				404.9	416.9
4332	96.2				254.8	351
4333	6.9				198.5	205.4
4334	11.5					11.5
4335	22				53.3	75.3
4339	48.3					48.3
4342	21				309	330
4344	26.1				369.9	396
10814	14.6				13.8	28.4
10817	17.4					17.4
10818	32.5				3.2	35.7
10819	48.3				202.6	250.9
48419				136.9		136.9
52411	170.2				301.6	471.8
52413					26.1	26.1
52414	0.4				0.375	0.775
52415	20.9				28.1	49
52416	16.1				0.8	16.9

52417	253.6				49.2	302.8
52418	58.5				148.3	206.8
59423	0.4		28		148.6	177
59424	685				51.6	736.6
59427	86.6				10.5	97.1
59428	6.2			28.5		34.7
59429	37.6				137.3	174.9
59430	23.9				700.2	724.1
Median	**20.9**	**22.1**	**8.3**	**28.5**	**51.5**	**59.05**

Seven green sturgeon were detected at the SF 9 Placement Site (median 12.8 minutes, range 2-72 minutes). Eight fish were detected at the Alcatraz SF 11 Placement Site, whereas 12 individuals were detected at the Alcatraz Control Site (Table 14). Exposure time at both sites was similar (11.3 minutes at the Control Site, 18.7 minutes at the Placement Site).

Table 14. Exposure time (in minutes) of green sturgeon at Alcatraz Placement and Control sites between May 2009 and August 2010.

Tag ID	Alcatraz Control	Alcatraz Placement	Total
2211	0.4		0.4
2237	0.4		0.4
4330	0.4		0.4
10815	0.4		0.4
59427	0.4	45.6	46
2222	2.3		2.3
2228	9.1	0.4	9.5
217	9.6		9.6
52415	13		13
2219	13.3	21.1	34.4
221	14.6	16.3	30.9
52417	19.4		19.4
2236	35.8	0.4	36.2
4339	56.5		56.5
59423	63.2	41.3	104.5
4333	78		78
223		63.5	63.5
10819		0.4	0.4
Medians	**11.3**	**18.7**	**16.2**

Thirty five green sturgeon were detected at the SF 10 Placement Site. The same number (mostly the same fish) was detected at the adjacent control site (Table 15). Exposure time varied from 5 to 1165 minutes at the Control Array, and from 4 to 639 minutes at the Placement Site.

Table 15. Exposure time (in minutes) of green sturgeon at the SF 10 (SP Array 1 A-D and 2 A-D) and Control (SP Array 1 E-H and 2 E-H) in San Pablo Bay between May 2009 and August 2010.

Tag ID	Control Array	SF10
217	5	15
219	293	52
221	32	24
223	66	123
1132		8
2211	1165	639
2212	15	3
2218	94	22
2219	142	16
2222	82	24
2228	118	133
2230		4
2236	6	4
2237	28	6
2247	23	18
4325	369	141
4330	160	201
4332	523	222
4333	317	276
4335	176	7
4339	75	13
4342	80	7
4344	21	40
10814	67	135
10819	155	17
52411	142	13
52413	28	
52414	70	6
52415	86	4
52416	8	20
52417	727	544
52418	259	96
59423	482	53
59424	74	30
59427	21	
59429	301	22
59430	805	345
Average	**200.4**	**93.8**

4 Discussion

4.1 Salmon

4.1.1 Migration Success Rates

In both 2009 and 2010, migration success from Sacramento to the Golden Gate (a distance of 207 km) was less than 25 % for both Chinook salmon and steelhead (Singer et al. 2011) However, migration success varied considerably between reaches and between years. Success for both species in the Delta was above 60% in 2009, yet dropped to below 45% in 2010. Conversely, successful migration through San Francisco Bay was only around 50% in 2009, yet increased to over 75% in 2010. This apparent reversal in the relative success rates (which might be assumed to reflect mortality) may be counterintuitive, given that flows were higher in 2010, and flows are often associated with increased survival (Simms and Ossiander 1981). Fischer *et al*. (1991) found that survival of salmonid smolts in the delta was positively correlated (r = 0.95) with volume of flow and that the survival rate changed greatly as the flow changed. This apparent paradox may have resulted from indirect effects of climate and flow– the 2010 releases occurred in March, one month later than in 2009. Additionally, during the 2010 outmigration period, the western coast of North America was experiencing El Niño conditions. This may have influenced the location and abundance of salmon smolt predators, such as striped bass, in the watershed.

Successful migration rates were higher in both years for Chinook salmon than steelhead, although this may not necessarily reflect different survival rates. The random delay on the steelhead tags was nominally twice that of the Chinook salmon, so fish being transported out of the Golden Gate at peak tidal flows are more likely to traverse the detection range of the array between pulses without being detected. Some steelhead, unlike Chinook salmon, may residualize and remain in freshwater for their entire lives. In both 2009 and 2010 we observed a much higher initial loss for steelhead than for Chinook salmon - over 120 steelhead in 2009 and 160 in 2010 were not detected anywhere downstream after release, compared with 12 Chinook salmon in 2009 and 18 in 2010. Tag retention studies conducted on hatchery fish of both species indicate that there are differences in tag shedding. Sandstrom *et al*. (2011) concluded that after 60 days, steelhead tagged with Vemco V7 ultrasonic transmitters shed their tags eight percent of the time. In contrast, Ammann *et al*. (2011) concluded that after 120 days 100 percent of Chinook salmon retained their tags, so that tag shedding is unlikely to be a source of error in our migratory success estimates for Chinook salmon. Another possible bias is that steelhead may be more affected by the stress involved in transport and release. The steelhead tagged in this study were of much larger size and transported in the same size tank as the Chinook salmon.

4.1.2 Transit Rates

Both species transited the entire study area, from Benicia Bridge to the Golden Gate, in under a week. In both years, the median transit time was 2.7 days, implying an overall transit rate of 17 km per day, or around a body length per second. Given that a large proportion of the fish were subjected to tidal sloshing at least once, this would suggest that they are moving directly and rapidly through the bay to the ocean. MacFarlane & Norton (2002*)* found that Chinook salmon smolts moved rapidly through the estuary, averaging 50 kmd^{-1} (3.7 body lengths per sec). MacFarlane (2010) concluded that Chinook salmon smolts gained little energy during their presence in the San Francisco Bay Estuary, and that they underwent a period of rapid growth upon entering the ocean, so that the nursery function of the estuary was deferred to the initial ocean residence. Melnychuk *et al.* (2007) measured travel speeds for steelhead migrating to the Strait of Georgia to be 0.7-0.9 body lengths (BL) per second, and a maximum of 3-5 $BLsec^{-1}$ in river currents of 1 ms^{-1}. For Chinook salmon there was no correlation with transit rates and tidal flows but steelhead seemed to have a small relationship with transit rates and ebbing tidal flows.

Other studies have found that flow (either tidal or discharge) has very low explanatory value with respect to transit rates (Tiffan *et al.* 2009). By using cross-section velocities at different river stretches Tiffan *et al.* (2009) found a strong relationship between water velocity and transit rates. They also found that fish spent more time actively swimming and meandering in deeper areas with lower water velocities suggesting that they may be cuing their downstream movement based upon water velocity. Greater than 50% of each species experienced at least one upstream movement between receivers during their outmigration. Given a semi-diurnal tidal cycle and an average transit time of 2.7 days, we might expect fish to be subjected to approximately six incoming tides as they move out of the estuary. It is likely that many more undetected upstream movements occurred out of the detection ranges of the receiver array, however, it was rare to detect a fish making more than three upstream movements. In the case of Chinook salmon, individuals for whom more than three upstream movements were detected were unlikely to reach the Golden Gate. This would suggest that repeated tidal sloshing is harmful to the smolts' chances of successful outmigration, and that the low frequencies of tidal sloshing in individuals may be due not only to the positioning of the array, but to a behavioral response to the incoming tide.

A significant number of smolts were detected at the Bay Bridge, and presumably entered the South Bay, perhaps transported by currents. However, many of these fish were eventually detected at the Golden Gate. Whether the presence of smolts from the Sacramento River in the South Bay and their subsequent success in reaching the ocean is a result of passive transport or rather an active strategy, is a topic that requires further study, although many detections at the Bay Bridge appeared to be fish which had been swept up from Alcatraz or the Golden Gate on incoming tides, after which they returned downstream.

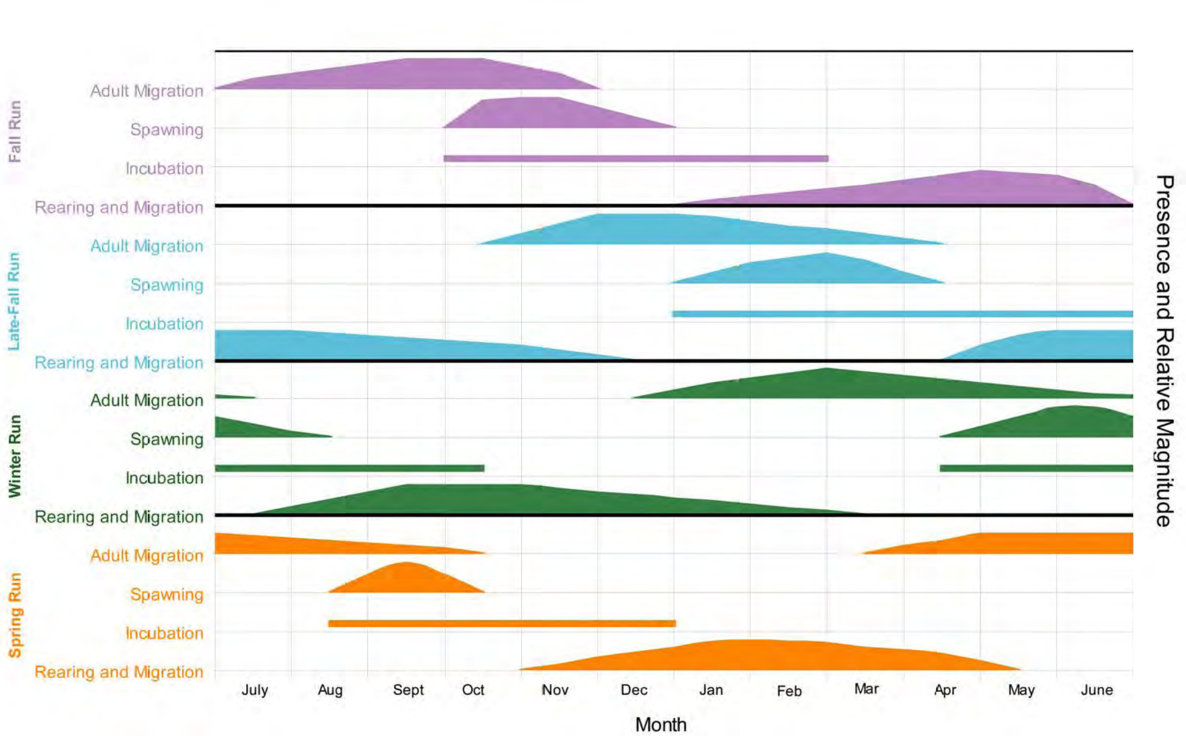
The detections at the flats array and the bridge cross sections both indicate that fish preferentially utilized the channel sections of the estuary. This is supported by the small numbers of fish detected at marina sites around the bay and tributaries. The exception to this was Martinez Marina, however, given the location of this site in Carquinez Strait, we might expect the receiver to detect fish coming through the strait and not necessarily entering the marina.

