Acoustic Tracking of Juvenile Chinook Salmon Movement in the Vicinity of the Delta Cross Channel.

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Executive Summary

A significant portion of salmon restoration efforts within the San Francisco Bay/Delta system have been aimed at reducing mortality of juveniles during their outmigration through the Delta. Efforts to reduce in-delta mortality have focused on a variety of issues, ranging from stranding mortality in agricultural diversions, to increased predation of smolts in the interior delta, to mortality related to pumping at the SWP and CVP. An emerging theme common to all these issue is the need for a better understanding of the physical and biological processes that determine whether a juvenile salmon in will be entrained in critical junctions or diversions.

The Delta Cross Channel (DCC) is the largest and most significant man-made diversion in the Northern Delta. The DCC consists of a man-made channel connecting the Sacramento River to the Mokelumne River system via control gates. In recent years, statistical analysis of marked-recapture data has led to concerns that endangered winter run Chinook juveniles migrating down the Sacramento River may be entrained in the Central Delta via the DCC. As a result, DCC operations have been modified to include gate closures during the fall and winter. Because DCC gate closures have very significant political and economic ramifications, a high premium has been placed on understanding the effects that the DCC has on juvenile salmon outmigrating through the Sacramento River System.

In the fall of 2000, a multidisciplinary team of scientists conducted a pilot study of juvenile Chinook movement in the DCC junction area. A central portion of this study

was the use of hydroacoustic transducers to track the movement of juveniles released in the Sacramento River upstream of the DCC. Data from this study indicated that in the section of the Sacramento River above the DCC, the rate and direction of juvenile movement seemed to be determined by the bulk flow in the Sacramento River. This finding led researches to pose a key question: Are emigrating smolts entrained in the DCC in direct proportion to the amount of flow entering the DCC? Because the answer to this question has very significant management implications, it formed the focus for the full-scale study conducted in 2001, and the focus for the analysis of study data.

On October 29th, 2001, and November 1st, 2001, researchers conducted two replicate studies of juvenile movement in the vicinity of the DCC. These studies were designed to provide the most information possible about salmon movement within the junction, given a limited number of experimental fish. During the course of each 30-hour study mass releases of coded wire tagged hatchery juvenile Chinook salmon were made throughout the tidal cycle upstream of the DCC. The movements of these fish were monitored using both traditional trawling methods and acoustic fisheries technologies. Release times for each study were chosen so that fish would reach the DCC on a slack, ebb, and flood tide in both light and dark conditions. Stationary hydroacoustic fish tracking units were mounted throughout the DCC junction area, recording the location, velocity, and target strength (size) of each fish passing through their beam. A boat-mounted unit was used to conduct mobile acoustic surveys of each release. In addition to hydroacoustic monitoring, surface trawls were operated in a near-continuous manner in both the DCC and in the Sacramento River for the duration of each study. Passive drifters released with each mass of fish provided information on the mean water velocity along each release path, and bottom mounted and boat mounted ADCPs were used to record the flows and velocities in the DCC junction branches. Boat mounted ADCP data was used to construct three-dimensional maps of the water velocity in the area immediately surrounding the junction of the DCC and the Sacramento River. The results of these field efforts were data sets containing information on the location and timing of fish movements through the DCC area for each tidal cycle, during the day and night, as well as a detailed record of the physical process effecting these movements.

In order to resolve temporal patterns in juvenile movement through the junction area, hydroacoustic data was combined with junction flow data and drifter arrival time data for each hydroacoustic fixed-station site. These combined data series showed distinct patterns in fish movement at each site, as well as differences in movement patterns between the October 29th and the November 1st studies. During the October 29th study, hydroacoustics were able to observe at least one pulse of fish associate with each release group. These pulses arrived after the passive drifters for each release group, with time lags that indicated that juveniles were swimming with a net upstream (into the current) swim speed on the order of one body length per second.

At Landing 63 (Immediately downstream of the DCC), a pulse associated with Releases One, Three and Four were observed moving downstream on portions of an ebb tide. Drifters from Release Two were observed moving into the DCC on a flood tide, and were followed by a large pulse of fish. Later during this flood tide, a group of fish thought to be from release 1 was observed moving upstream past Landing 63, immediately followed by another pulse at the DCC. Thus, it appears that during the October 29th study, fish tended to pass the DCC on an ebb tide, and be advected into the DCC from the Sacramento River, both upstream and downstream of the DCC, on a flood tide.

During the November 1st study a very different pattern was observed in the timing of juvenile movements. There were no significant pulses of fish observed at any of the stations associated with daytime drifter arrivals. In contrast, there were very large numbers of fish observed during dark hours, with small pulses superimposed on this signal following drifter arrivals. This suggests that most of the juveniles released during the day remained in the release area until dark, then moved downstream at the same time as fish released after dark. Such behavior indicates that these fish were in a pre-smolt condition, a fact that is supported by gill ATPase tests conducted by Natural Resource Scientists. As on the 29th, the highest rates of juvenile entrainment in the DCC were observed during flood tides.

In order to further examine the apparent interaction between tidal flow patterns and juvenile movements in the junction, hydroacoustic data from Landing 63 was post-processed to produce fish density distributions for a cross section of the Sacramento River below the DCC. These density distributions were combined with maps of the water velocities measured during each study, creating a record of the spatial distribution of fish and velocity in the junction area for each 30-hour study. The horizontal and vertical first moments of these fish density distributions were computed for each five-minute period thought to contain juveniles, and plotted with junction flows. These plots indicate that the distribution of juveniles in the Sacramento River is skewed towards the outside bank (And thus the DCC), and that changes in the horizontal distribution of juveniles in the cross section are linked to tidal changes in flow in junction branches. Such changes in horizontal position could predispose outmigrants to be entrained in the DCC on certain tidal phases, such as the end of an ebb tide, or in Georgiana Slough, on a full or slackening ebb tide. In addition, the combined velocity/density maps show that on a flood tide, the Sacramento River enters the DCC from both upstream and downstream direction. During these time periods, any juveniles in the junction area are almost certain to be entrained in the DCC. In addition, plots of vertical moment over time showed that during both studies juveniles exhibited a clear upward migration in the water column during dark hours, suggesting that juveniles are actively maintaining a specific depth during outmigration.

Based on the observed patterns in fish movement, a conceptual model of juvenile transport in junctions is proposed. This conceptual model groups physical process acting on juveniles in junctions into two groups: processes controlling the size and location of zones of entrainment for each junction branch, and processes that control the approach path that juveniles follow as they enter a junction. Thus, this model proposes that entrainment in a complex, tidally varying junction is controlled by the interaction between the Lagrangian forces acting on outmigrants upstream of a junction, and the Eulerian forces acting on juveniles when they enter a junction. This model has important implications for the design of future studies, as well as the interpretation of past data, because it implies that entrainment in a junction is controlled by process that vary on a range of temporal scales. This model implies that juvenile entrainment in a junction or diversion is not necessarily directly proportional to the percentage of flow entering the diversion, and therefore, it is possible to design and manage junctions to limit or enhance juvenile entrainment.

Background

In the early 1970’s the California Department of Fish and Wildlife observed a sharp decline in the number of returning Winter Run Chinook Salmon spawners in the Sacramento River at the Red Bluff Diversion Dam. In the years since, the Winter Run Chinook population in the Sacramento River has declined exponentially, reaching a historic low in the mid 1990s. This decline resulted in the Sacramento River Winter Run Chinook Salmon being the first salmonid population listed as a federally threatened species in 1989, and prompted federal, state, and local agencies and organizations to begin working to restore the Winter Run population (Botsford and Brittnacher, 1996). Over time, many of these efforts have been consolidated into the ongoing CALFED Bay-Delta restoration project, with the aim of restoring the populations of threatened or endangered species within the San Francisco Bay and Delta. Today, salmon restoration work in the Bay and Delta continues to focus on the federally listed Winter Run Chinook stock, but has expanded to include Fall Run and Spring Run Chinook as well. Many of these CALFED funded restoration efforts have been aimed at reducing the mortality of juvenile salmon emigrating through the Bay and Delta, with particular attention given to mitigating the effects of man-made diversions and intakes.

The Delta Cross Channel (DCC) is a manmade diversion that has received significant CALFED attention in recent years. The DCC is a diversion channel that was constructed to move high quality water (low salinity) from the Sacramento River through the Mokelumne River and San Joaquin River systems to CVP (Central Valley Project) and SWP (State Water Project) pumping facilities in the Southern Delta (Fig. 2). However, the creation of the DCC also provided a new pathway to the Central Delta for juvenile Chinook migrating down the Sacramento River. Tagged-recapture studies conducted on the Sacramento River indicated that juvenile Chinook salmon entering the Central Delta via the DCC have a lower survival rate than fish that pass the DCC and continue down the Sacramento (Newman and Rice, 1998). Thus, it appears that understanding the impacts of the DCC on outmigrating salmon requires answering to two distinct questions: a) What proportion of salmon emigrating down the Sacramento River are entering the Central Delta via the DCC, and b) What impact does entrainment in the Central Delta have on the ultimate survival of juvenile salmon? Because DCC operations have very significant political and economic ramifications, CALFED and other management agencies have placed a high premium answering these questions, with special emphasis on quantifying juvenile entrainment.

In the fall of 2000 a multidisciplinary team of scientists conducted a CALFED funded pilot study of juvenile Chinook movement in the DCC area, with the goal of determining the methods and equipment best suited for monitoring juvenile passage through the DCC junction. A central portion of this study was the use of boat mounted hydroacoustic transducers to track the movement of juvenile Chinook released in the Sacramento River upstream of the DCC. The hydroacoustic data collected in this study indicated that the rate and direction of smolt movement in the Sacramento River seemed to be determined by the mean water velocity in the channel, and demonstrated the viability of using hydroacoustics to monitor juvenile salmon in the Sacramento River. Based on these results, project PIs designed a study of fish movement in the DCC junction for the fall of

2001, with increased emphasis on hydroacoustic fish tracking, and special concern for measuring the hydraulic process in the DCC at very fine temporal and spatial scales. This report is focused on results of the 2001 study, with emphasis on investigating the temporal and spatial patterns of fish movement throughout the junction area, and understanding the physical and biological process that control them.

1. Introduction

Fundamentally, the problem of understanding salmon movement in the DCC junction is a question of understanding the interaction between outmigrating Chinook juveniles, and the dynamic physical processes that control water movement in the DCC junction area. However, one must recognize that relevant physical process within the DCC area are a result of interactions between process of a much greater scale; changes in Sacramento River flow, ocean tidal cycles, changing flow in the complex Sacramento – San Joaquin Delta, and human management actions throughout Northern California all effect the hydrodynamics of the DCC. Many of these large-scale processes also affect the timing and rate of salmon outmigration. Thus, understanding salmon movement in the DCC junction requires an understanding of the physical layout of the DCC within the context of the greater Sacramento – San Joaquin Delta, and an understanding of the biology of Sacramento Winter Run Chinook.

1.1 Physical Setting

The Sacramento River is a large alluvial river draining the northern half of California's Central Valley, from its headwaters near Mt. Shasta, to its terminus at the mouth of the Sacramento-San Joaquin Delta (Fig. 1). In very general terms, the Sacramento-San Joaquin Delta can be divided into three physical regions: The Upper Delta, which contains the Sacramento River system, the Central Delta, containing the Mokelumne and

San Joaquin River systems, and the Southern Delta, where the State Water Project (SWP) and Central Valley Project (CVP) pumping stations are located (Fig. 2). The CVP and SWP pumping plants are critical components of California's fresh water supply system; The Delta provides drinking water for 20 million Californians, and irrigation water to over 4.5 million acres of farmland, much of this water is drawn from the Delta at the CVP and SWP facilities (Ruhl, in prep).

The Sacramento River accounts for the majority of the fresh water entering the Delta (~75%), and has the highest water quality of any major tributary to the Delta (Rhul, in prep). Thus, water quality at the SWP and CVP facilities can be improved by moving water from the Sacramento River down through the Central Delta to the pumps in the Southern Delta, especially during low flow periods. Because the Delta Cross Channel is the primary tool available to water managers for controlling this process, it has become critical for maintaining water quality in the Southern Delta under the current management paradigm.

The Delta Cross Channel (DCC) is a 1.1 km long diversion channel constructed by the Bureau of Reclamation in 1951 to connect the Sacramento River to the Mokelumne River System. The Western end of the DCC connects to the Sacramento River 43.5km upstream of the confluence of the Sacramento and San Joaquin rivers, at the outside of a long westward bend in the Sacramento River (Fig. 3). The eastern end of the DCC empties into Snodgrass Slough about 2.7 km north of the Slough's confluence with the North Mokelumne River. Other important waterways in the DCC junction area include

Georgiana Slough, which joins the Sacramento River 0.9 km downstream of the DCC, and Steamboat and Sutter Sloughs, which connect to the Sacramento River about 9.7 km above the DCC. Georgiana Slough is the only other local pathway for exchange between the Sacramento and Mokelumne Systems, while Steamboat and Sutter Sloughs rejoin the Sacramento River about 20 km downstream of the DCC, effectively bypassing both connections to the Central Delta. Flow into the DCC is controlled via moveable control gates located at the DCC-Sacramento junction. These gates are usually closed during periods of high flow, and opened during periods of low flow to improve water quality in the Southern Delta.

One of the most important consequences of the DCC's location relative to the Sacramento and Mokelumne systems is that the water surface elevation at both of its ends varies due to tidal forcing. However, due to the complex geometry of the channel network in the Upper Delta, the tidal signal is not the same at each end of the DCC, and water levels in the Sacramento and Mokelumne systems do not change in phase with each other. The result of this complex, tidally varying forcing is a unique, bi-directional flow pattern in the DCC (Fig. 4). The flow in the DCC can be thought of occurring in 4 phases relative to the tidal forcing in the Sacramento River. When the Sacramento reaches a full ebb tide, flow in the DCC is negligible, and slowly increase towards Snodgrass Slough as the Sacramento ebb tide begins to decrease towards slack. As the Sacramento River upstream of the DCC approaches slack water, the Sacramento River downstream of the DCC reverses direction, and begins to flood up and into the DCC, boosting DCC flows towards Snodgrass slough. The DCC continues to flow towards

Snodgrass Slough until the end of the Sacramento River flood tide, when DCC flow can briefly switch direction and flow into the Sacramento River. DCC flow then decelerates to slack at the completion of a tidal cycle.

While tidal forcing accounts for the majority of short-term changes in DCC flow, most long-term variations are driven by flow changes in the Sacramento River. As flow in the Sacramento River increases, the net flow in the DCC also increases, but the overall percentage of Sacramento flow entering the DCC decreases. In addition, increases in Sacramento River flow decreases the relative strength of tidal fluctuations in the junction area, changing the tidal flow pattern in the DCC. However, the most important consequence of changes in Sacramento River flow is in DCC gate operations; if flow in the Sacramento River exceeds 25000cfs, the DCC gates must be closed for flood control purposes. Between 1956 and 2002, the flow in the Sacramento River at Freeport, CA during the month of December (peak of Winter Run outmigration) ranged from just over 7,000cfs, to over 70,000cfs. Thus, the conditions that winter run juveniles encounter in the DCC junction can vary greatly from year to year, depending on the fall and winter flows in the Sacramento River.