4.1.3 Exposure Times

Those fish which were present at marinas or dredged sites other than the main shipping channel were only present at receiver sites for short periods of time, and mostly for less than 30 minutes. Although this time refers to the presence within range of a receiver, and should be scaled up in terms of the entire site, together with the rapid overall transit times this provides evidence that the fish do not utilize the estuary to any great extent other than as a conduit to enter the ocean from the freshwater system. Other studies (Dawley *et al.* 1986 and Simenstad *et al.*1982; both cited in LFR 2004) have shown that juvenile Chinook salmon may either move rapidly through estuaries or reside there for up to 189 days. It is important to note that late-fall run Chinook salmon exhibit stream-type life histories and these fish typically do not spend extended periods of time rearing in estuaries (Moyle 2002). Therefore, these results may not be applicable to Central Valley fish that exhibit ocean-type life histories.

There was no evidence of fish residing at particular sites for extended periods. As such, direct interactions between individual fish and dredging activities are likely to be infrequent and brief. One of the major potential risks of dredging activities to juvenile salmonids identified by LFR (2004) was direct entrainment, which usually results in the death of the individuals entrained. By avoiding periods when large numbers of outmigrating salmonid smolts are likely to be in the area, dredging windows address this issue. However, the indirect interactions should be considered when undertaking a full analysis of the risk posed to Chinook salmon and steelhead smolts by dredging activities. Suspended sediments and increased turbidity can provoke a range of negative responses in fish, including respiratory interference and puncturing of structures (LFR 2004). Levels of dissolved oxygen (DO) near the Bay floor may decrease from 80-85% to 20-30% within minutes after dredged material is released, but recovered to ambient levels within ten minutes (USACE 1976, cited in LFR 2004). According to a study by Varanasi *et al.* (1993), significantly higher chemical contaminants (AH's and PCB's) in the stomachs of salmonid smolts and evidence of immunosuppression resulted from the fish being exposed to highly polluted estuarine waters in Puget Sound, Washington. However, the NMFS Biological Opinion (Whitlock 1999) concluded that body burdens of toxins in juvenile salmon and steelhead in San Francisco Bay were below chronic toxicity levels even with the pre-LTMS dredging regime (LFR 2004).

Table 55. General Life History Characteristics of Upper Sacramento River Chinook Salmon (from Vogel and Marine 1991).



Denotes presence and relative magnitude

Denotes presence only

Four distinct runs of Chinook salmon occur in the San Francisco/San Joaquin watershed. These runs are named for the season during which adults make their upstream spawning migration. Fall run and late-fall run are listed under the Endangered Species Act as "Species of Concern", spring run are listed as "Threatened", and winter run are listed as "Endangered". Adult Chinook salmon are present in the Sacramento River throughout the entire year (Yoshiyama *et al.* 1998). Juvenile Chinook salmon emigrate from the Central Valley throughout most of the year with overlap between runs (Figure 55) but are likely present throughout the river and in the San Francisco Estuary in every month of the year due to overlap in the timing of emigration (pers. comm. Yoshiyama). From this study we have determined that late-fall run Chinook salmon transit the estuary quickly but caution must be exercised when considering them as surrogates for other runs. The same is true when considering late-fall run fish as surrogates for pathways that other runs of salmon may take through the estuary. It is reasonable to expect that smaller fish would be more susceptible to tidal sloshing and would therefore take longer to exit the estuary. These fish may also act more like particles and be swept onto the flats or into marinas. It is also possible that these fish would be affected to a greater extend by dredging activities either because they are less capable of avoiding active dredging operations or that they may be less tolerant to toxins that have been re-suspended in the water column. Steelhead are an iteroparous species meaning they are capable of multiple reproductive cycles throughout their lifetime. Therefore, many Central Valley steelhead may transit the San Francisco Estuary four or more times. Hallock *et al.* (1961) found that juvenile steelhead migrated downstream during most months of the year, but the peak period of emigration occurred in spring, with a much smaller peak in fall. The emigration period for naturally spawned steelhead juveniles migrating past Knights Landing on the lower Sacramento River in 1998 ranged from late December through early May, and peaked in mid-March (DFG unpublished data cited in McEwan, 2001). In this report we did not address the effects that toxins in the sediments of the San Francisco Estuary may have on juvenile and/or adult fish exposed to them. In order to determine the length of exposure that may adversely affect these fish, studies should be conducted on other runs as well as on the response of these fish to exposure to the sediments in the San Francisco Estuary. Studies should also be conducted on multiple exposures to toxins due to the fact that Chinook salmon transit through the estuary twice (once as a juvenile, once as an adult) and steelhead may transit four or more times.

4.2 Green Sturgeon

The only known spawning region for the federally listed Southern Distinct Population Segment (DPS) of green sturgeon is the Sacramento River. Spawning adults returning from the ocean must therefore migrate through the San Francisco Bay estuary to reach the spawning grounds. More importantly, there is a gap in our knowledge of the juvenile and sub-adult life history of this species (Allen & Cech 2007, and it is thought that young individuals may reside in parts of the delta and/or estuary for up to three years (Nakamoto *et al.* 1995), where they feed on a variety of benthic organisms such as crustaceans, clams and annelid worms (Radtke, 1966). Juveniles become capable of tolerating saline conditions at an early age (Allen & Cech 2007), and enter the delta/estuary system in their first year (Nakamoto *et al.* 1995). At present, adult green sturgeon have been tagged or tracked in studies mostly carried out by the University of California Davis (Heublein *et al.* 2008, Kelly *et al.* 2007) as well as three juvenile green sturgeon tracks (Mike Thomas in prep). Adults making spawning runs upstream tended to travel rapidly through the Bay once they entered through the Golden Gate in March/April, whereas two outmigration periods were identified – those adults which returned downstream immediately after spawning, and those which over-summered in the river and returned downstream in late fall (Heublein *et al.* 2008). Our results showed that tagged green sturgeon were present in all sections of brackish water (from the Golden Gate to Freeport) throughout the year (Fig. 50), although in greater numbers in fall and winter. The greatest presence of fish in the Bay occurred in fall. However, the presence of fish in the Bay was limited to only a few days, with the exception of one individual which oversummered in the Bay. We also found two distinct outmigration periods, with several fish leaving to the ocean in Oct-Nov 2009 and another group leaving in January 2010. Fish entered the system in February and March 2010. However, not all fish entering the system went on to make upstream movements beyond Carquinez bridge. Several were only detected at the Golden Gate, while others went as far as San Pablo Bay before returning to the ocean.

The risks posed to green sturgeon from dredging activities must therefore be identified for two life stages – those fish which spend most of their time in the marine environment, and enter the estuary to migrate upstream to spawn; and those juvenile fish which may reside in the Bay for extended periods. Migrating adult and juvenile sturgeon may be at risk to direct effects of dredging and plumes of deposited material. Resident juvenile green sturgeon feeding on benthic organisms may also be at risk of indirect effects such as bioaccumulation of toxins, or modified benthic communities/food sources.

Between 2001 and 2002, five subadult (101-106 cm total length [TL]) and one adult (153 cm TL) individuals were tracked for up to nine days were associated with the bottom (Kelly *et al.* 2007). One individual swam directly out of the Bay into the ocean, but the remaining individuals moved in both channel and shallow areas, although preferentially in the latter, generally along the bottom, although fish were more likely to be within the top meter of the water column when making directional movements. Our cross channel arrays showed that more green sturgeon were detected in the channel than along the shallow areas, although information on their depth at these sites is not available. They may orient to the strongest current to navigate upstream to their spawning grounds.

Green sturgeon were not generally found at marina sites for longer than a couple of hours, with the exception of one individual which remained within range of the Vallejo Marina receiver for two days. Presence at marinas may increase the risk of propeller strikes, propeller strikes in general throughout the bay are not uncommon (pers com Brian Delano, Department of Fish and Game boat operator)

In 2011, a team of researchers at UC Davis aims to tag resident juvenile and subadult green sturgeon in the Bay. The movements of these fish in relation to our array of receivers will provide much needed information on the non-migratory fish which utilize the Bay on a residential basis.

4.3 Future work

In 2011 the focus of the study will be shifting towards green sturgeon. The array will remain in the same configuration to detect salmonids that will be tagged by other researchers as we will not be tagging Chinook salmon and steelhead for the LTMS fish tracking study. By keeping the array in the same configuration, 2011 will need to serve as a pilot study for detecting green sturgeon in the estuary. We will also be adding four monitors at the SF9 placement site in northern San Pablo bay below Carquinez Bridge. We will determine whether or not these monitors remain in the exact location of deployment. If the monitors remain in the same position we may be able to deploy a Vemco Positioning System (VPS) in this location. The VPS allows researchers to track the movements of fish in two dimensions as they traverse through the placement site. It is possible that these tracks can be correlated to a placement event to determine potential behavioral changes when sediment is placed in the bay.

DRAFT -- NOT FOR ATTRIBUTION

Acknowledgements

We would like to thank Chuck Morton and Charlotte Cashin for scheduling boat time and assisting on the Caltrans vessel with the maintenance of the monitors deployed on the Bay Bridge and Richmond San Rafael Bridge. We greatly appreciate the help from everyone in the UC Davis Biotelemetry Laboratory (Mike Thomas, Anna Stephenson, Gabe Singer, Phil Sandstrom, Dennis Cocherell, Michel Buckhorn, and Jamilynn Poletto) for volunteering their time to assist with the surgical implantation of the tags. We would also like to thank Arnold Ammann and Cyril Michel at the Santa Cruz office of the NMFS for maintaining the database which made it possible to assemble detections from many different studies. Finally, we would like to acknowledge David Woodbury for his input into the design of the study.