Changes in Sacramento River flows not only have an important effect on the hydraulic conditions in the DCC, but they also affect the flow in other important junctions in the area. As flow in the Sacramento River increases, flow in Georgiana, Steamboat, and Sutter Sloughs increases, but the relative percentage of the Sacramento River flow entering these junctions decreases (Burau in prep). In addition, if the DCC gates are closed for either flood protection or fisheries protection, the flow in Georgiana, Sutter, and Steamboat Sloughs increases (Burau in prep). As a result, percentage of Sacramento River water entering these junctions is greatest at times of low Sacramento River flow, and during times when the DCC gates are closed. This fact could have significant implications for the study of salmon entrainment in the Central Delta, because DCC gates are traditionally closed to protect Winter Run during periods of very low flow on the Sacramento River; it is possible that this increases the number of fish entering the Central Delta via Georgiana Slough. Conversely, the relative increase in flow entering Sutter and Steamboat sloughs could increase the number of fish bypassing the DCC/Georgiana junctions. Thus, understanding the effects of the DCC on salmon entrainment in the Central Delta is more complicated than simply knowing the number of fish entering or leaving the DCC at a given time, and requires combining knowledge of the dynamic physical process affecting flow patterns in the all the relevant junctions, with knowledge of the biological process affecting salmon movement within these flows.

1.2 Salmon Physiology and Outmigration

The many variables and interactions between variables associated with the migratory behavior of young salmon are complex and not completely understood (Kreeger and McNeil 1992). Abiotic factors which may have primary influence on young salmon outmigration include photoperiod/date, water temperature, and flow. Other abiotic influences include barometric pressure, turbidity, flooding, rainfall, and wind. Biotic factors affecting outmigration can include stock (e.g., fall-run or spring-run), life history stage, degree of smoltification, parental origin (e.g., hatchery or wild), size of juveniles, location (e.g. distance from the ocean), food availability, predation, competition, etc. (Burgner 1991, as cited by Kreeger and McNeil 1992). Thus, the migratory behavior of an individual fish is difficult to predict, but we can summarize different migratory patterns by grouping juveniles by general life history strategy.

Chinook salmon exhibit multiple life-history strategies that can broadly be grouped into two categories, an ocean type, and a stream type life-history. It appears that the majority of imperiled salmon stocks are ones with a stream-type life-history (Northwest Power and Conservation Council 2000). Ocean type fish either start their migration as fry, or as first-summer juveniles. Fry, in particular, may emigrate immediately after emergence, and movement is thought to be triggered by high flow events that displace young fish. First-summer juveniles will tend to remain in the river for a longer period of time, but will still emigrate as sub-yearlings without over-wintering. There is relatively little to differentiate the outmigration and rearing phases of this life-history type. On the other hand, Stream type fish will over-winter in higher order tributaries then move rapidly downstream the following year as yearlings, with little time spent holding in mainstem habitats. For either pattern of salmon outmigration, downstream movement is not continuous but rather a discontinuous pattern of movement and holding. This pattern changes depending on life-history status, but takes the general form of a "migratory spiral", where fish migrate downstream for a period of time, followed by a period when they hold and feed along protected shoreline habitats.

Such a spiraling movement pattern is most common on a diel basis, but depending on the age of the fish this pattern can vary. Sub yearling fish are prone to select slower water along shorelines, and spend more time holding and feeding in shallow water. The most active outmigration appears to occur during nighttime hours, specifically at dusk, and often just before dawn. For small fish, movement occurs out into the main channel at night, but for only short time periods; this results in a very protracted outmigration rate. As fish grow, the length of movement periods increase, eventually to the point where movement is almost continuous, and is no longer restricted to nighttime hours. This is illustrated by the observation that outmigration rates for smaller juveniles early in the season tend to be lower than those of larger juveniles later in the season (Northwest Power and Conservation Council. 2000). This difference in outmigration rate is due to the physiological changes juveniles undergo during smoltification, such as increased buoyancy, decreased swimming performance, and noticeable physical changes such as loss of parr marks. Gill ATPase level is another measure of degree of smoltification for a given fish; many studies indicate that fish with higher ATPase levels tend to migrate at faster rates than individuals with lower ATPase levels. There is some evidence, however, to suggest this same pattern may not hold as true for hatchery fish (Dauble et al. 1989)

When emigrants move into the river and away from the shoreline they select specific areas within the water column. The larger the fish the more oriented they are towards the surface. Juveniles often position themselves head first into the flow (positive retro-axis orientation), which may be the most metabolically efficient means of maintaining position as they are moved downstream. Laboratory experiments demonstrated that at slow velocities fish essentially hold in the water column or exhibit some upstream movement, but, as a threshold velocity is reached, fish actually reduce their swimming speed and are displaced. (Nelson et al. 1994). Fish were also more likely to be displaced at night than during the day. Juveniles are also able to actively recognize and seek out regions of high velocity and take advantage of turbulence and surges, which may aid in outmigration (Schreck et al. 1995).

Much of this behavioral pattern of flow positioning is now being taken advantage of in designing fish bypass structures on numerous facilities. Prior to studies of flow selection by juveniles it was assumed that the amount of water spilled or diverted for the benefit of fish passage was directly proportional to the number of fish passed (Northwest Power and Conservation Council 2000). This has been shown in almost all cases to be a false assumption, and the actual numbers differ greatly depending on the flow patterns encountered at each project. In the Columbia River successful bypass operations have been designed where it was recognized that juveniles where moving with bulk flows through the reservoir. Accelerating flows, such as near some surface collectors can also act as attractants. Effectiveness of attractant flows is dependent on fish age (Giorgi et al. 1988). More developed fish have a greater tendency to flush and are more likely to be caught by surface bypasses, as they tend to orient higher in the water column than younger individuals, which prefer deeper depths.

In summary, salmon outmigration is controlled by a combination of factors, all of which have significant management implications with respect to water distribution and movement. Particularly important is the idea that emigrating fish time their movements in a spiraling fashion, alternating periods of movement with those of rest and feeding. Furthermore, it is important to consider that sub-yearlings have a greater tendency to move at night than during daylight hours. In addition, as juveniles mature, they have a generally become more surface oriented, and tend to increase their daytime movements. Finally, it is becoming increasingly clear that all salmon have the ability to use the complex, turbulent, nature of the river during outmigration, rather than being simply "swept downstream" by bulk flow.

1.3 Migration Pathways and Management in the Sacramento River System

The Sacramento River system is unique in that it hosts four distinct runs (fall, late-fall, winter and spring). The alternate life-history strategies employed by the different runs are a mixture of ocean type and stream type fish, with 82-90% of all emigrants being of the ocean type (Groot and Margolis 1991). Many smolt survival and transport issues are similar to those found elsewhere. Flow variability and/or discharge during outmigration correlates with survival (Kjelson et al. 1982, Brown 1986, Cramer 1997, Unwin 1997), and may be an important aspect helping regulate diversity in salmon populations (Jager and Rose 2003). Larger numbers of fish are observed to be emigrating when flows are higher in the river (USFWS, 1995 Annual Report). Emigrants typically show a pronounced diel pattern of abundance with most fish moving nocturnally (Johnson and Martin 1997).

Unlike most other river systems where dams are the dominant human control on salmon outmigration, many of the problems associated with smolt survival in Sacramento River arise from in-Delta mortality, which is affected by numerous diversions, changes in flow routing, large scale pumping plants, and complex interactions and tidal influences between them. This has lead to a variety of water management operational constraints and management alternatives (EWA, VAMP e.g.), aimed at limiting losses of outmigrating salmon. The DCC and vicinity has become one focus of attention in recent years as an area that may have significant impacts on outmigrating salmon.

During the late-fall and winter months, juvenile salmon, including winter, late-fall and tributary spring-run, emigrate past the DCC on their way to the ocean. These fish are generally 120-150 mm in length and initiate their outmigration during storm-induced increases in flow and/or turbidity that correlate with physiological/behavioral changes associated with smoltification. Studies conducted with 70-90 mm juveniles in spring months suggest that outmigrant survival is substantially lower for fish that pass through the Central Delta, via the DCC, than for fish staying in the main river channel (USFWS 1996 and Newman and Rice 1997). Wintertime experiments using larger late-fall run, (110-120mm) as surrogates for winter run, have shown a survival rate for fish in the Central Delta that is between 5 and 70% of the survival rate of fish remaining in the Sacramento River (Delta Action 8 studies). As exports increase from the pumping plants, survival of juvenile salmon decreases. Based on these smolt survival data, the DCC gates are now required by the 1995 Water Quality Control Plan to be closed from February 1 through May 20 of every year, with additional optional closures available during half of the days in the November-January period at the discretion of the fishery management agencies.

Data obtained in these studies, and subsequently used for management actions, have relied upon coded wire tagged fish releases. In these studies, large numbers of tagged juveniles were released upstream of the DCC, or in other locations, and survival was estimated based on the number of tags recaptured at a point downstream. While this has provided valuable insight on salmon survival, the relatively large-scale nature of these studies makes it difficult to determine underlying patterns of smolt outmigration that led to the observed results; it is not possible to use this data to answer specific questions of how entrainment occurs at each junction in the river, or to address complex interactions between junctions, or to study the fate of a given fish. As a result, there is currently a lack of knowledge of the specific pathways juveniles are utilizing during outmigration. This lack of understanding is illustrated in part by some modeling exercises used to examine smolt transport through the Delta from the San Joaquin system (Flow Sciences 1998). Model results using tracers as surrogates for juveniles showed most particles ended up at the pumping plants, yet studies with juveniles showed the majority did not become entrained as the model would have suggested.

Currently, DCC operational decisions are based on the seasonal timing of juvenile presence in the river, but do not take into account behavioral aspects that might impact salmon survival. This is not only the case in the Sacramento River, but was historically true for the Columbia River System, where flows were modified during migration periods. Recently, survival concerns have prompted many studies to focus on finer scale behavioral patterns of smolt migration near critical structures and in specific river sections. In fact, behavioral characteristics are becoming a management tool at many facilities. Common approaches to answering questions about these issues include using extensive radio-tracking of fish to determine their fate (Demko et al 1988, Vogel, 2004), and the use of hydroacoustics and/or acoustic tags coupled with flow mapping to describe fine-scale behavior of fish in relation to flow parameters (Northwest Power and Conservation Council 2000).

1.4 Study Design and Motivation

In the fall of 2000, project PI's conducted a pilot study of fish movement in the Sacramento River in the vicinity of the DCC. This study was designed to identify process controlling the outmigration of juvenile salmon through the DCC junction area. The data collected in this study clearly showed that in the Sacramento River upstream of the DCC, tidally varying currents controlled the rate and direction of juvenile salmon movement. As a result, a transport perspective was assumed in the development of the 2001 study; this approach was based on the underlying assumption that riverine transport processes are the primary influence on the migration pathways utilized by juvenile Chinook Salmon. However, it was recognized that the effects of these hydrodynamic processes are modified by salmon behavior, so that juvenile transport within a junction is ultimately controlled by an interaction between physical transport process and salmon biology.

The objective of the 2001 study was to examine correlations between spatial and temporal variations in fish distributions and spatial and temporal variations in physical process near the DCC, with the goal of identifying the specific physical process and behavioral responses controlling juvenile salmon entrainment in the DCC. Researchers recognized that these relevant processes and behaviors, as well as their relative importance, had the potential to change over both daily and tidal time scales. As a result of this understanding, and the study's transport-based approach, researchers formulated three hypotheses to guide data collection and analysis efforts. In combination, these hypothesis encompassed the anticipated range of physical and biotic controls to salmon movement, and were formulated in terms of directly measurable quantities; spatial and temporal distributions of Chinook Salmon in the DCC.

Hypothesis (1): Juvenile salmon move into the DCC in direct proportion to flow

Implications for DCC gate operations: This hypothesis suggests that fish densities are spatially and temporally homogeneous. If this hypothesis is true, a water quality benefit can't be achieved during periods when juvenile salmon are outmigrating past the DCC without entraining fish into the Central Delta.

Hypothesis (2): Juvenile salmon movement into the DCC is affected by diel period

Implications for DCC gate operations: If this hypothesis is true, the DCC gates could be operated according to diel period to provide fish protection without compromising water quality.

Hypothesis (3): Juvenile salmon movement into the DCC is affected by tidal current phase

Implications for DCC gate operations: If this hypothesis is true, the DCC gates could be operated by tidal current phase to provide fish protection without compromising water quality.

Researchers also recognized that the temporal and spatial distributions of fish densities within the junction with respect to tidal current phase would constrain what can be accomplished with gate operations to minimize fish entrainment into the Central Delta through the DCC, regardless of whether the underlying mechanisms that control these distributions are hydrodynamic, or behavioral in origin.

2. METHODS

The study was optimized for observing both temporal and spatial patterns in salmon entrainment and distribution, and spatial and temporal patterns in relevant physical processes. In addition, the nature of the hypothesis dictated that these patterns be observed for a complete tidal cycle, and for a complete diurnal cycle. For this reason, the 2001 field study was broken down into two identical, 30-hour, field efforts. These two efforts were timed to bound potential diurnal/tidal combinations for fall and winter periods. At the most basic level, the study consisted of three parts: release of large numbers of juvenile Chinook salmon upstream of the DCC throughout the tidal cycle, observing these fish with hydroacoustics, and measuring water velocities in the junction area.

2.1 Juvenile Chinook Mass Releases

Approximately 60,000 sub-yearling Chinook salmon were released during the course of each 30 hr study, using a total of 120,000 fish from Coleman National Fish Hatchery. Fish were acclimated for a period of 24hrs in floating net pens prior to release into the river (Fig 5). Six release groups of 10,000 fish occurred on October 29th thru the 30th, and six groups on November 1st thru the 2nd. Three releases were performed during the day and three at night. Releases were timed to allow for the arrival of fish (based on the assumption that juveniles would travel at approximately the same velocity as the water) at the Delta Cross Channel during peak ebb tides, peak flood tides and peak cross channel flow. All fish were injected with coded wire tags (CWT). Four sets of tags were used;

CWT 95 and 96 fish were released October 29th thru the 30th, and CWT 97 and 98 fish were released November 1st thru the 2nd. Each release alternated which CWT tag was used. For example, if the first release was CWT 95, the second would be CWT 96. A series of passive drifters equipped with D-GPS loggers were released with each group, to track the movement of the parcel of water in which fish were released.

2.2 Acoustic Data Collection

The movement and location of fish from each mass release was monitored using hydroacoustic technology. Acoustic data collection was performed using both fixed station systems and boat-mounted mobile systems. Biosonics Inc., Seattle, Washington, manufactured all of the acoustic units utilized in this study. Both of the boat-mounted units were equipped with side-looking dual-beam echosounders (DT-5000); these are identical to units used in the 2000 pilot study. The fixed station units employed side-looking split-beam echosounders (DT-6000).

Side scan technology was chosen for the boat-mounted units due to the shallow nature of the river, and side scan's narrow beam pattern (6.5 – 7 degrees). Each boat ran a track starting below the DCC at the Walnut Grove Bridge, moving upstream towards a turnaround point along one bank, then returning downstream to the bridge along the opposite bank (Fig. 6). Initially, boats ran upstream to the release point. At mid-day on the 29th the turnaround point was moved to only 1 km above landing 63. This was done to shorten the transit time for each survey, and increase the surveys temporal resolution in the DCC area. Transects were performed continuously for 30 hrs following the first releases during both studies. A D-GPS connected to the hydroacoustic control laptop provided geo-referencing of boat location for each acoustic ping.

Fixed split-beam stations were mounted in the Delta Cross Channel, Georgiana Slough, Landing 63 (just downstream of the Delta Cross Channel), and on a Jon Boat moored 1.5km upstream of Landing 63 (Fig. 6). Twelve-volt deep cycle marine batteries were used to power units in the DCC and on the Jon Boat, while 120V ac shore power was available to the other units. Hydroacoustic data was collected continuously at these sites for the entire week of the study beginning at 0600 on October 29th, and ending at 1200 hrs on November 2nd, with the exception of the Jon Boat unit, which was only operated during release times for security reasons.

The unit on the Jon Boat (201khz, 6.2. degree beam width) was mounted on a platform one meter below the water surfaced aimed horizontally out into the river at a downward angle of three (3.0) degrees. This angle allowed researchers to scan from just under the water surface, to just past center channel. During the October 29th releases this boat was moored on the East (river left) bank of the river, during the November 1 releases it was moored on the West (river right) bank.

Fixed station units at the other three sites were all operated in a similar manner. An aluminum bracket with a center pole (Fig. 7, Fig. 8) was used to mount the transducer. The pole with attached transducer was lowered to a depth of 2.5 m below water surface, with the transducer aimed horizontally out into the river. At landing 63 the transducer on the East bank was mounted to a platform that was lowered via winch to a position just offshore in about 2.5 m of water. A marker buoy was placed at this site to warn boaters away. A stepper motor attached to each transducer allowed us to rotate the transducers vertically to sample different portions of the water column. Each transducer was geo-referenced and served as a reference point from which tracks of individual fish could be placed in the three- dimensional context of the river. For all systems (boats, fixed) Biosonics Visual Acquisition Software V4 was used to log data (Fig. 9). Data were recorded at a rate of 4-5 pings per second and logged continuously to dell laptop computers. Data collection ranges were set to 45 -50m with a sensitivity of -54 db. Maximum range was determined based on the amount of background noise present in the river (primarily boat wakes). Data thresholding was squared, and water temperatures were left at the default value of 20^0 C. Visual on-screen display was set to -40LogR, which is used for target strength estimation and echo counting.

The primary difference between the boat mounted systems and the fixed location systems was in the type of data obtained. For all hydroacoustic echosounders the position of the fish in the beam is the most critical aspect of determining its size. Fish in the direct center of the beam return the strongest target strength, and represent a true target size, while those nearer the edge of the beam return a weaker signal. Thus, return signals need to be corrected for the fishes' position in the beam. The differences between each system determine how this correction is made, and determine the types of information that can be obtained on each target. A dual beam system uses a narrow and a wide beam. To determine off-axis position, the strength of the targets are compared between the two beams to determine an off-axis angle that can then be corrected to true target strength. The limitation of this is that even though the correct target strength is returned, the only other information available is the range to the target (Z). The target's position in the X,Y plane is not attainable. Further, because differences in target strength are being measured, these systems are more susceptible to the effects of noise, compromising estimation of target size. A split-beam system is exactly what the name implies; the beam itself is split into four quadrants. The split-beam measures the phase differences of the echoes returning to each quadrant, allowing for the calculation of an in-beam position for each target based on the phase separation of the returning signal. Thus, researchers using a split beam system can build a three-dimensional picture of any given fish as it swims through the beam. Noise does effect measurement of fish position, but the errors are not as great as with the dual beam. A detailed description of the post-processing procedures used to obtain fish positions from the raw hydroacoustic data can be found in Appendix - A.

2.3 Trawling Data

Researchers made an effort to ground-truth the hydroacoustic data collection using traditional trawling methods in the DCC area. Personnel from the California Department of Fish and Game, and the U.S. Department of Fish and Wildlife were responsible for operating the trawls and compiling catch data. Midwater trawls were used in both the Sacramento River and the DCC; both trawls were operated near-continuously for approximately 30 hours following the first mass release, with a target tow duration of 20 minutes. Both trawls used nets with a mouth size of approximately 10' x 30'.

2.4 Physical Data Collection

Hydrodynamic Data

A variety of instrumentation was used to document the basic flow structures in the area of the DCC. Beginning at broad spatial scales, side-looking hydroacoustics were used to monitor the flows (discharges) at five locations in the northern Delta (Fig. 10). Flow stations at the DCC and Georgiana Slough were combined with the USGS-run permanent flow sites on the Sacramento River above the DCC (station WGA) and below Georgiana Slough (Station WGB), (Burau and Ruhl 2000), allowing for flow measurements in all of the channels in the immediate vicinity of the DCC. To measure flows at smaller spatial scales, three upward-looking ADCP's were deployed in the junction of the Sacramento River and the DCC. These instruments were used to document the flow structure at the DCC for several months before and after the mass releases. In addition to the fixed deployment stations, a boat mounted, downward looking ADCP was used to map water velocities at the Sacramento/DCC intersection. This system was used to collect water velocity data continuously during each 30 hour study, collecting a total of about 60, 30 minute transects for each study. The data from these transects was then temporally and spatially interpolated to create 3 dimensional maps of water velocity in the Sacramento River and the mouth of the DCC (Dinehart 2003).

Meteorological Data

A meteorological station was installed on a piling in the DCC to monitor the wind speed, wind direction, solar radiation, and barometric pressure in the study area.

Surface Drifters

Drifters (Fig. 11), fitted with internally logging D-GPS receivers, were released at the same time as each group of CWT fish. At the drifter/juvenile release site, 3 drifters were released on each side of the center-channel salmon release pen, so that 6 drifters were release simultaneously with each group of salmon. The drifters provided a passive measurement of the mean velocity in the upper meter of the Sacramento River, and an estimate of the time of travel to the DCC and Georgiana Slough for the parcel of water each group of juveniles was released into.

2.5 Generation of Landing 63 Juvenile Spatial and Temporal Distributions

Fish Count Time Series

After post-processing, the Biosonics' hydroacoustic data provided a time, location, and velocity for each fish that passed through the acoustic beams. Using this information, temporal distributions of fish passage were generated for each beam, showing the timing of fish movements during the study. To estimate numbers of non-target species present at any given time, trawl data showing numbers of other species caught were used, as well as background fish levels determined at times when juveniles were not present.

To examine gross temporal patterns of movement, targets (juveniles) were binned into 10 minute intervals and abundances and direction of movement plotted against time, drifter arrival and flow. Numbers of juveniles passing each acoustic transducer during any given time period were presented as actual numbers of fish; potential beam biasing was ignored for this portion of the study. Total numbers of fish passing could be summed for a given release, and numbers compared between the DCC, Georgiana Slough, and the mainstem Sacramento to ascertain relative numbers of juveniles being diverted.

Spatial Distributions

Biosonics' target data was loaded into Matlab software, geo referenced, and assigned a geo-referenced velocity, time stamp, and target strength (surrogate for size). For the purpose of this analysis, all targets were filtered so that only targets of –50 dB to –40 dB were included, bracketing potential juvenile sizes. Filtered targets were grouped based on the time that they passed through the beam, so that each target was assigned to one of approximately 365 contiguous, 5 minute, temporal bins. These temporal bins were associated with an array of three dimensional flow maps, so that every 5-minute group of fish targets corresponded to a map of average water velocities occurring during that 5-minute period. This method of spatially and temporally referencing the fish track data allowed for the computation of fish spatial distributions for any time period during the study, with 5-minute resolution.

After meshing the fish target and flow field data sets, three dimensional fish spatial distributions were calculated for each 5 minute temporal bin (Fig. 12). These spatial distributions were calculated by dividing the Sacramento River cross section in the landing 63 area into imaginary regions, and then counting targets within each region.

These imaginary regions can be though of as discrete spatial bins in the X-Z (East-Elevation plane) river plain, as illustrated in (Fig. 13). The bins divided the river's X-Z cross sections with 5 m horizontal spacing, and 1 m vertical spacing, resulting in 13 vertical bins, and 20 horizontal bins. Horizontal bins were positioned so the center of the river cross-section occurred at the junction of horizontal bin 10 and 11, and the boundaries of the bins were approximately aligned with Sacramento River ebb tide streamlines. Horizontal bins 1 and 20 correspond to the western and eastern riverbanks respectively. The resulting horizontal bin pattern divided the river into 20 segments along lines roughly perpendicular to downstream streamlines. The vertical bins were aligned so that they covered between –9 m and +3m, referenced to NAVD 88 (Fig. 13). It is important to note that the Sacramento River's free surface elevation fluctuated on the order of a meter due to tidal forcing; the average surface elevation was located at approximately +1.5m NAVD 88.

After establishing bin boundaries, each fish target was assigned to a bin based on the location of its track center point within these boundaries. Spatial distributions of the number of fish per bin could be produced for a variety of time periods, such as the distribution shown in Fig. 14. However, such distributions reflect only the number of fish counted in each portion of the river, not the overall distribution of fish in the river. In order to draw conclusions about the actual spatial distribution of fish in the river, bin count distributions were corrected to remove spatial biases introduced by the non-uniform coverage of the hydroacoustic beams.

Beam Biasing

Because acoustic beams expand along the beam's axis, the volume of an acoustic beam is conical, with a spread angle on the order of 3-7 degrees for Biosonincs Equipment. This beam geometry results in spatial biasing of the acoustic fish count data, because the beam samples a larger volume of water in the center of the river than near shore. If fish were uniformly distributed in the river cross-section, hydroacoustics would detect more fish in the center of the river (Fig. 15). As a result, a distribution of fish counted per bin does not accurately reflect actual fish spatial distribution in the river. In order to address this problem, beam coverage for each bin was calculated via numerical integration. By normalizing number of fish counted in each bin by total beam volume for each bin, a fish density (fish/m3 of beam coverage) distribution can be obtained for any fish count distribution. (It is worth noting this method is the conceptual equivalent of the conventional process of normalizing trawl catch by trawl effort.) Because fish density distributions are more representative of actual fish spatial distributions than fish count distributions, they were used for observing and quantifying patterns in juvenile movement for this study.

Horizontal and Vertical Moments

In order to quantitatively compare fish density distributions from different time periods, horizontal and vertical first moments were calculated for each distribution. The horizontal first moment (M_H) is a measure of the distance from the center of the river to the horizontal center of mass (COM) of a given fish density distributions. In the coordinate system used for this analysis, M_H is 0 for a distribution COM located at river center, greater than 0.0 for a distribution COM East of river center, and less than 0.0 for a distribution COM West of river center (Fig. 13). Similarly, M_V values increase positively above NAVD 88 datum, and negatively below the datum (Fig. 13).

Total Number of Fish

In addition to computing horizontal and vertical moments, the total number of fish was calculated for each 5 minute time step, and for each specific fish density distribution.

3 RESULTS

3.1 Data Quality and Limitations

Mobile Tracking

Mobile tracking during 2001 was difficult to assess; results were not as clear as data collected during the 2000 releases. A larger number of boats than was expected traversed the study site during these surveys. This led to a high level of noise in the system, making data very difficult to interpret (Fig. 16). As a result, large numbers of small fish were undoubtedly dropped because of restrictive assumptions made during analysis, and high background levels of noise from boat-wakes masked the detection of other small fish. Due to limited availability of software at the time this data set was analyzed, analysis was performed using an alternative method, which appeared to be less effective in detecting smaller fishes. For the purposes of this report we did not include an analysis of mobile tracking data.

Fixed Stations

Fixed station tracking of juveniles resulted in a vast improvement over the previous tracking exercises. We were able to map, with some limitations, accurate position of fish within the water column, and obtain estimates of total numbers passing for releases that could be detected. For this report we did not attempt to calculate beam bias for each station, but instead present numbers as total fish passing each point.

There were some times when weather conditions or equipment failures prevented us from acquiring data at all sites. On October 29 we were not able to observe the first release passing by the Jon Boat due to some short-term equipment difficulties with one of our laptop computers; the first set of drifters passed this site at 800hrs, but data acquisition did not begin until 1000hrs. We were unable to acquire hydroacoustic data at any site between 2400hrs on October 29th and about 700hrs on October 30th, due to a rainstorm. The acoustic noise imparted by rain effectively blinded transducers that were scanning near the surface, preventing the acquisition of any usable data. During the November 1st study, all units were able to acquire data for the full thirty hours, except the Jon Boat, which lost battery power at 2400hrs on November 1st.

Species Differentiation

Because hydro-acoustics cannot differentiate between species of the same size, the ability to separate the behavior of migrating juveniles from the behavior of other species of similar size is critical. Threadfin and American Shad were two species present in high numbers; their presence potentially limited our ability to differentiate between juveniles and other fish. Sizes of shad ranged form 71-103mm for Threadfin and 64-132mm for American, which was almost identical to the observed size distribution of salmon. However, data from trawling indicated trends in the presence of juveniles and shad that were used to determine potential percentages of each for specific time periods. For the releases of October 29th , 395 salmon were caught in the Sacramento River along with 640 shad. Numbers in the DCC were 71 and 147 respectively. On November 1st, the percentage of shad as a proportion of total catch was much lower: 786 salmon and 326 shad for the Sacramento River, and 30 salmon and 49 shad for the DCC. Because the distribution and timing of shad capture varied between the DCC and the Sacramento, catch data was used to help determine when salmon were most likely the dominant fish observed by the hydroacoustics.

3.2 Temporal Patterns in Salmon Movement

Comparing patterns in the number of fish observed at each site over time, with group drifter arrival times at each site, provides insights into outmigration behavior, swimming speed, and response to tidal currents for each release group. For example, if a large pulse of fish were observed passing a hydroacoustic site after a corresponding group of drifters, it would indicate that the fish were swimming into the current as they moved downstream. Similarly, a group of drifters passing a site without any corresponding pulse in fish might mean that the release group was exhibiting holding behavior. Thus, by observing the temporal patterns of fish movement at each monitoring site we can build a picture of the movement and behavior of juvenile salmon released during the study.

Jon Boat Summary

Patterns of fish movement past the Jon Boat showed the same overall trends for each release date (10/29, 11/01) (Fig. 17, Fig. 18). Few fish were observed during the day in the water column; there was a large crepuscular pulse of fish at dusk, and strong pulses of fish were associated with drifter passage at night. For both release dates, far greater numbers of fish were counted during the second day of releases than during the first. In general, fish were predominately located near the surface and towards the center of the river, with a slight bias (5-10m off center) towards the west bank (Fig. 19). This bias could be a real difference or systematic error introduced by moving the transducer for the different release days. On both dates somewhat more diffuse clusters of fish were observed nearer shore and deeper in the water (Fig. 19).