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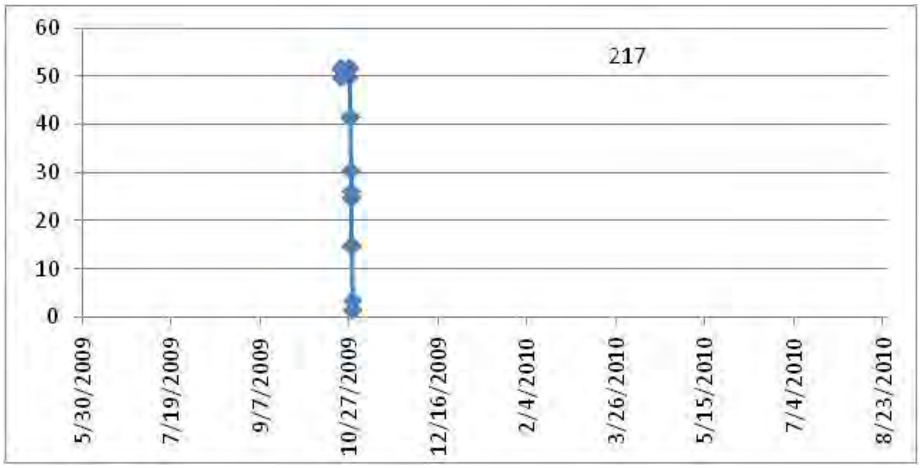
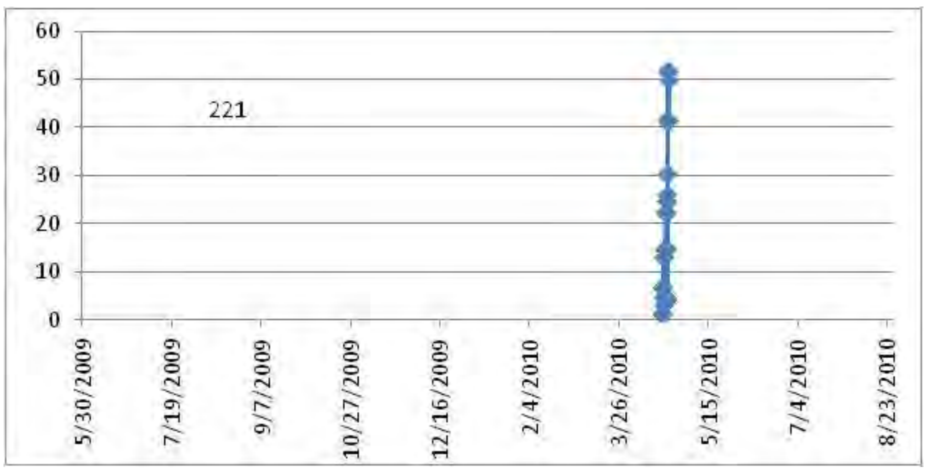
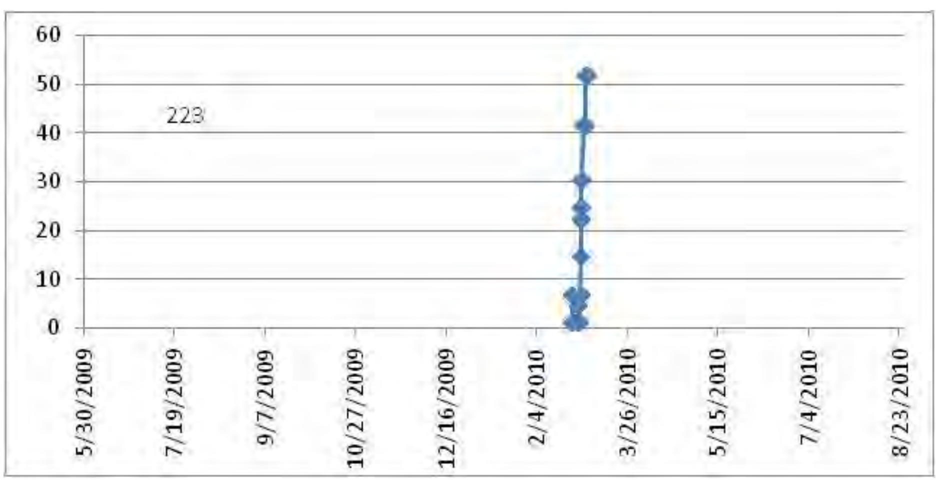
DRAFT -- NOT FOR ATTRIBUTION

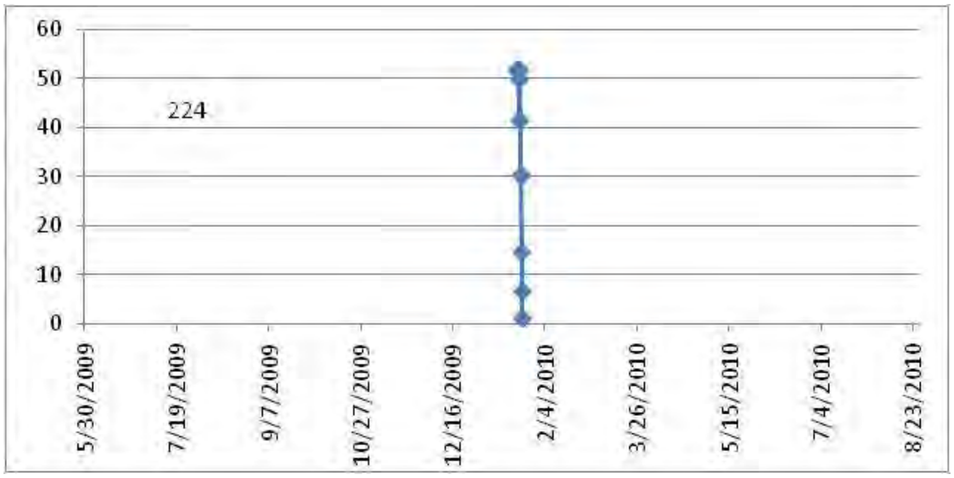
Appendices

Appendix 1. Green sturgeon movements through the San Francisco Estuary.