Synopsis of Jon Boat Daytime Observations

On October 29th the first release was prior to start of operations on the Jon Boat. Drifters for release two arrived at about 1000hr. There was a small pulse of targets at this time (Fig. 17), though numbers are small, and visual observations indicate that these counts were probably not significantly above background levels, making it hard to determine how many of these fish might be juveniles. Fish at this time were not uniformly distributed within the beam, but tended to be more in the center channel of the river with fish either near the surface or between 2.5m to 5 m in depth (Fig. 20). Release three drifters arrived just after noon. At this time flow was decreasing in the river. There is a spread out pulse of fish between about 1200 and 1400 hours, though most appear to be heading upstream. There is a possibility this represents either the passage of juveniles from this release, or an upstream movement of fish released earlier. Targets were in the right size range for juveniles, and with slowing flows, our directional estimates may not be accurate. Almost all targets were near center channel and surface oriented (Fig. 20). On November 1 results were similar for the first three sets of releases during the day; we could detect no pulses of fish moving by the transducer at any time (Fig. 18). For all targets sampled during the day there appeared no definite pattern in water column positioning (Fig. 21).

Synopsis of Jon Boat Nighttime Observations

At dusk on both October 29th and November 1st, large increases in the number of fish in the water column were observed during the crepuscular period (Fig. 17, Fig. 18). These represent a combination of juveniles, and threadfin shad in the same size range as juveniles. The evening pulse on November 1 showed a larger percentage of fish moving upstream than on October 29. This is a direct result of milling behavior of feeding fishes during periods of low discharge; on October 29th discharge was much higher at dusk than on November 1st, as low flow was about 1.5 hrs later on the 1st due to tidal changes. For both dates crepuscular distribution in the water column is reasonably uniform (Fig. 21)

Large pulses of fish were associated with drifters passing the transducers during the night on both the 29th and the 1st (Fig. 17, Fig. 18). These strong pulses are most likely juveniles moving downstream slightly behind the drifters. Fish were distributed unevenly, either being located near the surface and towards center channel of the river, or nearer the shore and deeper (Fig. 19). Without correcting for beam biases we counted approximately 330 juveniles for release 4, or 3.3% of the total 10,000 released, and 150 or 1.5% of release 5. On November 1st only one night set of drifters was counted, over 1000 fish, or 10% of the release was detected.

Synopsis of October 29th Observations at Landing 63

Due to range limitations each transducer could only count fish associated with the shore it was mounted on, and we were unable to completely calculate potential bias due to sampling volume. At Landing 63 on October 29th the first release was represented by large numbers of fish arriving in two separate pulses (Fig. 22, Fig. 23). A large group of fish passed along the West shore almost coincident with the first drifters passing. These fish tended to form a band along near shore and fairly deep in the water column (Fig. 24). Following this, another group of fish passed down the East shore a short time later at a similar depth (Fig. 25). The majority of the fish came down in this second pulse, with a maximum of nearly 200 fish detected per 10 minute interval, about half this number was observed on the west side. Baseline numbers of fish present at Landing 63 averaged about 25 fish per interval.

The next set of drifters did not pass Landing 63, but during this time period, 1319 fish identified as potential juveniles moved upstream past the transducers towards the DCC. Given that the downstream moving pulse associated with the first release contained 1322 potential juveniles, it is very likely that many of the fish observed moving upstream during this time were juveniles from Release One being advected back upstream in the floodtide flow reversal.

Similar to other sites, drifter arrivals during the night of October 29th were associated with more defined groupings of juveniles than were observed during the day. Release Three drifters passed Landing 63 just after dark, accompanied by a very large pulse of fish. Based on the large number of shad caught in the trawls at this time, it is likely that most of these were not salmon (Fig. 26). Trawl data indicate salmon associated with the release were captured beginning about 2000 hours, correlating with a secondary pulse observed in the acoustic data. It is likely that this pulse represents the majority of Release Three juveniles. Drifters from release four passed at approx. 2100 hours, immediately followed by a large pulse of fish. Drifters from release five and six passed during the rainstorm, so no information is available on fish movements for these releases.

Synopsis of November 1st Observations at Landing 63

Releases on November 1st, as at other sites, showed different patterns of fish movement. A pulse of fish came through just after dawn (Fig. 27), however, it was prior to the release of juveniles, and likely represented a school of shad. During the day we saw no evidence of any juveniles moving through the area, despite the passage of release drifters (Fig. 28, Fig. 27). At dusk very large pulses of fish were observed moving past Landing 63. Based on trawl catches, it is likely these mostly represented salmon, and it appears they were a mixture of juveniles released during the night, and those released during the day (Fig. 29). Compared to October 29th, a much smaller proportion of total catch was shad. Similar to October 29th, trawl data and acoustic data from November 1st indicates that the first pulse of juveniles after dark lagged the drifters by a couple of hours, so the large crepuscular pulse might have been shad. On both dates, these drifters spent several hours essentially not moving due to low flows. Actively swimming salmon might have moved upstream during this time, causing in the observed time lag.

Synopsis of October 29th Observations in the DCC

As would be expected, no indication of fish was observed in the DCC for release one; during this time there was little flow entering the DCC (Fig. 30). During the second release all drifters went into the Delta Cross Channel. A large pulse of fish was associated with the passage of the drifters from release two around 1200 hours (Fig. 31). The levels on the graph are represented as a subset of counts (one-minute of every five minutes), thus to equate these numbers to Landing 63 and Georgiana Slough the scale should be multiplied by five. If the beam bias patterns between the DCC and Landing 63 are similar, almost as many fish moved through the DCC with this group of drifters as moved past Landing 63 with the first group of drifters, indicating that almost all juveniles passed into the DCC. This was a broad pulse with multiple peaks; it its likely that the initial peak was movement of fish into the DCC from upstream, with the secondary peak actually being Release One fish advected back upstream past Landing 63 (Fig. 22, Fig. 23) then into the Cross Channel. (Fig. 32). Most fish were in the upper portion of the water column; we observed very few deep targets (Fig. 33).

During night hours on the 29th large numbers of fish were detected acoustically, however, it is unlikely many of these were juveniles. Trawl data indicated the presence of many shad, and the fact there was little directed movement of fish indicates these were resident fishes that moved off shore to feed at night. Acoustic analysis indicates a high degree of milling behavior among the fish, as there was no apparent directed movement. (Fig. 34). The next set of drifters that could have entered the cross channel arrived at about 2400 hrs, which coincided with the start of a rainstorm. There was no useful data until the following morning.

Synopsis of November 1st Observations in the DCC

On November 1st the results were much the same as observed at other sites. There were no measurable pulses of fish during the day (Fig. 35). We observed significant numbers of fish moving in on the evening of the 1st. The pattern of movement was that of a large spread out pulse of fish over several hours. Water velocity patterns indicate that the first pulse of fish should have been observed in the DCC with Release Five just before 0200 hrs, and that fish from this group could have been split between the DCC and the Sacramento River. A weak pulse of fish was observed entering the DCC at this time, though there was no significant pulse detected at Landing 63. The next pulse entered the DCC with release-six just after peak flow into the DCC; this pulse was much larger than the first pulse, as would be expected given the increase in DCC flow. This pulse was probably a combination of fish from release five and six.

Georgiana Slough

Data analysis for Georgiana slough proved extraordinarily difficult due to unforeseen effects of transducer placement. The transducer was set at an angle to achieve maximum range. This resulted in a skewing of fish tracks that made them difficult to analyze. In general, the number of fish entering Georgiana Slough was much higher than expected.

Synopsis of October 29th Observations in Georgiana Slough

As with Landing 63, coincident with the arrival of the first set of drifters a large pulse of fish was observed moving through Georgiana Slough (Fig. 36). Though a single transducer limited our ability to observe the West shore, the distribution of fish in the beam indicates we may have observed the majority of targets passing the unit (Fig. 37). Fish were concentrated towards the East bank at a depth of about 2m. Without correcting for beam bias, it appears a large percentage of the fish passing Landing 63 may have moved down Georgiana Slough during this release. A secondary pulse occurs a short time later, which may represent fish that had originally passed the slough, then moved back up and in to the Slough with flow reversal in the Sacramento. Night passage of juveniles was difficult to assess on the 29th; there was a large pulse of fish associated with the crepuscular period, but trawl data indicates that there was also a large number of shad in the water at this time. A pulse of fish did not accompany release-four drifters. However, prior to the arrival of release four, the transducer had been rotated down five degrees to examine a different portions of the water column; this may have resulted in the beam passing under fish entering Georgiana Slough.

Synopsis of November 1st Observations in Georgiana Slough

On November 1st the transducer was again rotated up to level, yet daytime observations indicated no pulses of fish moving through the slough (Fig. 38). At dusk large numbers were counted, and based on trawl data just upstream, many of these were salmon. A large peak about 1900 hours is coincident with the lagged drifter passage observed at Landing 63. About 2200 hours another large peak occurs coincident with drifter arrival.

Summary of fixed tracking results

After examining patterns in fish movement past each station, it appears that patterns in fish movement are influenced by both tidal and diurnal cycles. As illustrated by the DCC and Landing 63 results from release 1 and 2 on October 29th, the tidal currents seem to have a very significant effect on the direction fish move in the junction area. It appears that during certain tidal phases, such as a full flood or ebb in the Sacramento, downstream moving fish will almost completely bypass one of the junction branches. In addition, Georgiana Slough results suggest that entrainment in Georgiana is at least partially correlated with tidal phase. The fixed station results also indicate that in addition to effecting movement in junctions, the currents in the Sacramento River seem to influence the rate of juvenile downstream movement.

Because the passive drifter releases provided a good estimate of mean water velocity in the upper water column, it is possible to estimate the mean swimming velocity for the juvenile releases on October 29th. Swim speed estimates were made by correlating drifter arrivals at landing 63 or the DCC (depending on flow patterns), with spikes in the number of fish moving down stream. Juvenile swim speed was calculated based on the time difference between drifter arrivals and observed fish pulses. During the daytime releases the average smolt swim speeds were on the order of 1 bl/s upstream. However, the evening swim speeds were consistently on the order of 0.05 bl/s, suggesting different swimming behavior during dark hours. These findings are consistent with current research on juvenile Chinook swimming performance (Nelson et all, 1995).

The day/night difference in estimated swimming speeds illustrates the importance of diurnal changes in juvenile behavior and location. For both days of release there was a fairly well defined diurnal pattern of fish movement (Fig. 17, Fig. 18); most fish detections occurred after dark, with a large pulse of fish observed at dusk. In general, for both 10-29 and 11-01 very few fish were observed during daylight hours, and large numbers of fish were observed at night.

3.3 Landing 63 Spatial Analysis

Spatial analysis at Landing 63 was based on hydroacoustic data from time periods when juveniles were thought to be present. Time periods considered to be indicative of juvenile behavior during the October 29th study were identified as periods closely following the arrival of drifters in the landing 63 area that contained large pulses of fish moving in a coordinated manner (Fig. 39). In addition, the majority of the October 29th first flood tide was included as a smolt period, as it appears that two pulses of fish from the 1st drifter release were advected upstream past the transducers. This resulted in analysis of two time periods associated with the first release, and single time periods associated with the third and fourth releases.

For the November 1st study, nighttime periods that had significantly more fish tracks than the October 29th background nighttime time periods were considered to be indicative of juvenile behavior. The result of these criteria was that the majority of the fully dark period of the November 1st study was classified as a salmon period (crepuscular not included) (Fig. 40).

Overall Fish Density Distributions

Overall fish density distributions for each 30 hr study show the distribution of all fish tracks recorded during the studies, providing a visual summary of the behavior of both salmon and non-salmon in the study area (Fig. 41). Distributions are skewed towards the Eastern bank of the river, and the highest fish densities are located near the edges of the river. Almost all fish detected were located in the upper half of the water column; the highest fish densities occurred between –4 m and –1m (referenced to NAVD 88). In addition, both distributions show a sub-peak of fish in the near surface portion of the water column (in red), located in the horizontal center of the river.

Salmon Period Distributions

In order to observe spatial patterns in salmon movement, data from the October 29th and November 1st releases were separated into salmon periods as described above, and a "background" time period was identified during the final 5 hours of the October 29th study, when few juveniles were expected in the Landing 63 area (Fig. 39). Fish density distributions for juvenile periods are heavily skewed towards the Eastern bank, with horizontal first moments of 10.5 and 5.9 meters East of river center respectively (Fig. 42). In contrast, the background distribution shows fish distributed across the mid -upper portion of the water column almost uniformly, with a slight western bias. This distribution had a horizontal moment of 1.2 meters west of river center. The differences between the smolt period distribution and the background distribution suggest that one or more processes are biasing juveniles towards the Eastern bank.

Juvenile Horizontal Signal

The overall salmon period distributions suggest that during certain time periods, horizontal distribution of juveniles in the river is skewed towards the Eastern bank. Horizontal position of migrating fishes in this area is important, as fish moving through the junction on the outside of the bend, (Eastern bank in the Landing 63 area), seem to have a higher probability of being entrained in the DCC and in Georgiana Slough. To investigate the relationship between horizontal distribution of juveniles and regional flow patterns, a time series of the horizontal first moment for smolt periods was created for both sets of releases. These time series consist of horizontal moment calculations for every 5-minute portion of identified salmon time periods. The time series were smoothed with a rolling boxcar filter (Filter width of 5 points), and linearly interpolated between missing points. To obtain a horizontal signal that spanned a complete tidal period, the smolt period signals from Oct 29th and Nov 1st were co-registered based on tidal phase, so the end of the Nov 1st signal could be considered a continuous extension of the Oct 29th signal. The Oct 29th signal was further broken up into a day and night portion, to help disaggregate any diel pattern in the data.

The resulting time series plot is shown in Fig. 43, with the October 29th and the November 1st horizontal first moment time series shown in red and blue. This signal represents the changing location of the horizontal center of mass of fish density distribution in the Landing 63 area, and appears to be coherent, and partially correlated with the flow in the Sacramento River and the DCC. Most importantly, the signal is positive for almost the entire study period, which means the center of mass for juveniles observed in this area is nearly always east of river center. This observation has significant implications for juvenile transport in the junction area, because it means that juveniles are not uniformly distributed within the Sacramento River cross-section, and therefore, juvenile entrainment in the DCC is not necessarily directly proportional to water entrainment.

Another important aspect of the juvenile horizontal signal is that it has features corresponding to physical processes in the junction area. For example, the most negative point on the horizontal signal occurs during slack water; fish tracks for this period indicate that the fish were exhibiting milling behavior that happened to distribute them west of river center (Fig. 44, Fig.46). Conversely, the most positive portion of the signal occurs during the last third of a strong Sacramento ebb tide, when fish tracks appear to be aligned with water vectors moving towards the outside of the bend (Fig. 45, Fig.46). In fact, it appears that there are portions of the signal that are affected by each tidal flow pattern in the junction (Fig. 46). To better understand the relationship between tidal currents and distribution of juveniles, the four tidal flow patterns that appeared to effect the signal were examined in detail: The end of ebb tide flow pattern, the flood tide flow pattern, the beginning of ebb tide flow pattern, and the full ebb tide flow pattern.