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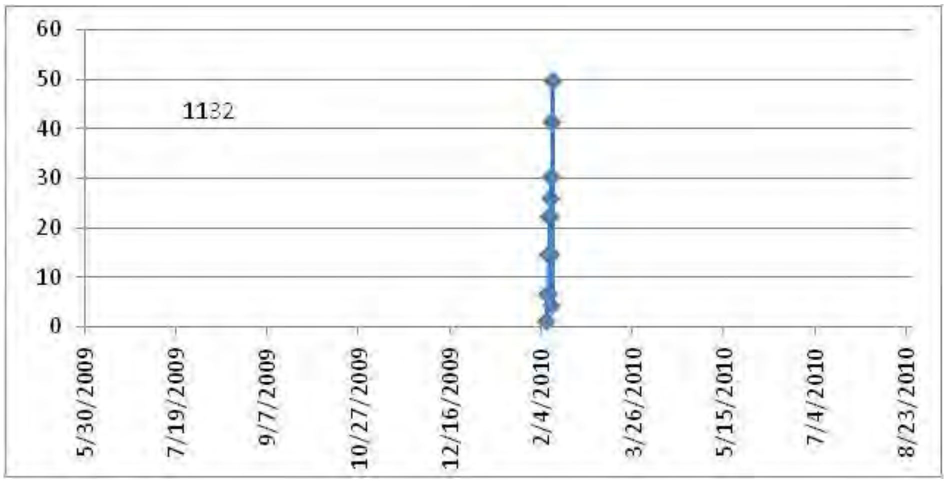
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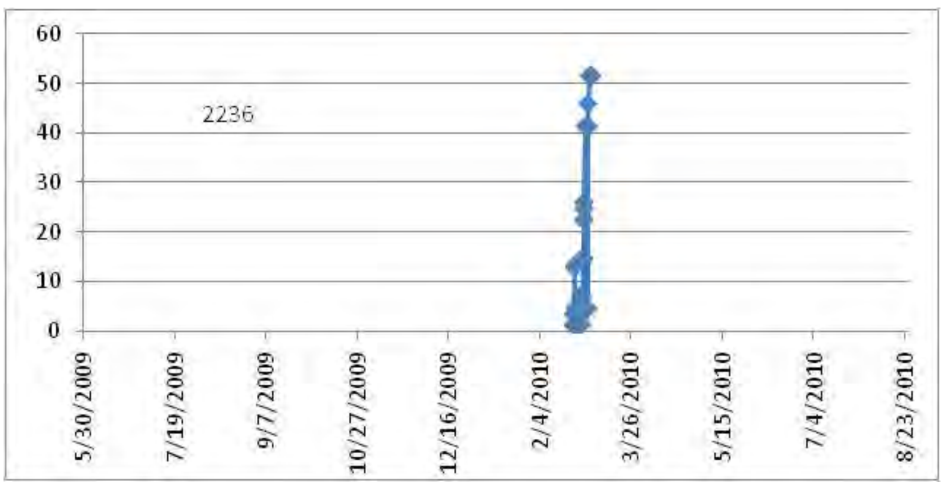
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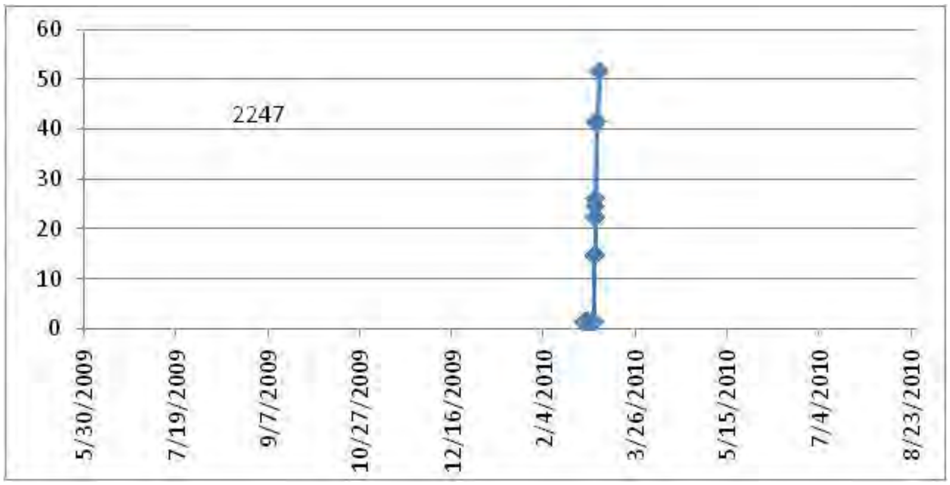
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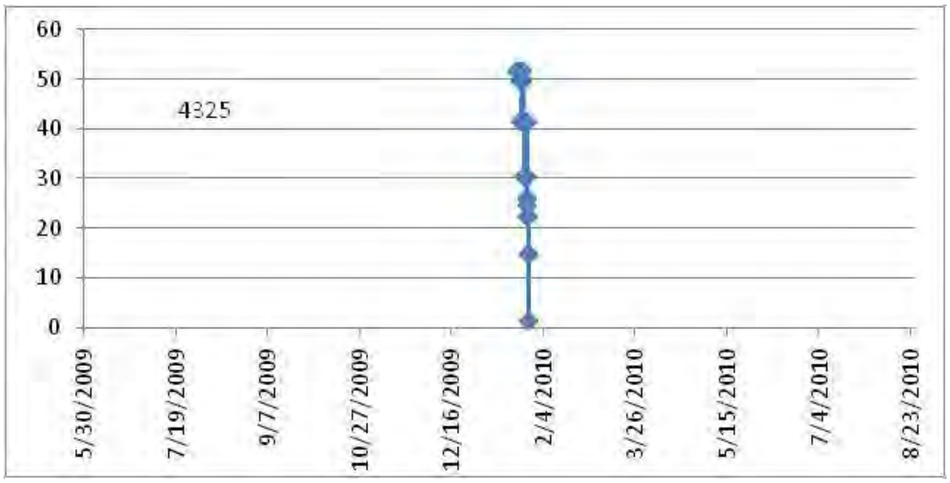
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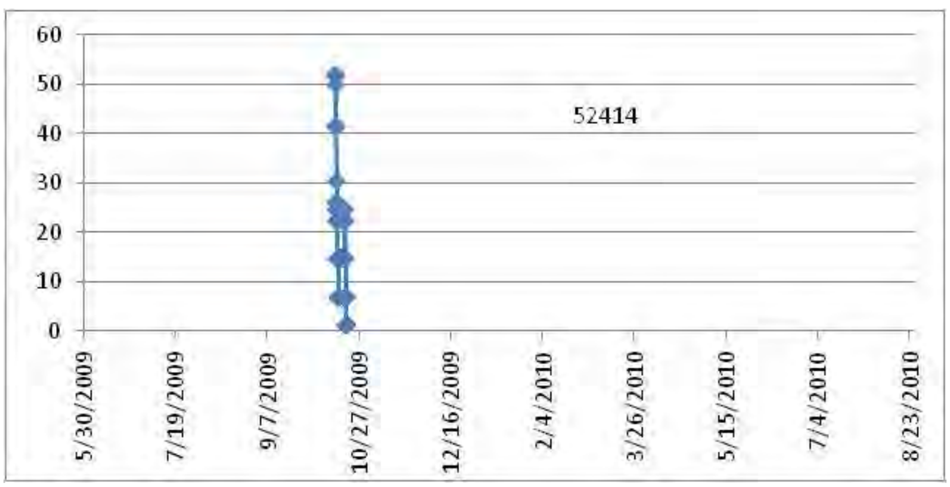
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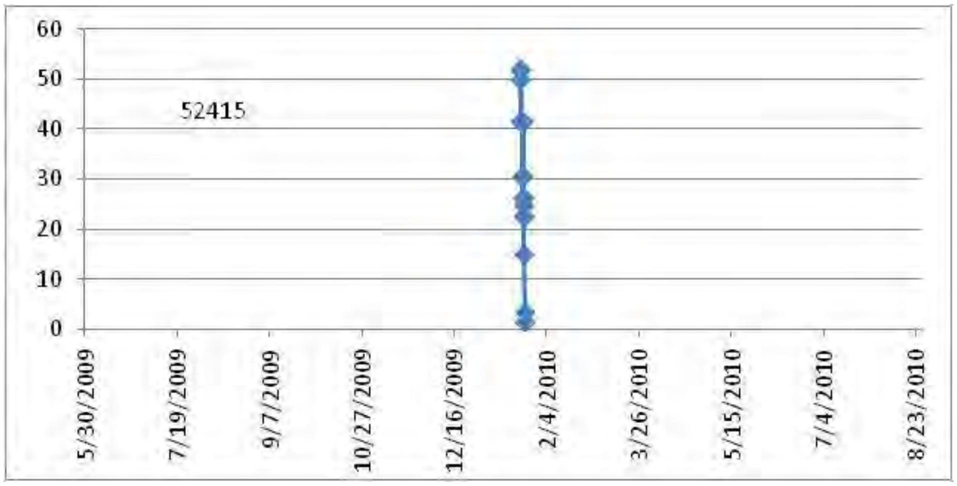
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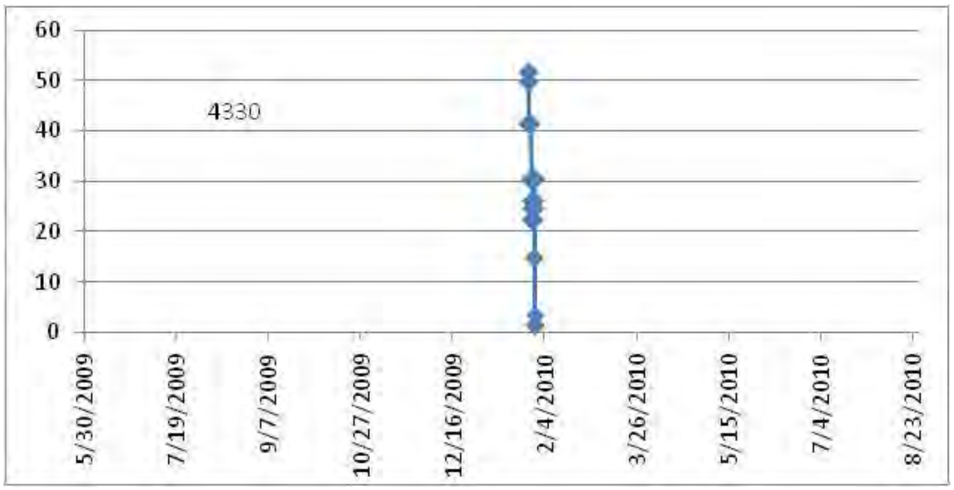
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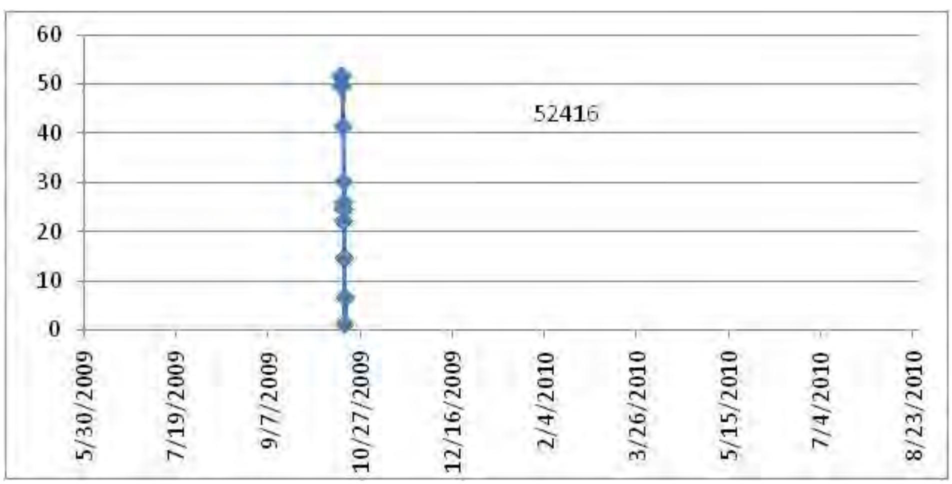
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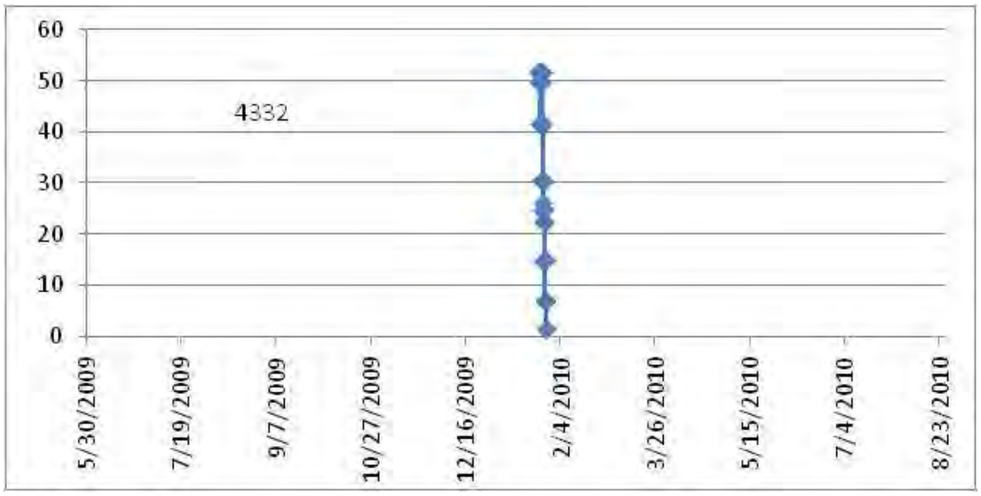
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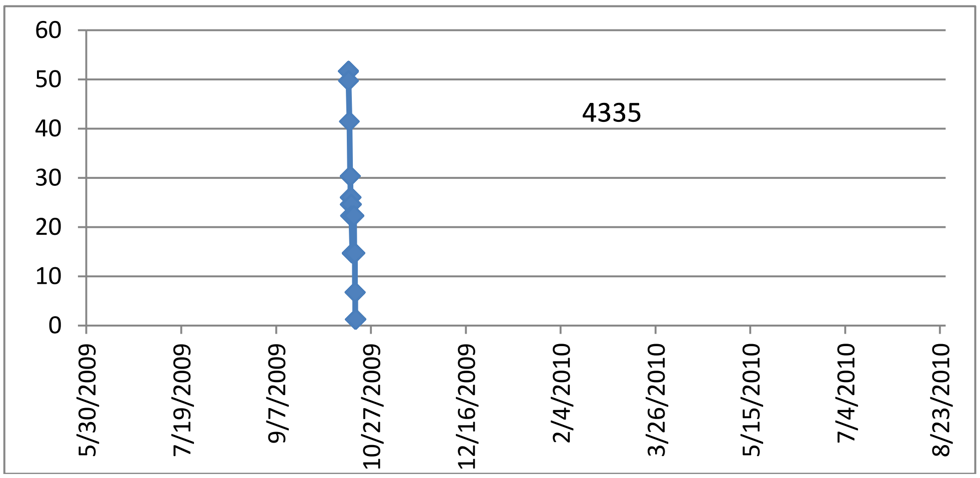
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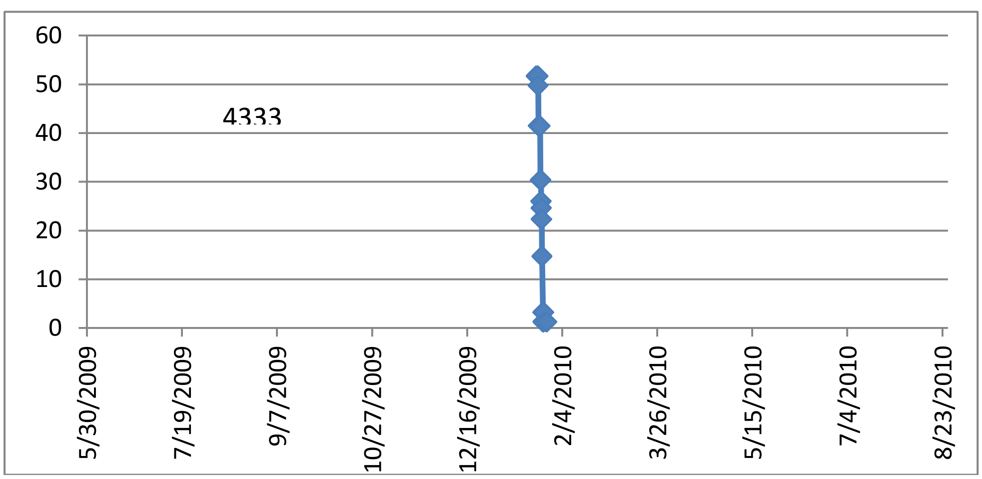