End of ebb tide flow pattern: Sacramento River flowing downstream into the DCC

During the end of a strong Sacramento River ebb tide, a portion of the Sacramento River flows downstream into the DCC. As a result, the streamlines in the DCC-Sacramento River junction are skewed towards the DCC and the east bank of the Sacramento River

(Fig. 47). Interestingly, fish density distributions for this portion of the tidal cycle are also skewed towards the eastern bank of the Sacramento River. This is evident in the horizontal moment signal, which has peaks at the end of each ebb tide (Fig. 46), and in the actual fish density distributions from these time periods (Fig. 47). Almost all fish detected during this time period were on the far eastern edge of the river; the distribution for this time period had a horizontal moment of 18 m east of river center. These results agree with qualitative observations made during mobile tracking; during mobile tracking the majority of the targets detected were observed on the outside of the Sacramento River bend, especially during an ebb tide.

Flood tide flow pattern: Sacramento River flowing upstream into the DCC

As the Sacramento River transitions from slack water to full flood, it begins to flow upstream into the DCC. Based on the timing of fish pulses, it appears that fish passing the junction area on the previous ebb tide are moved upstream towards, and into, the Delta Cross Channel on a flood tide. This observation is supported by fish tracks from this time period, which are aligned with streamlines moving upstream towards the DCC (Fig. 32). Fish density distributions for this tidal phase are skewed significantly towards the eastern bank, and appear to be affected by the relative strength of the flood tide (Fig. 48). On October 29th, when the flood tide had a stronger influence on the flow in the DCC, fish density distribution was more significantly skewed towards the eastern bank than during the same time period from the November 1st study. This can also be seen in the horizontal signal, where the peak associated with the flood tide for October 29th is larger than the peak associated with the November 1st flood tide (Fig. 46).

Beginning of ebb tide flow pattern: DCC flowing into the Sacramento River

The most centralized fish density distributions observed during the salmon periods occurred during the beginning of ebb tides, when the DCC emptied into the Sacramento River. This tidal period corresponds to a low point in the horizontal signal (Fig. 46), and distributions for this tidal period have horizontal moments near or below 0.0 (Fig. 49, Fig. 50). This is not surprising, as streamlines in the junction during this period are skewed towards the center of the river by flow exiting the DCC (Fig. 51).

Peak ebb tide flow pattern: Sacramento River bypassing the DCC

During a peak ebb tide, the Sacramento River mostly bypasses the Delta Cross Channel; there is little flow into the DCC, and stream lines of maximum velocity are located in the center of the river at the study cross section (Fig. 30). That said, the horizontal moment signal for both the 29th and the 1st is significantly greater than 0.0 for this tidal period (Fig. 46), even when there is no flow into the DCC. Although the density distributions from this time period were not as skewed as for the end of an ebb, they both were biased towards the eastern bank with horizontal moments of 9.5 m east of river center and 11.4 meters east of river center (Fig. 52, Fig. 53). The combination of these facts suggests that juveniles are not simply following a path of maximum velocity through the junction, and are being moved towards the outside of the bend by some combination of processes.

Vertical Movements

Temporal patterns in the numbers of fish observed at each station showed a clear day/night pattern in the timing of fish movements. In addition, statistical analysis of the raw target data from the DCC showed fish were, on the average, about 0.15 m closer to the surface during the night than during the day (T_{430}=-10.31, $p<0.001$) (Fig. 33). This observation led us to examine patterns in the vertical position of juveniles at landing 63. During dark periods thought to contain juveniles, fish tended to be about one (1.0) meter higher in the water column, and tended to be more centralized in the river cross section (Fig. 54, Fig. 55). There were two tidal phases when we were able to observe salmon passage during both dark and light conditions. Both times the dark distribution had lower horizontal and higher vertical moments (Fig. 46).

To observe changes in the vertical position of fish over time, smoothed (rolling boxcar, width of 3 points) vertical moment signals were plotted for the October 29th and November 1st studies (Fig. 56). On October 29th there was a clear 1.5 meter increase in the vertical first moment that occurred during the evening corpuscular period. This rise was sustained throughout the evening data record (Unfortunately, rain noise corrupted the second half of the 29th night data set). This apparent corpuscular rise is also evident in the data from the November 1st study. However, juveniles were just arriving in the DCC area during the corpuscular period on the 1st, so it is not clear whether this observed rise was a result of juveniles or shad. In either case, the November 1st vertical moment signal oscillated about a constant peak of –1.5 meters during night periods thought to have salmon. Thus, it appears that the vertical position of fish during dark was consistent between the October 29th and November 1st data sets. In addition, both data sets indicated a rise during the morning corpuscular period, and a subsequent descent as sunlight increased.

To better parameterize the diel vertical migration of juveniles, a brief effort was made to understand the mechanism(s) triggering said migration. Fig. 57 shows the same smoothed vertical moment signal for each study as in Fig. 56, but overlaid with the normalized, smoothed light signal, and the normalized, smoothed light first derivative. Although a longer data record is required for significant quantitative correlations, it appears the observed evening vertical rise and the morning rise and descent be cued by either by the rate of change in sunlight, or by the amount of sunlight.

4 DISCUSSION

4.1 Summary of Evidence Used to Test Hypotheses

Entrainment Timing and Dynamics

Both the DCC and Georgiana slough appear to be effective fish diverters. Each time a set of drifters entered the Cross Channel, a pulse of fish was associated with them. It is hard to estimate an exact number of fish entering the DCC due to sampling bias, but counts were similar to numbers associated with drifter passage at Landing 63. We made the assumptions that similar counts likely meant similar numbers of fish. Under certain tidal conditions, large numbers of fish passing landing 63 were followed by large numbers of fish entering Georgiana Slough. In fact, our counts of fish at Georgiana Slough were similar to counts at the DCC, which indicates that a substantial portion of fish entered Georgiana Slough after passing Landing 63. Further, if a release of fishes had passed landing 63 they could still be entrained by the Cross Channel during a floodtide flow reversal. It also appears that fish passing Georgiana slough may be advected back into the slough on a flood tide. This data is supported by Dave Vogel's radio tracking results that show almost all tagged fish entered Georgiana after passing Landing 63, and that the relative entrainment of radio tagged fish was similar to what we observed at the DCC (Vogel, 2004). Both Dave Vogel's data, and trawl returns, indicate that fish entrained in the DCC do not remain in the channel, but instead quickly follow high flows through it.

Based on these observations, it appears that in the broadest sense fish do go with the bulk flow in the river. If a release of fish arrives at the DCC when the majority of flow is entering the Cross Channel, they are very likely to be entrained. Further, fish that have moved downstream of the DCC in the Sacramento River are still likely to become entrained if they are in the bolus of water that moves back upstream towards the DCC on a flood tide. However, the observed spatial distribution of juveniles in the Landing 63 cross section suggests that juveniles are not uniformly distributed with the Sacramento River. Upstream of the DCC there was a bias towards the Western shore, as juveniles followed a path similar to the one taken by the drifters. Coming into the bend at the DCC fish are moved to the outside (DCC side) of the bend and are heavily biased towards the East bank of the river. This pre-disposes them to entrain in the DCC, or passing that, into Georgiana Slough.

Diel Movement Patterns

Compared to smolt releases in 2000, 2001 releases during daytime periods did not correlate well with defined peaks in juvenile passage. The first release on October 29th was the only daytime release observed at Landing 63 and Georgiana Slough, and the second release was the only daytime release observed to move into the DCC. Nothing was observed that could be regarded as significant smolt movement during the day on November 1st. On both dates, however, large increases in numbers of fish counted occurred during the crepuscular period. Based on trawl returns, this pulse of fish represented a combination of feeding shad moving laterally out from the margins of the river, and juveniles from releases that had occurred earlier. Drifters passing acoustic sites at night always had large pulses of fish slightly lagging them. This observation fits well with the idea that salmon released during this study were pre-smolts or just in the early stages of smoltification.

Lack of active migration was an unforeseen circumstance for the study; it did not limit our ability to interpret data, but did affect how our hypotheses were tested. Early smolts and pre-smolts don't tend to move during daylight hours, but instead hold until evening hours. The higher the level of smoltification, the less the diel influence. Data provided by Dave Vogel (Natural Resource Scientists Inc.) showed levels of gill ATPase in the fish indicative of a pre-smolt condition (Vogel, 2004 or personal communication). Preliminary analysis of radio-tagged fish released with the groups of juveniles further indicated fish were not actively migrating when released (Vogel, 2004). Presumably, if the released fish had higher levels of ATPase, they would have been more likely to move during the day, resulting in much different patterns in observed fish movements.

4.2 Hypothesis testing

Hypothesis 1 implied that juvenile salmon always move into the DCC in direct proportion to flow, and that juvenile salmon are evenly distributed throughout the river cross section. While we did see high fish entrainment correlate with high flow into the DCC, we also observed significant numbers of fish being entrained in the DCC and Georgiana slough when comparatively little water was moving into these junctions. In addition, the observed spatial distributions of juveniles in the Landing 63 cross section clearly show that juveniles are almost never uniformly distributed within the river cross section.

Hypothesis 2 suggests juvenile salmon movement into the DCC is affected by diel period. We found strong evidence of this occurring, which is not surprising given typical ocean type outmigrant behavior. Support for this hypothesis indicates we can get a management benefit from closing the DCC gates every other tide, provided those closures are occurring at night. Closure at night would be expected to have a more positive impact on outmigrants, since there appears to be a disproportionate number of juveniles moving during the night. However, it is important to understand that night closures would disproportionately protect early ocean type outmigrants, and would be less effective at protecting late ocean type and all stream type outmigrants.

Hypothesis 3 suggests tidal phase influences juvenile salmon movement into the DCC. There is strong support for this hypothesis. Movement of juveniles into the DCC was under strong tidal controls. Tidal shifts are what controls the amount of water entering the cross channel, when tides are such that all water from upstream enters the cross channel combined with flow reversals downstream of the cross channel we can expect nearly all juveniles in the affected area to be entrained. We have not yet looked at lower flows due to the timing of releases this past year. Development of our conceptual model of smolt passage should help address number of smolts being diverted when flows are not as extreme. Thus, to fit our results into the hypotheses we generated we, rejected hypothesis 1 and found support for hypothesis 2 and 3.

4.3 Refined Conceptual Model of Smolt Outmigration

Processes Controlling Horizontal Movements

Given that we have accepted Hypothesis two and Hypothesis three, we can use evidence from the Landing 63 spatial analysis to better understand the interactions between diel changes in juvenile behavior and tidal forces that are controlling outmigrant movement in the junction. The current structures and fish density distributions from the beginning of the ebb tide, the end of the ebb tide, and the flood tide all suggest that during these time periods, fish are being advected along streamlines in the junction; if streamlines were biased towards the DCC (end of ebb, flood), then the fish density distributions were biased towards the outside of the bend. During early ebb tide, the water flowing out of the DCC skews streamlines towards the center of the channel, and, fish density distributions are more centralized. However, the degree to which these distributions are skewed towards the outside of the bend suggests that fish are probably slightly biased towards the outside of the channel before they enter the current structures in the immediate vicinity of the DCC. More strikingly, during a full ebb tide, when there is no water entering the DCC and junction streamlines are not skewed, fish density distributions are still skewed towards the outside of the bend (Fig. 30, Fig. 52, Fig. 53). These two observations indicate that some additional process is moving fish towards the outside of the bend. Because fish observed at the johnboat were in the upper, central portion of the water column, it is likely that this outward movement is occurring in the bend between the johnboat and the DCC. It is likely that the process being hinted at by these results is secondary circulation.

Secondary circulation drives water on the surface of a river towards the outside of a bend, and water on the bottom of a river towards the inside of a bend. If a river-bourn object is buoyant or surface oriented, it will be selectively advected to the outside as it moves through a bend. One result of juvenile Chinook smoltification is increased physical buoyancy and increased surface preference. It is very likely that during ebb tides, when secondary circulation effects are likely to be strongest, surface oriented juveniles are being advected towards the outside of the Sacramento River bend, so that their distribution is slightly skewed before they reach the current structures in the junction. When fish bypass the DCC on a peak ebb tide, secondary circulation could continue to move them towards the outside of the river, potentially increasing their chances of being entrained in Georgiana Slough.

Resistance to Vertical Movement

The flow field and fish density distribution shown in Fig. 46 are from the October 29th study, and occurred during the day, when juveniles tended to be located lower in the water column. If one examines Fig. 58, which shows the November 1st fish density distribution for the same tidal phase occurring during the night (when fish tend to be higher in the water column), there were almost no fish detected on the right hand side above –2.4 meters, but there were fish detected in the upper portion of the water column closer to the center of the river, and a huge spike of fish detected below –2.4 meters. Given that the elevation of the bottom of the DCC is located at about –2.4 meters, this may indicate that fish that passed the DCC on the outside of the bend below the DCC were less likely to be entrained than fish that were more centralized, but at the same elevation as the DCC entrance. Given that upstream hydroacoustics on the johnboat showed almost no juveniles in the bottom half of the Sacramento, it is assumed that the observed spike is not due to fish moving up from deeper portions of the river. If this is the case, then the location of this spike indicates that juveniles passed just under the entrance to the DCC without being entrained, while more centralized fishes moving less than a meter above were entrained. The implication here is that juveniles are more resistant to vertical changes in location than horizontal changes. This observation is consistent with studies on the Columbia River system that found migrating juveniles to be highly resistant to changes in their vertical orientation within the water column (Northwest Power and Conservation Council 2000).

Entrainment Zone Model

Based on these observations of juvenile movement, we can refine hypothesis two and three to form an improved conceptual model of juvenile transport. The underlying basis for this revised model is the concept of juveniles advecting downstream via weak positive retro-axis motion ranging from 0.1-1 bl/s, with diel variations in swim speed and holding periods. Juveniles appear to stay in the upper half of the water column, with diel variations in vertical center of mass. Their surface preference makes juveniles vulnerable to outward movement in secondary circulation patterns. This movement skews cross-sectional distribution of outmigrating juveniles towards the outside bank as they move around bends. Once these fish enter junction areas, their cross-sectional position, combined with the local flow patterns will determine their fate. Thus, strong advection dominates the horizontal movement of juveniles over short time and length scales, but other process play an important role in determining the location of juveniles as they approach and enter critical junctions.

This model gives rise to the concept of juvenile entrainment zones for junction branches. As illustrated in Fig. 59, for any junction one can delineate zones in the upstream branch with water velocities sufficient to advect juveniles into each downstream branch. Once a smolt enters one of these zones they are quickly advected into the corresponding junction branch. Because these entrainment zones are based on the flow structure within a junction, they will change in size and location throughout the tidal cycle, and change in response to alterations in bulk flow. Critical to this conceptual model is the observation that the spatial distribution of juveniles in a junction is not usually uniform, and can be skewed towards one or more entrainment zones. As a result, smolt entrainment in a junction branch will not always be proportional to the amount of flow entering said branch, and can vary considerably throughout the tidal cycle. For example, it seems that during certain tidal phases, secondary circulation patterns act to skew juveniles into the entrainment zone for Georgiana Slough, resulting in disproportionately high entrainment rates.

4.4 Implications for Modeling

One implication of the entrainment zone model is that prediction of smolt passage through complex junctions requires:

a) Knowledge of the local flow patterns in a junction throughout a tidal cycle and for all relevant flow rates, so that one can predict entrainment zones, and

b) Knowledge of the channel geometry, flow patterns, and fish behavior upstream of the junction in order to predict the spatial distribution of juveniles entering junction entrainment zones.