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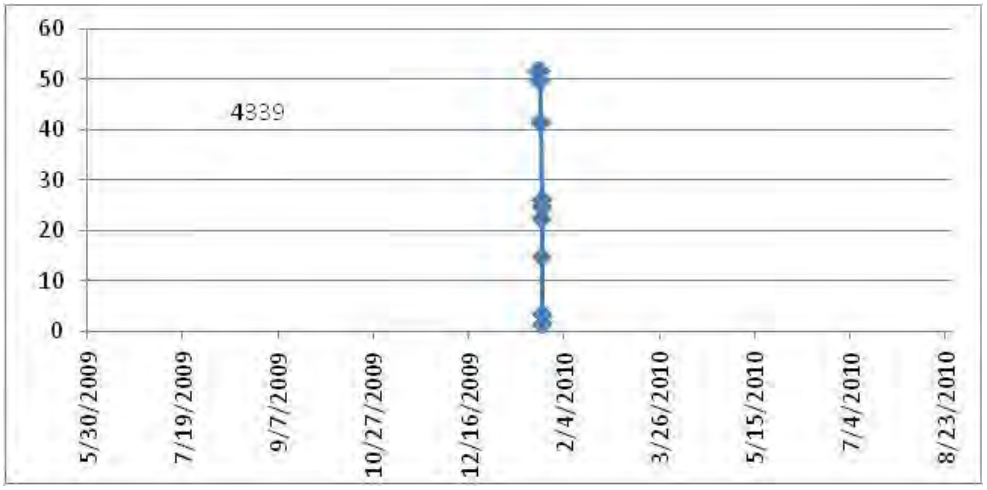
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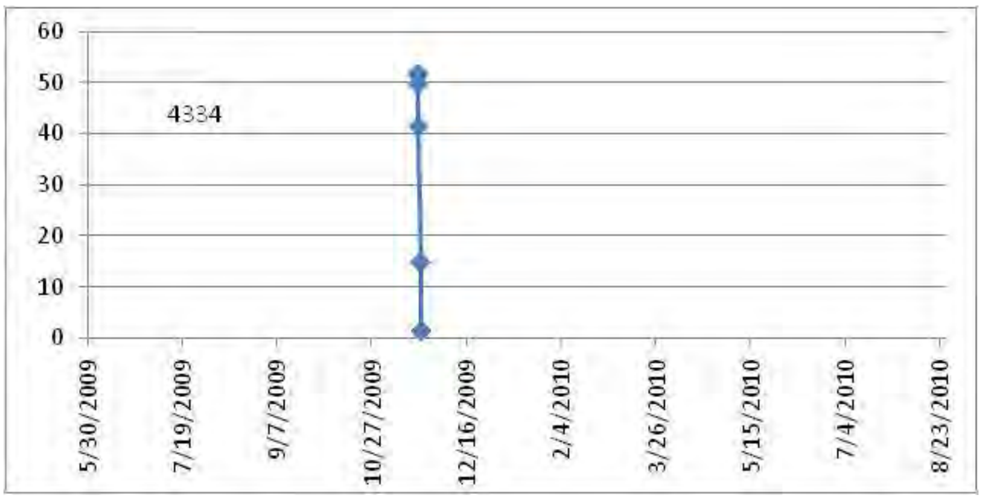
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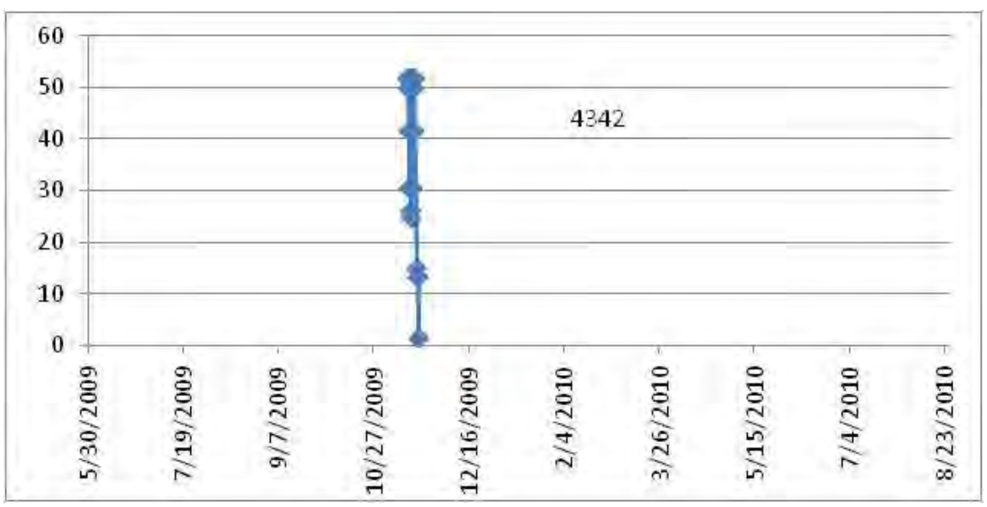
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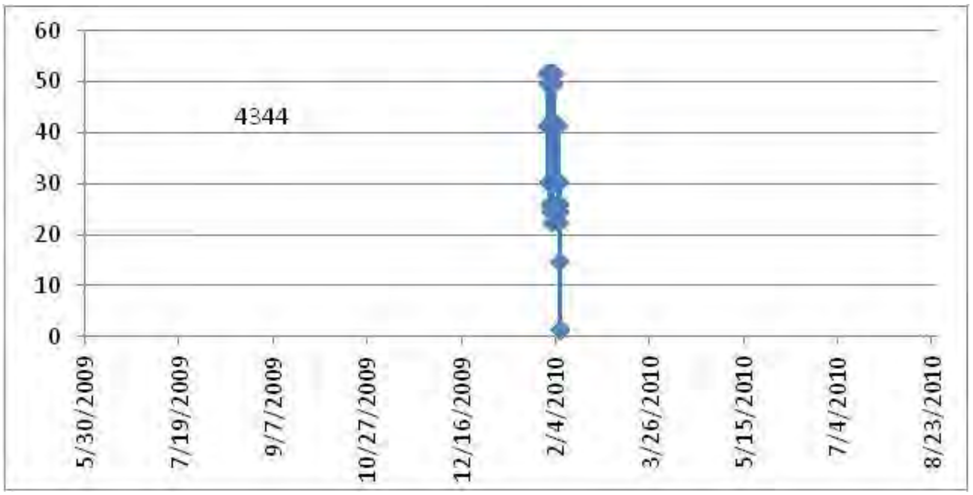
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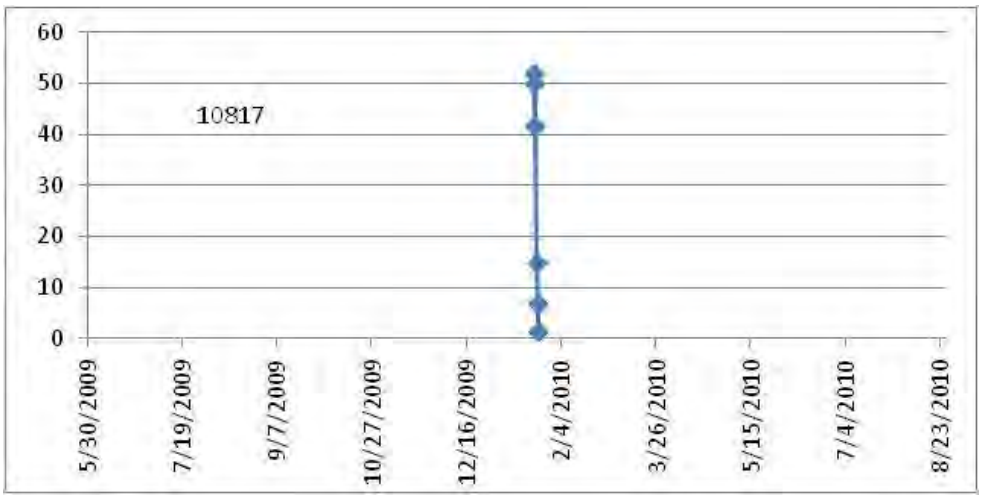
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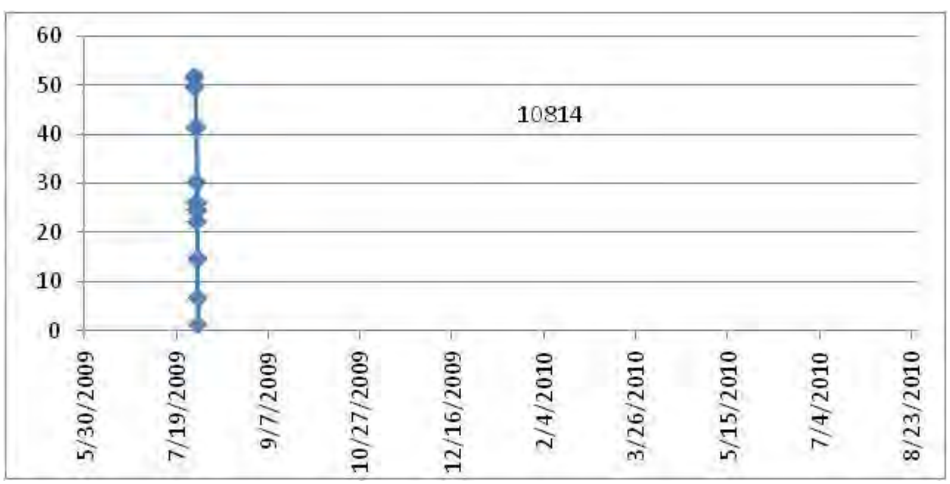
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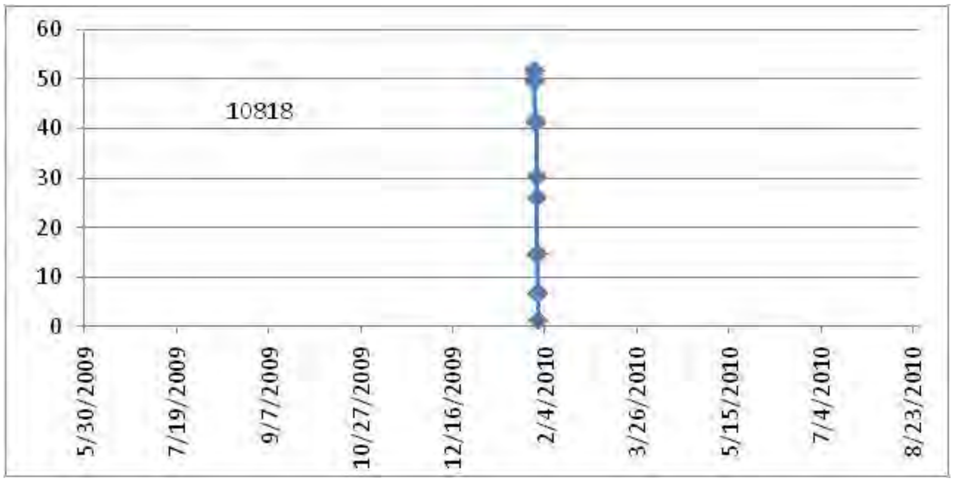
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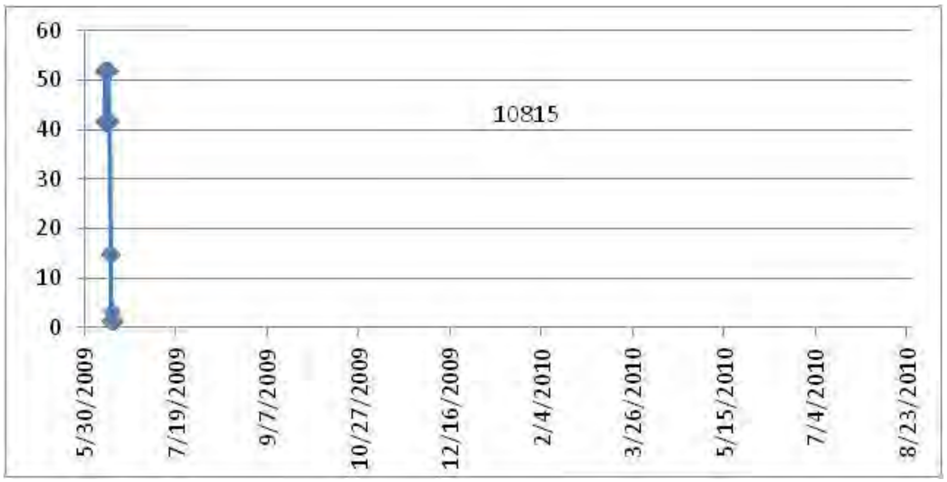
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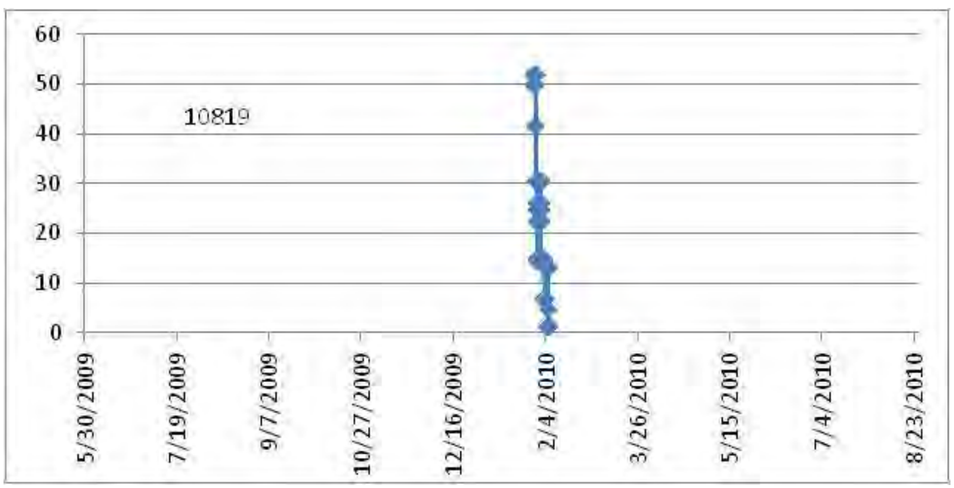
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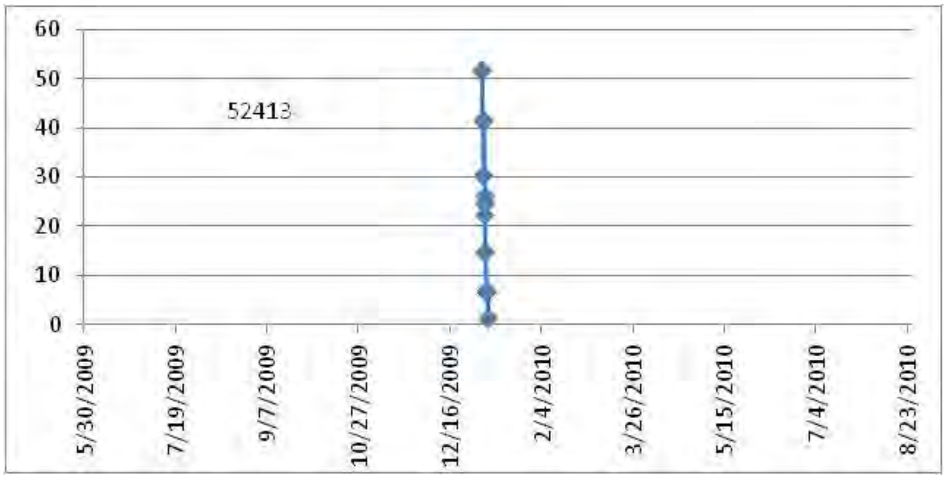
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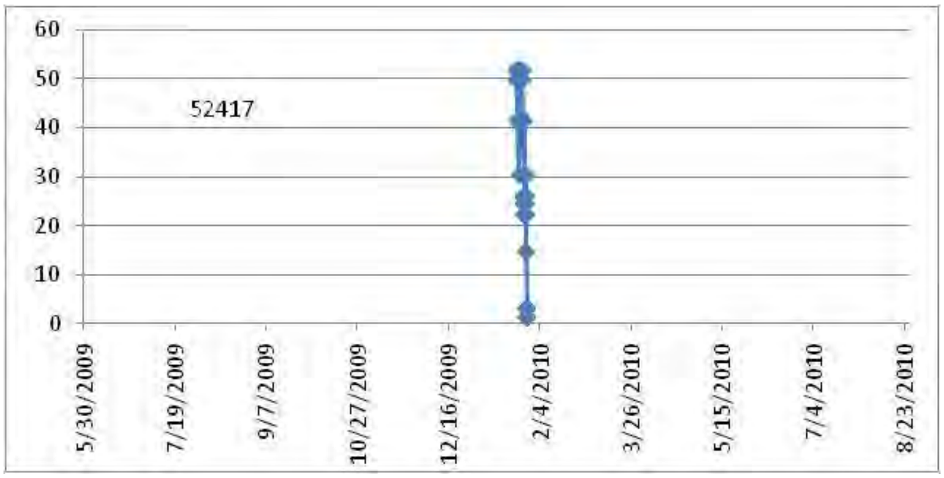
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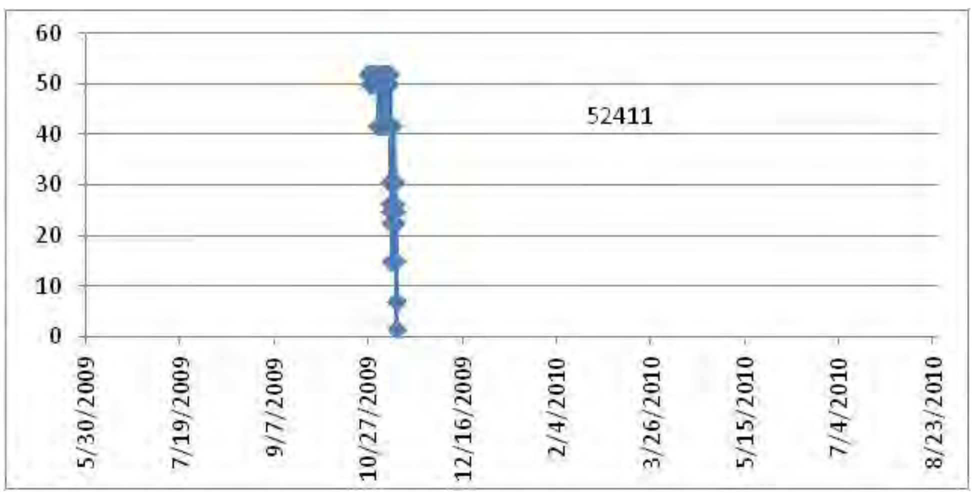
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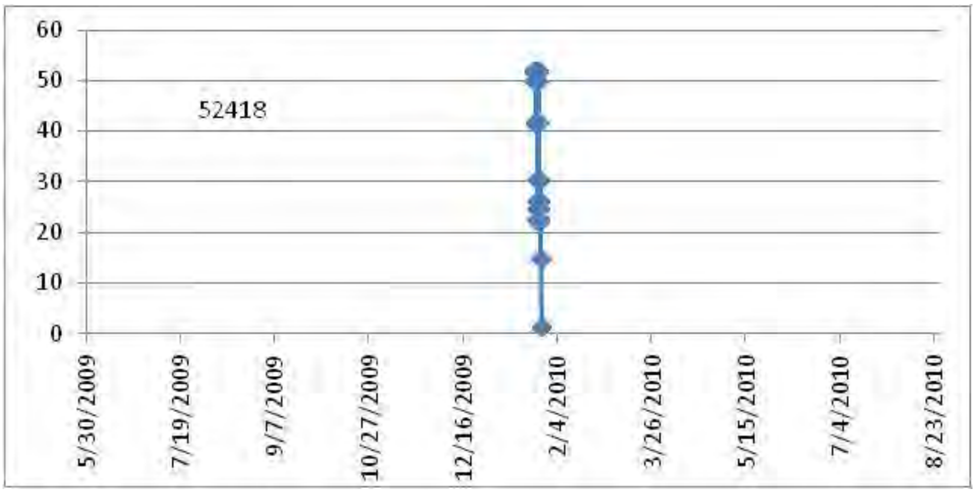
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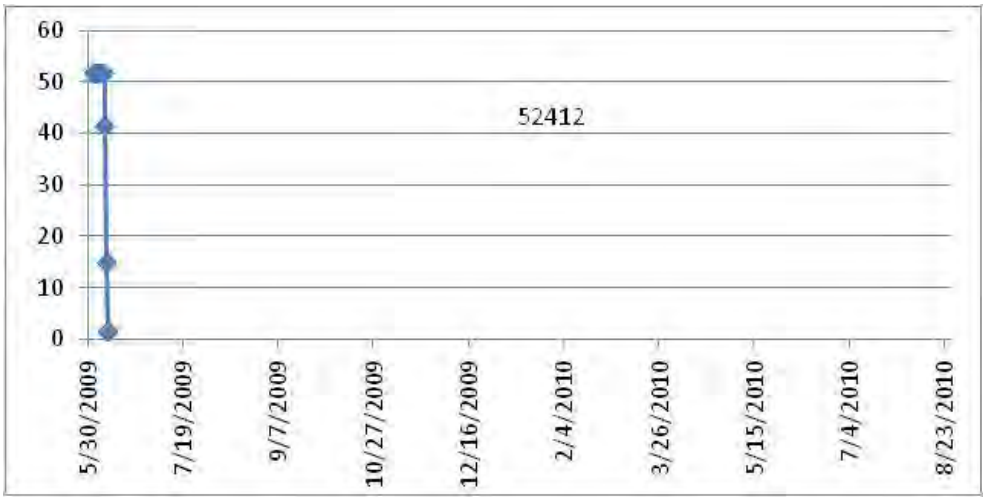
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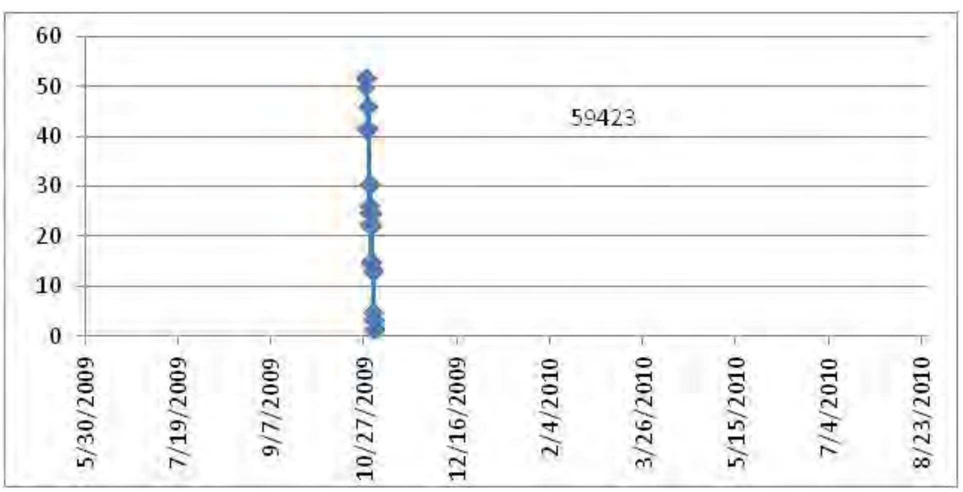
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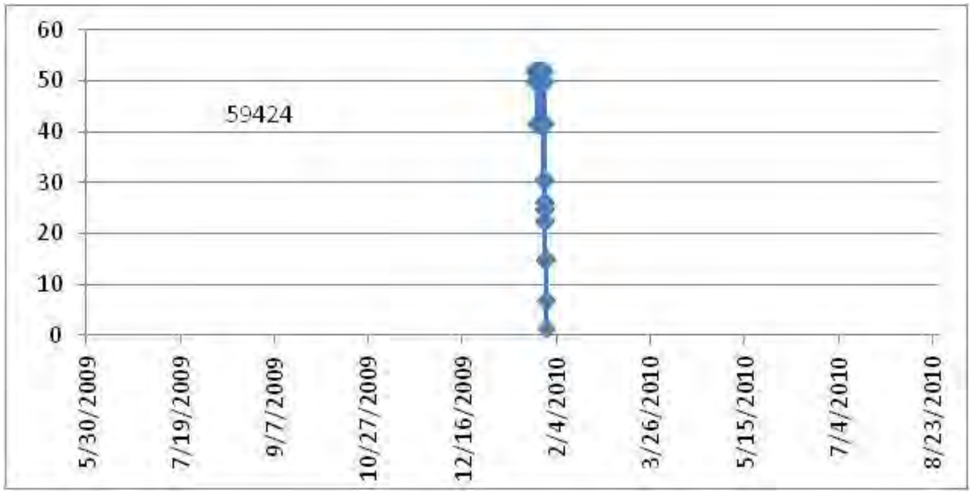
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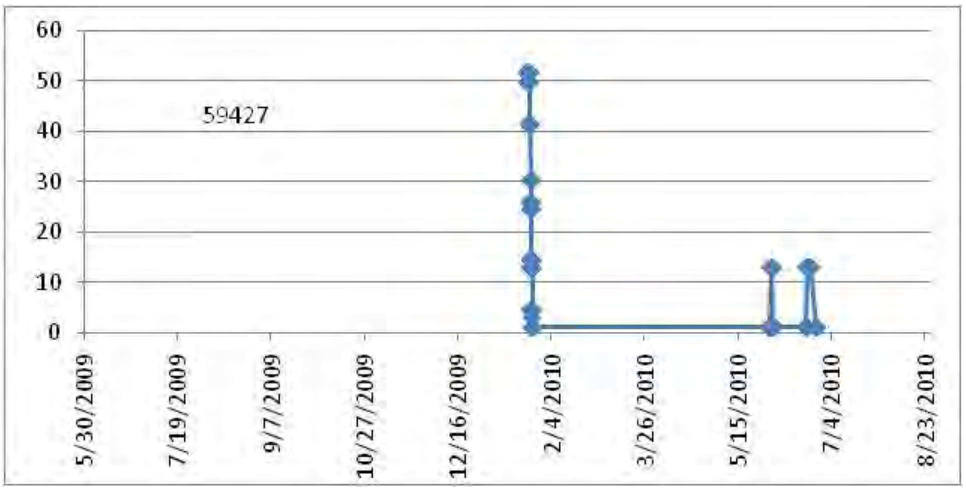
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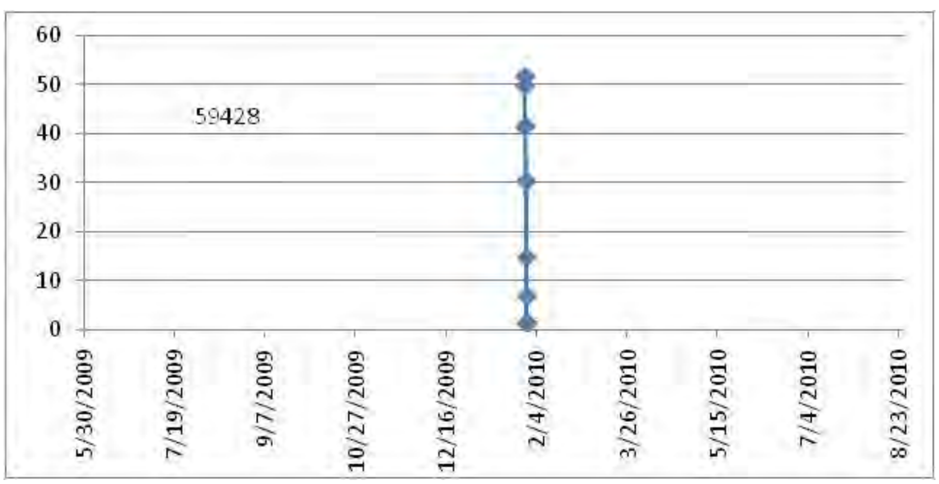
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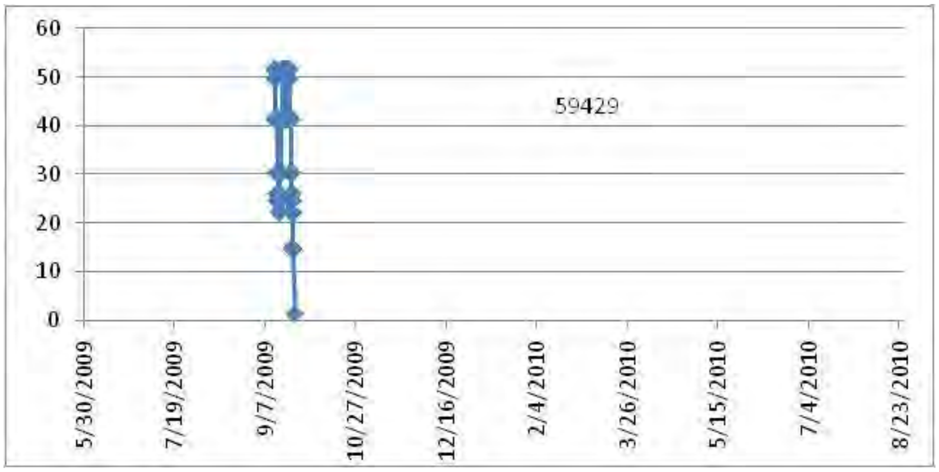
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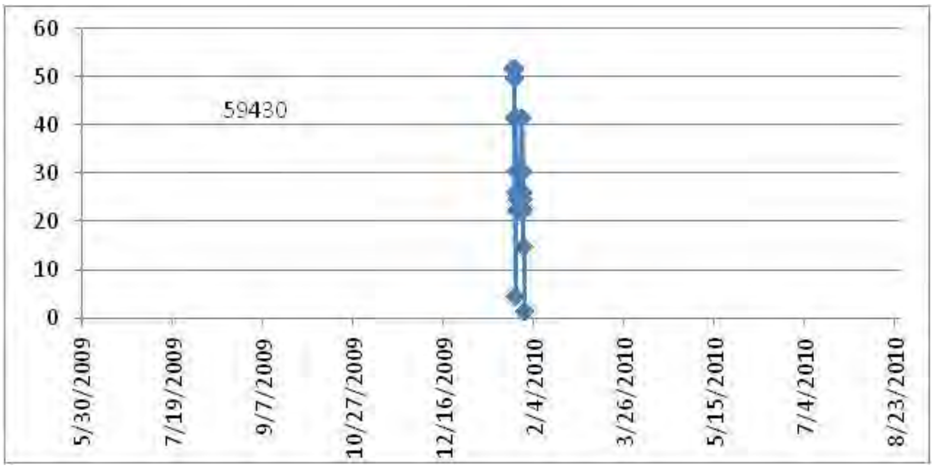
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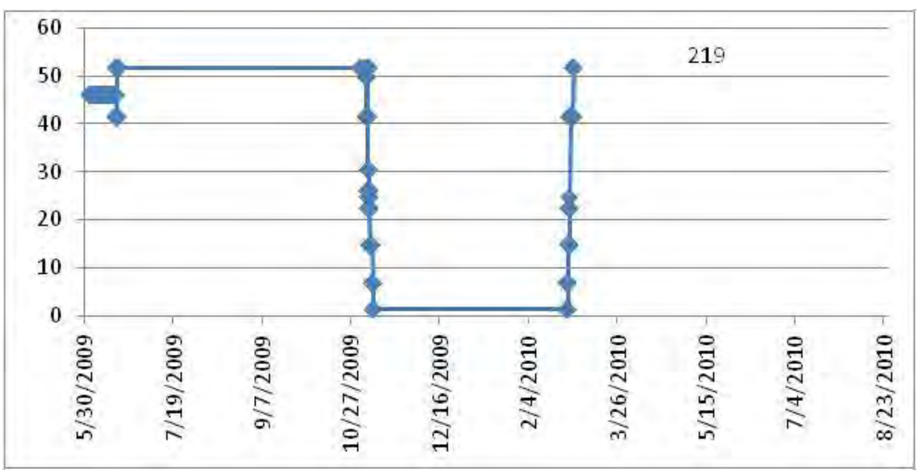