While a significant research effort is required to gain this information for a given junction, if it is obtained scientists and managers should be able to predict junction passage with reasonable accuracy, allowing them to develop management strategies based on quantifiable hydrodynamic processes and a juvenile behavioral model. Given that hydrodynamic models have become sophisticated enough to produce accurate predictions of temporally varying flow structures, it seems realistic to expect that one could develop a coupled behavioral/hydrodynamic model of smolt outmigration capable of estimating the spatial distribution of juveniles at any point along an outmigration route. Thus, a model capable of predicting smolt fate for a variety of real or hypothetical junctions could be obtained by merging existing hydrodynamic models (SI-3Dj, e.g.) with “juvenile tracking” modules.

4.5 Implications for Trawling

Given that the trawling in the Landing 63 area was done in a manner that sampled the upper 3-4 meters of the central water column, one would expect increases in catch to correspond with the diel vertical migration of observed fishes. However, as one can see in Fig. 57, trawling catch of target species was not correlated with the diel vertical migration of observed fish, but appears to be entirely dependent on light. Considering that there were almost certainly juveniles in the upper central portion of the water column during the corpuscular period on October 29th, the complete dependence of the catch data on absence of light indicates significant visual boat/net avoidance. This observation is corroborated by hydro-acoustic work on the Fraser River in B.C. that indicated boat avoidance behavior in migrating sockeye (Xie et al, 2002). It is also worth noting that the period of heavy rain during the October 29th study that acoustically blinded the transceiver did not appear to affect the trawl catch, supporting the concept of visual rather than acoustic net avoidance. Clearly, severe visual net/boat avoidance will introduce a light/dark bias into trawling data, and suggests a need for more robust groundtruthing technologies.

4.6 Implications for Georgiana Slough

This model of juvenile outmigration behavior suggests the DCC entrainment zone will be smallest during a Sacramento Ebb tide. However, the Georgiana Slough entrainment zone appears larger than the DCC's during this tidal phase, and secondary circulation appears to be moving fish towards this zone on strong ebb tides. In addition, we believe that those fish that do manage to pass the DCC and Georgiana Slough during an ebb tide are still susceptible to being advected back upstream into Georgiana Slough on a flood tide. Thus, it appears that fish bypassing the DCC on an ebb tide must pass Georgiana Slough during the same ebb, and then escape entrainment on the subsequent flood tide, before they can continue down the Sacramento River. In addition, work by Burau et al. (2003) indicates that flow into Georgiana Slough increases when the DCC gates are closed; this could result in a larger entrainment zone for Georgiana Slough, and a more pronounced secondary circulation pattern; effectively increasing entrainment in Georgiana Slough. If this is true, then there is a two-phase synergy between the DCC and Georgiana Slough that has important implications for juvenile entrainment; when gates are open, Georgiana Slough is optimized to entrain fish bypassing the DCC, and when gates are closed, Georgiana Slough entrainment could be enhanced by increased flow.

4.7 Implications for the Design of Future Studies

Because of the tidal influence on salmon entrainment, release schedules can pre-dispose fish to go down one channel or another depending on their timing. Thus, estimates of juvenile entrainment can be artificially high or low depending on release times. Increasing the number of releases for a given tidal cycle could help eliminate this bias. In addition, combing acoustic results with results of tracking studies conducted over broader time scales using acoustic and radio tagged fish could help average out potential biases.

Further, data demonstrated most smolts released during the day held until dusk prior to starting significant movement. Smolts moving at dusk would not be entrained in the DCC, because there was little or no flow into it at this time period. This results in an artificially low estimate of entrainment. If the DCC flow had been high in the evening hours we would have expected to see a disproportionate number of fish passing down the cross channel. Results using smolted fish might be different because there is typically more daytime movement as well. It is important to note, however, that a majority of ocean type salmon moving down the Sacramento do not do so as full smolts, while stream type outmigrants behave like highly smolted ocean types.

This year we learned that there are a tremendous number of fish in this section of the Sacramento River, and most of them are in the size range of salmon juveniles, and therefore acoustically indistinguishable. Future Studies in this area will need enough salmon targets in the river to dominate behavior of resident fishes. In addition, at least one other technology should be used to differentiate between species; although extremely inefficient and expensive, traditional trawling methods should work for dark periods, and acoustic or traditional underwater cameras could be used during light periods.

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Appendix A – Echo Processing of Hydroacoustic Data

Software used in the analyses of data was Sonar Data's EchoView v2.25 and v3.Analysis of the acoustic data consisted of a series of steps, designated as

a) Observation
b) Calibration and Thresholding
c) Regions for Exclusion (Noise)
d) Echo Extraction
e) Trace Formation
f) Output Formatting/Quality Assurance

These steps are discussed in detail in the following sections.

a.) Observation

Acoustic files were approximately 30 minutes in length. Files were visualized by "play-back" in the EchoView program, providing a high-resolution color echogram of the file. Comments were recorded on presence of fish targets, as well as regions overshadowed by acoustic interference. The primary source of acoustic interference was volume reverberation from bubbles produced by the underwater exhaust of boats transiting the study area (Fig. 16).

b.) Calibration and Thresholding:

Calibration consisted of entering data on water temperature (used for speed of sound calculation), and acoustic system information including, beam angle, frequency, range gates for analysis. Thresholding was used to limit as much noise as possible. Much of the volume reverberation was observed at a relatively low level. Data files were collected using a –65 dB or -56db threshold. Since this level is considerably less than the anticipated acoustic size of juvenile salmon juveniles, we re-played the visualization at a –50 dB level. This process removed a considerable amount of the acoustic interference, allowing a more rigorous evaluation of the acoustic data.

c.) Exclude regions of bad data:

Even with the increased threshold, it was observed that some regions were masked by high noise events, and no fish data could be recovered from these regions (Fig. 16). Note that at this expanded resolution, individual fish echoes can be seen. Polygons can be drawn on the data field screen with the mouse to denote areas of exclusion e. Care was taken to include the noise within boxes minimizing the inclusion of fish traces. Boxes are allowed to overlap to insure that all obscured regions are excluded. Regions of exclusion were primarily a result of boat wakes.

d.) Echo extraction:

First, the signal was further thresholded at the –50 dB level. Although some probability of missing small targets existed, the reduced probability of generating echoes from noise was thought to justify this choice. Pulse width was used as a primary filter to test the returning wave shape. Echoes from reverberation should have corrupted wave shapes in comparison to point-source target echoes (small fish). The pulse width was measured at the half amplitude (endpoint criteria = -6 dB). The pulse width measurement was compared to the nominal transmitted shape (0.4 ms). Echoes with pulse width measurements less than 0.5 times the nominal or greater than 1.5 times the nominal were rejected. The next filter is the maximum allowable beam compensation. This puts a limit on how far off the center axis of the transducer beam a target can be. For these analyses we set the level to 10db. A target could be 10 db off peak and still be include in the analysis. The further off the beam axis a target is past a certain point, the less reliable our estimate of size and position are. The final step is to examine the standard deviation of the angles of the samples in both the x and y range. Samples that fall outside the specified range will be rejected

e.) Trace formation

While the eye and brain of the human observer completes this task automatically, the computer must be programmed to accomplish this task. This process has many names and is often called fish tracking, or tracing. Trace formation may be either 2-dimensional, using range and time, or 4-dimensional, using time and X/Y/Z position produced by a split-beam system. EchoView's $\alpha-\beta$ Fish Tracker implements a fixed coefficient filtering method as presented in Blackman (1986). The filtering process selects out single targets as candidates for a track. The algorithm is applied to either split or dual beam data from a single target detection process. These are implemented as the 4D and 2D algorithms for split beam data (i.e. targets with range, angles and time) and dual beam data (i.e. targets with range and time) respectively. The sensitivity of the tracker to unpredicted changes in position and velocity is controlled by the Alpha and Beta gains respectively. Since the dual-beam only provide data on range and target size the 2-d tracking model was employed. Split-beam data was analyzed initially using a 4-d process taking into account target, however, high noise levels in the river forced use to open the target gates to a point where 2-d tracking was more feasible.

Each fish echo that has passed the echo extraction tests is characterized by a ping number (time) and range. These provide X and Y coordinates. When a candidate echo is received, it “opens” a new trace. The range of this first seed echo is projected horizontally. A “tracking window” is centered about this position to provide a range window in the following ping. Any echo inside this range window must by definition be correlated to the seed echo. If multiple echoes fall inside the window, a best fit is calculated and that echo is linked to the original seed echo, providing a fish trace containing two echoes. Again, the echo that is closest to the center of the window is selected to be linked to the growing fish trace. A maximum range can be specified, outside of which echoes will not be included. This is useful when fish are close together to avoid the track jumping from fish to fish. A “ping gap” value is entered by the user to define when the trace is completed. If a gap of 4 is entered, then an active fish trace may miss 3 echoes and still search for candidate echoes. When the fourth echo is missed, the trace is completed and passed on to the trace filtering processes. In the final stage we specify how short a track can be. The more targets in a track, generally mean the more reliable a track is.

f.) Output formatting and Quality Assurance

The trace formation analytical process produces a data file with a line (record) for each fish trace accepted by the trace filtering. Each trace is coded by date, time, and contains some trace information such as mean target strength and range, and number of echoes for dual-beam data. For split-beam in addition we get angular data such as off axis distances, velocity. The direction of travel is calculated as an angle varying between 0 and 360º. The split-beam coordinate system may be considered as a compass, with North oriented in the direction opposite the cable connector on the transducer. This direction would represent 0 degrees. A clockwise rotation of 90 degrees would indicate a direction corresponding to East. Depending on how the transducer was mounted, the direction column indicates the vector direction in a plane normal to the acoustic axis, with zero degrees opposite the connector. Thus a fish with direction of between 0.1 degrees and 179.99 degrees would be considered as going from left to right across the transducer face.

The data files produced by the trace formation process were imported into Excel spreadsheets. The range and angular position columns were selected in each file and plotted as a scatter plot. The scatter plot was evaluated for data grouping to search for anomalous distribution of fish. The analytical strategy for processing this data set was to minimize the type 2 errors. We define a type 1 error as missing a valid fish, and a type 2 error as including a false fish, or one created from reverberation or interference. Given the noise levels observed during data collection, we concluded that the type 2 errors could overwhelm the data set and provide a greater source of bias than type 1 errors.

Consequently, we used echo selection criteria and trace formation criteria to minimize the formation of false fish traces. The high noise levels, combined with this strategy, may have selected against the smaller fish targets.

Figure 1. Map of Delta Region showing Delta Cross Channel linkage to Central and South Delta.

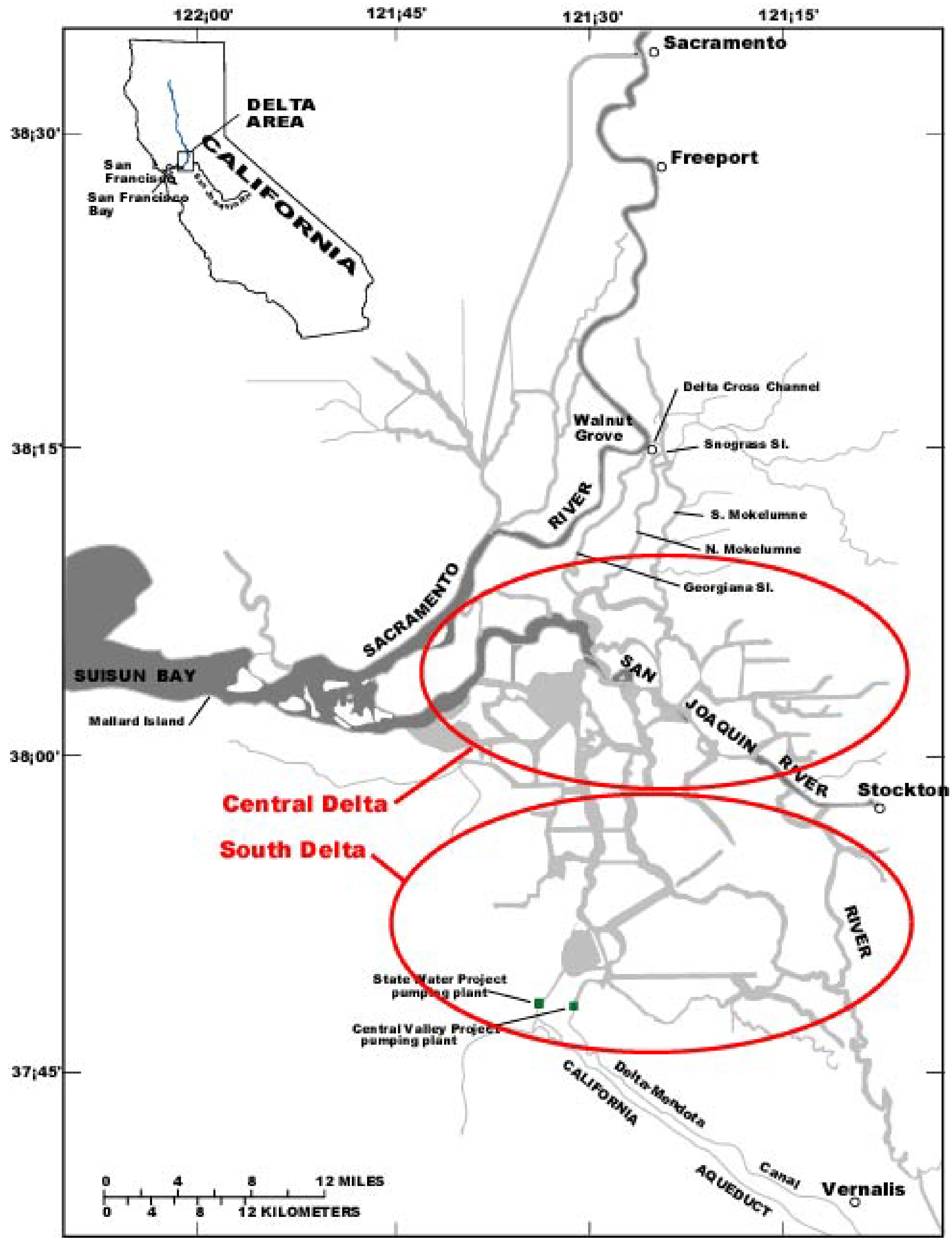


Figure 2. SVP and CVP pumping plants.