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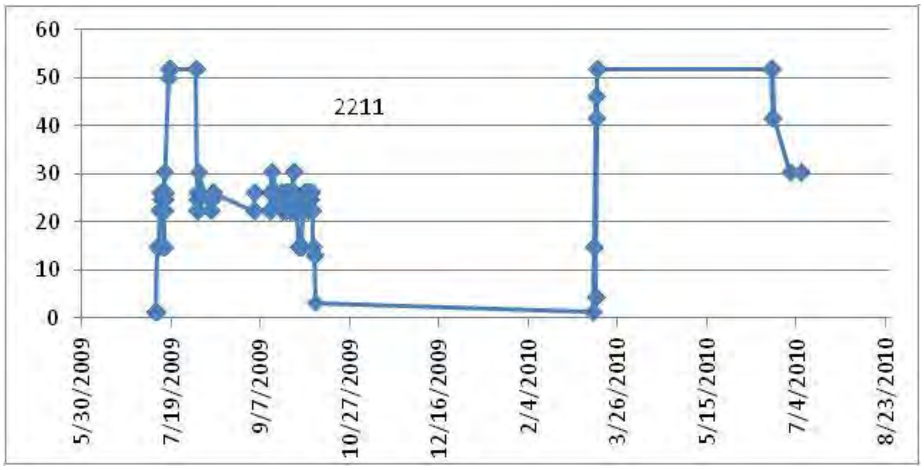
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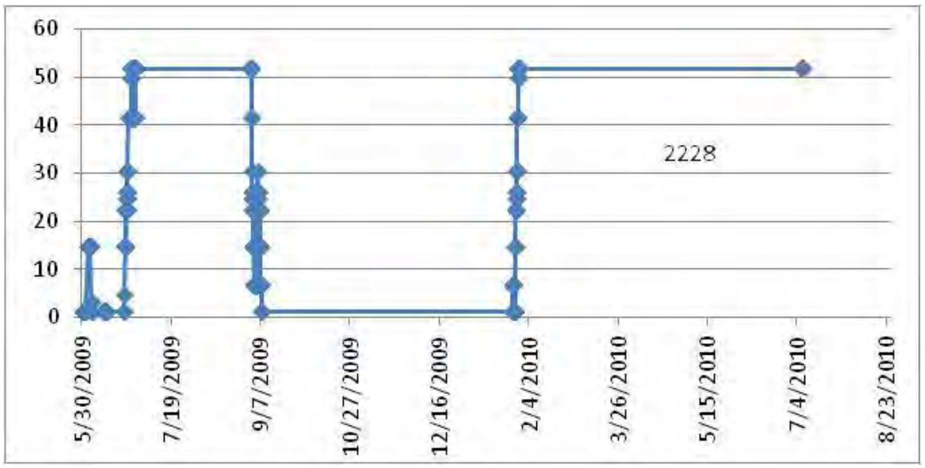
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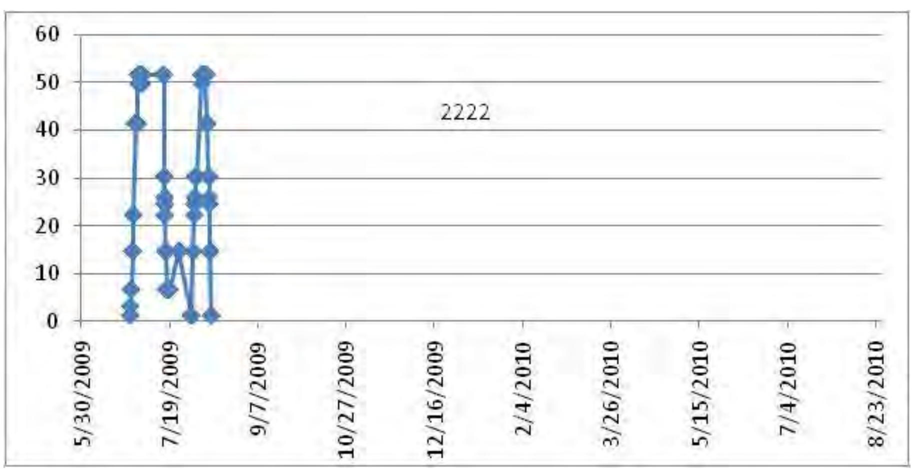
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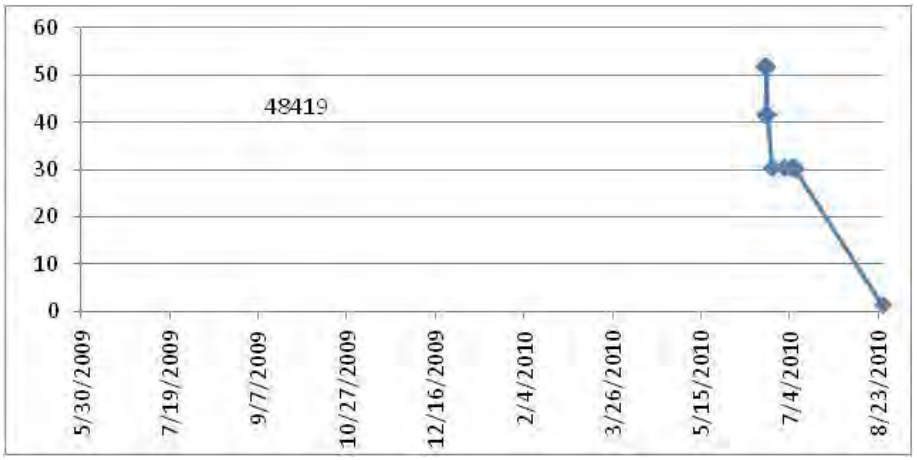
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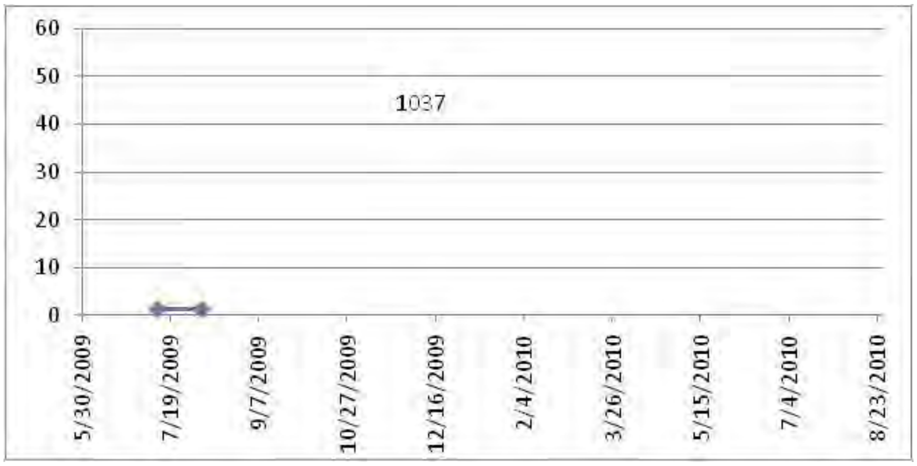
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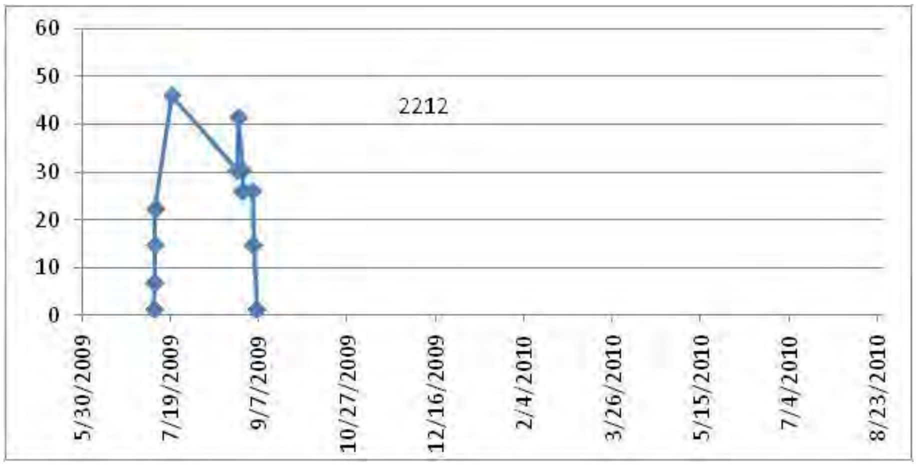
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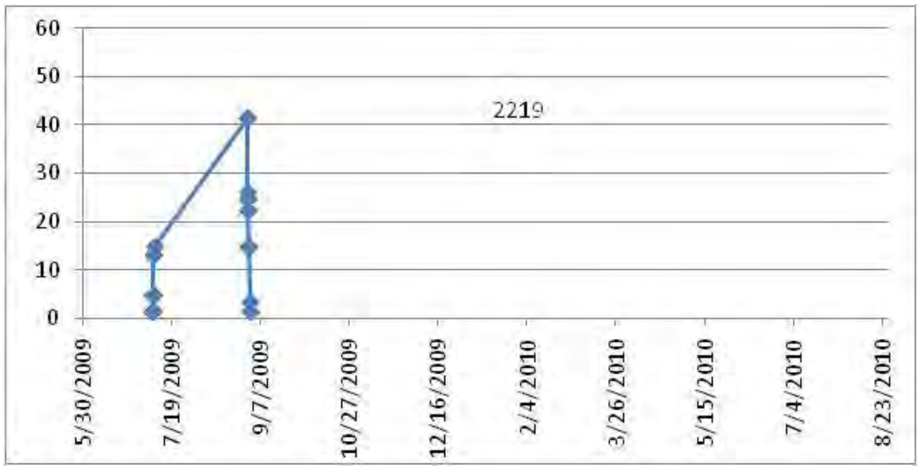
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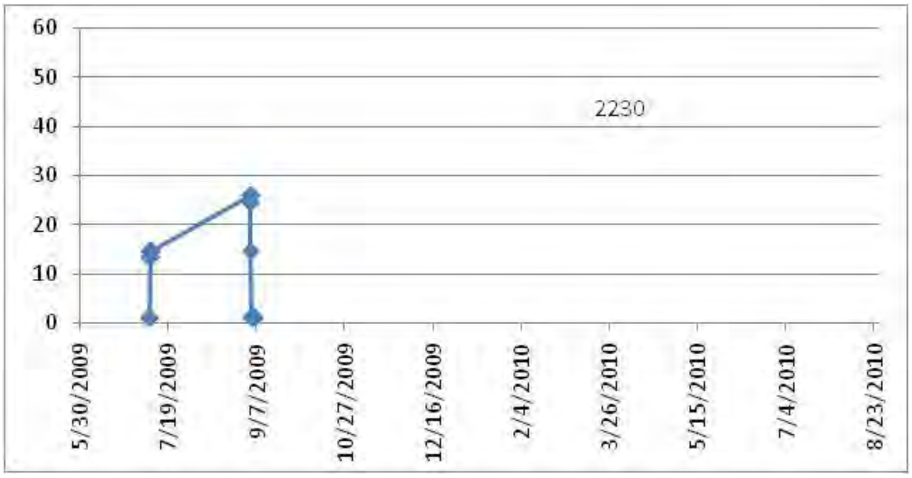
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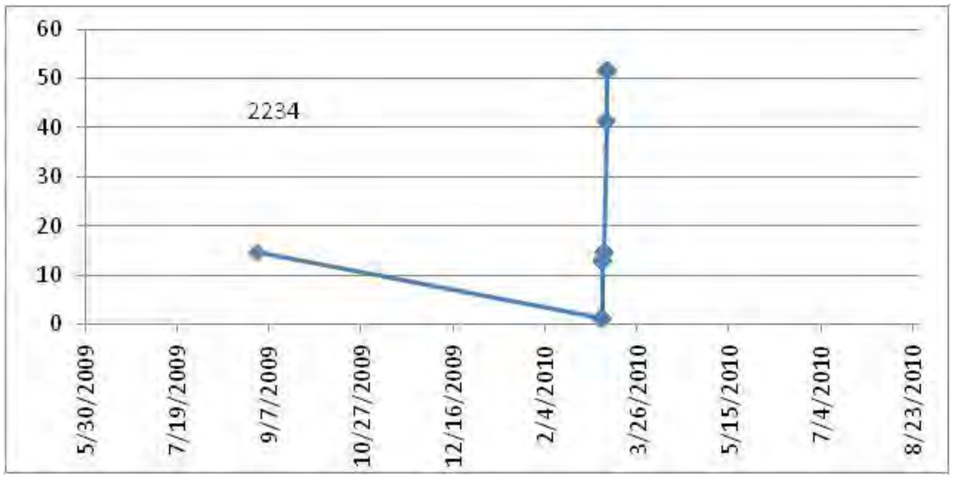
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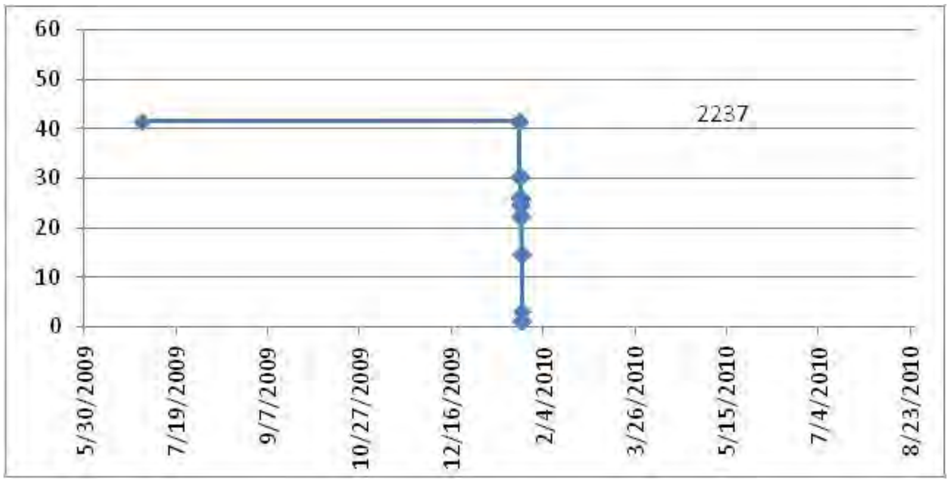

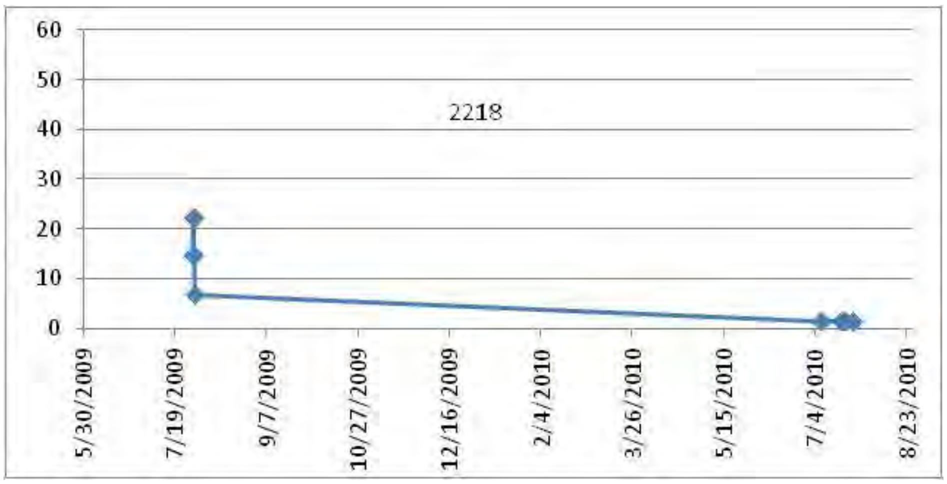

DRAFT -- NOT FOR ATTRIBUTION