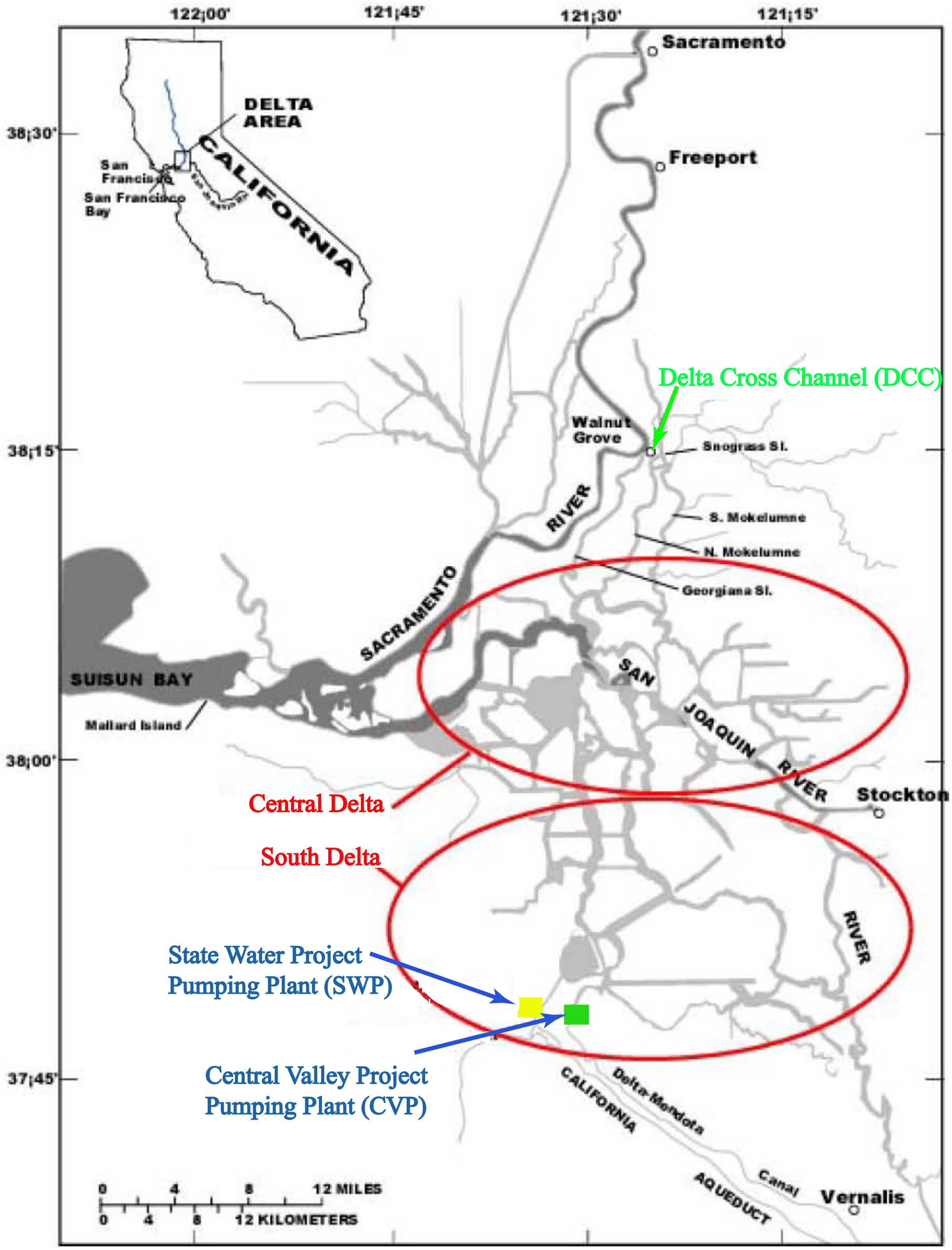


Figure 3. Local map of the DCC turnout on a westward bend in the Sacramento River.

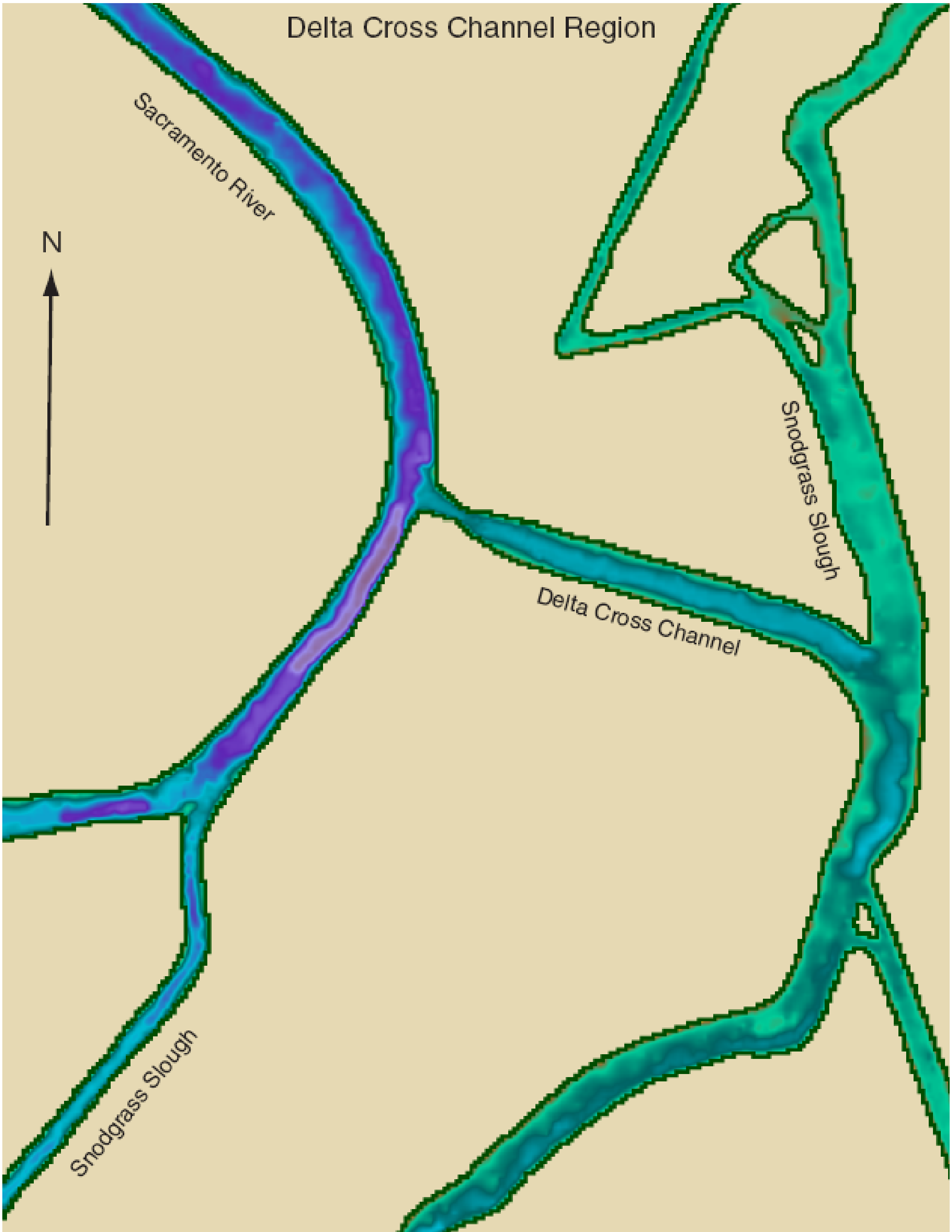


Figure 4. Vector maps showing water velocity patterns in the DCC junction area for a complete tidal cycle. (Each map represents about 1 hour)

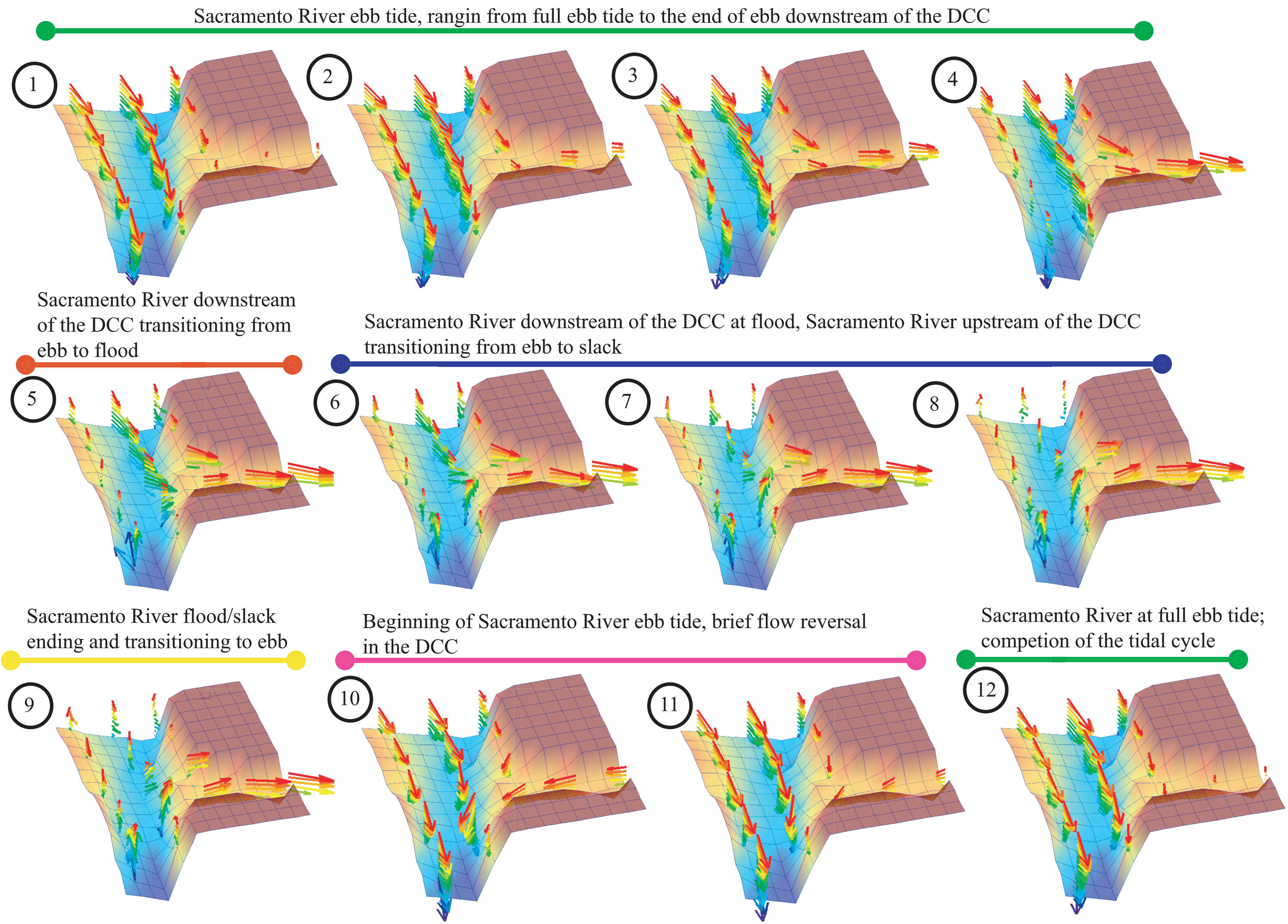


Figure 5. Illustrations of juvenile holding pens.

Approximately 60,000 sub-yearling Chinook salmon were pumped into net pens during the course of each 30 hr study, using a total of 120,000 fish from Coleman National Fish Hatchery

Fish were acclimated for a period of 24hrs in floating net pens prior to release into the river

Figure 6. Relative locations of acoustic sampling sites in relation to the DCC

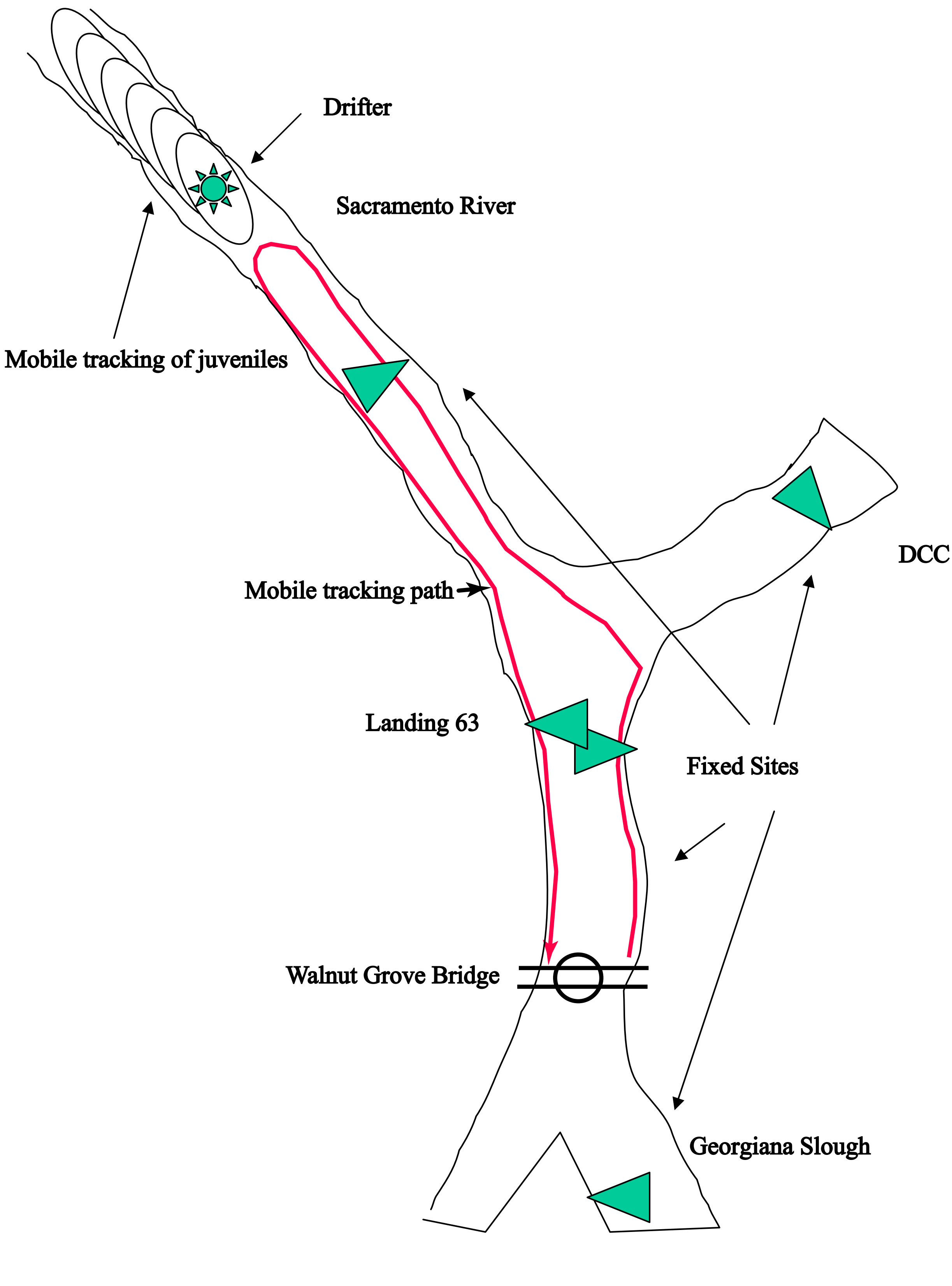


Figure 7. Typical mounting design for acoustic unit.

Figure 8. Schematic showing relative transducer placement and beam coverage at each fixed station site.

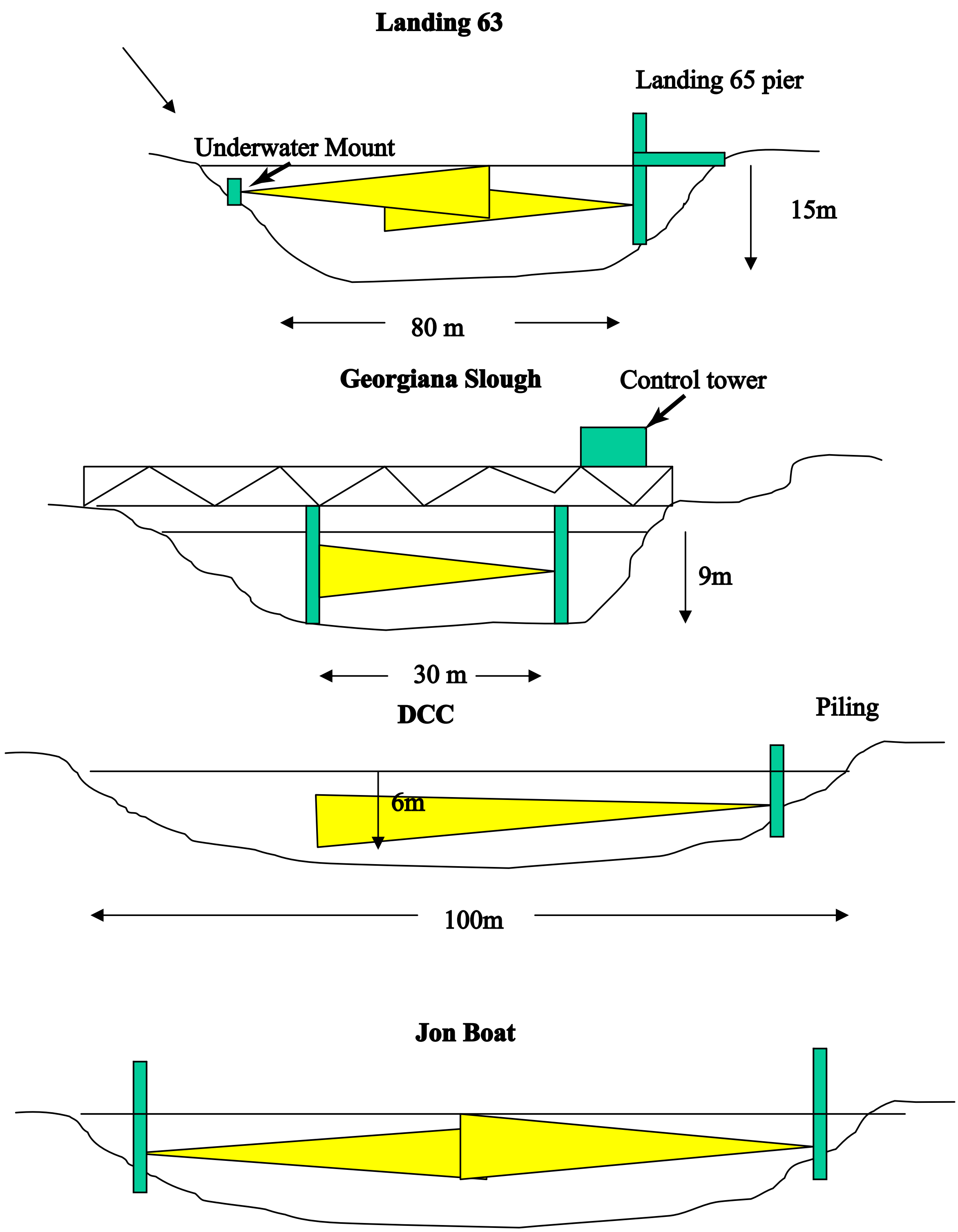


Figure 9. Example screen from Biosonics Visual Acquisition Software V4.

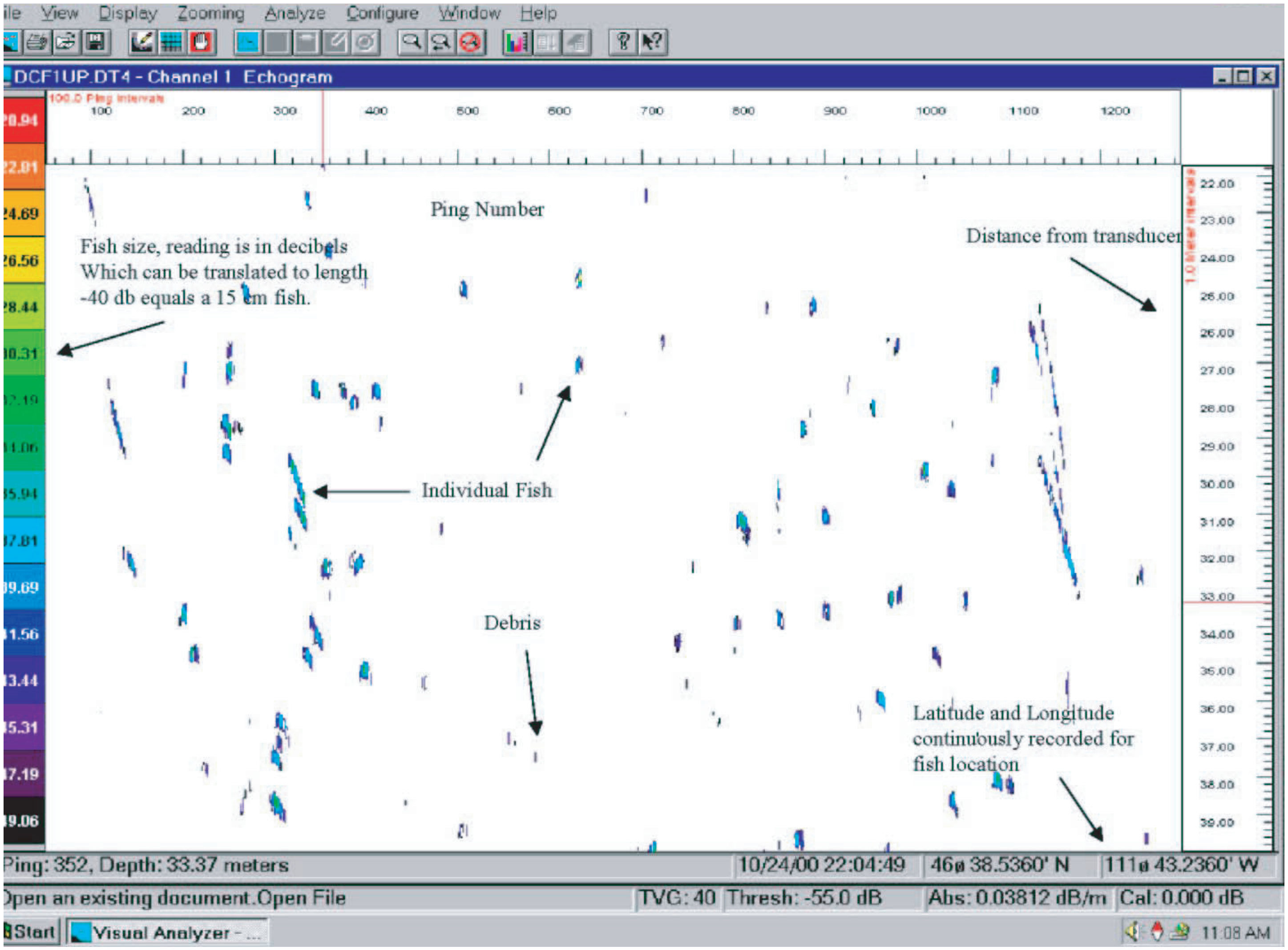


Figure 10. Map of Delta region showing flow gauging stations.

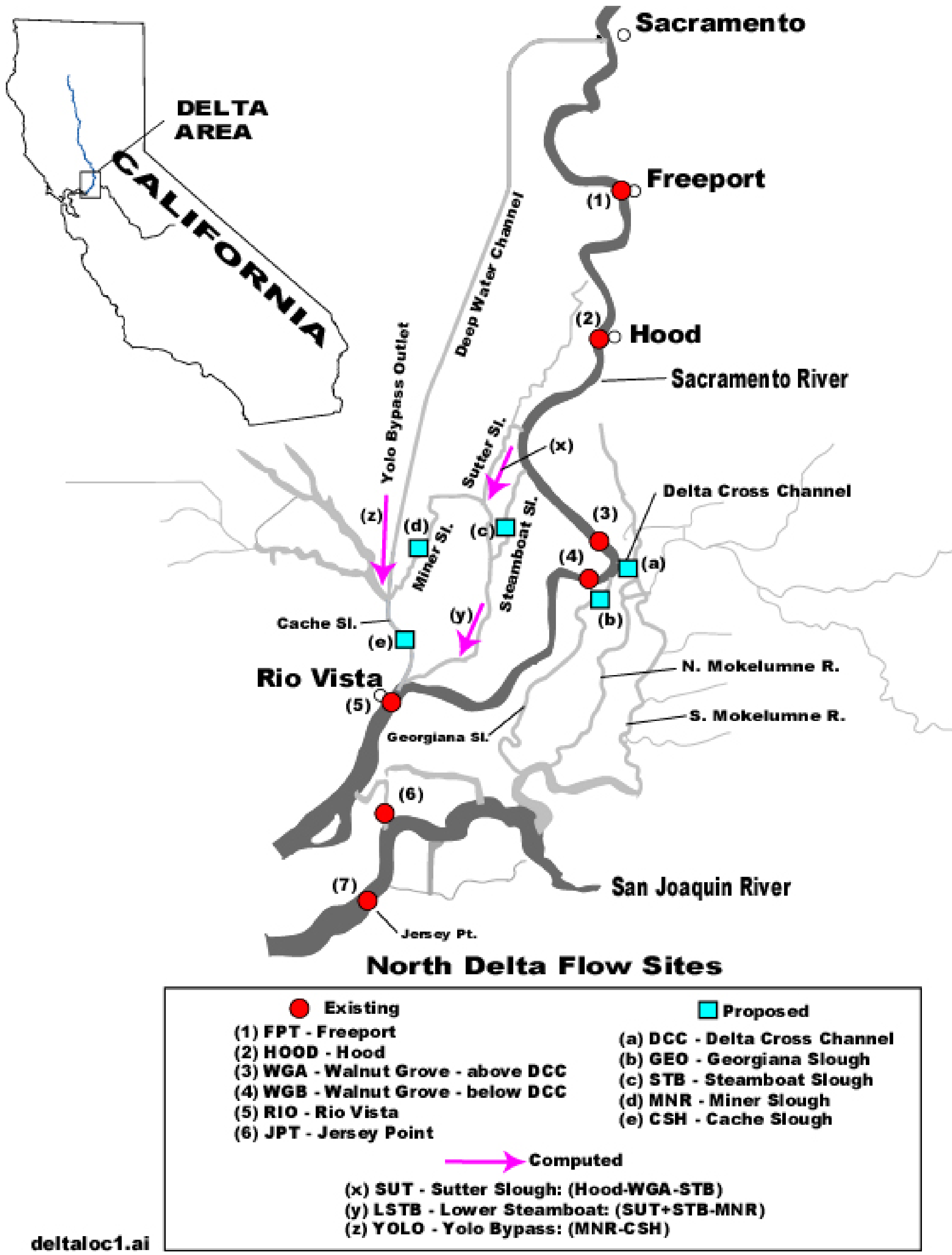


Figure 11. Picture showing release of drifter used to follow mass release of juvenile salmon.

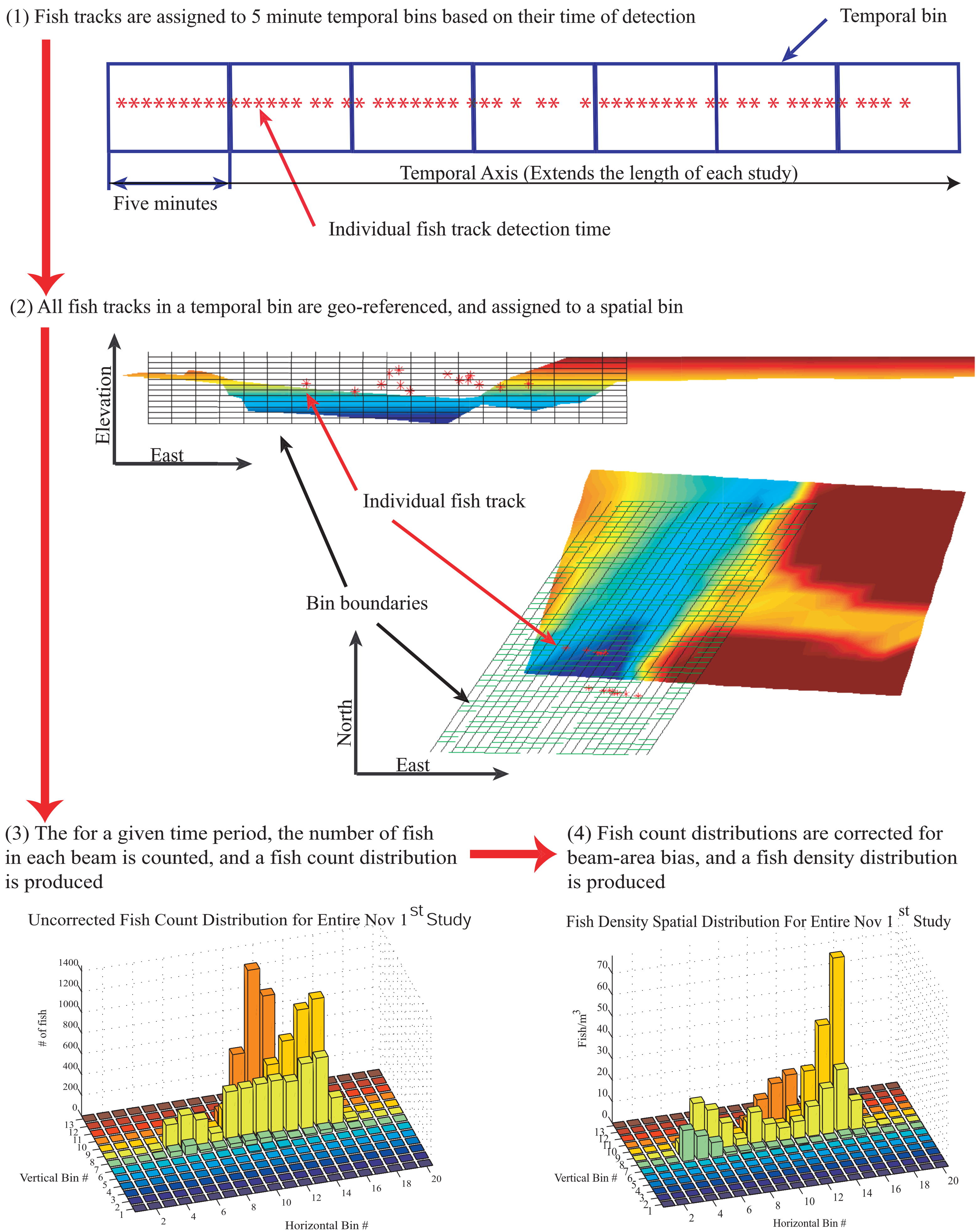


Figure 12. Progression of steps in fish density distribution analysis.

Figure 13. Schematic of spatial bins.

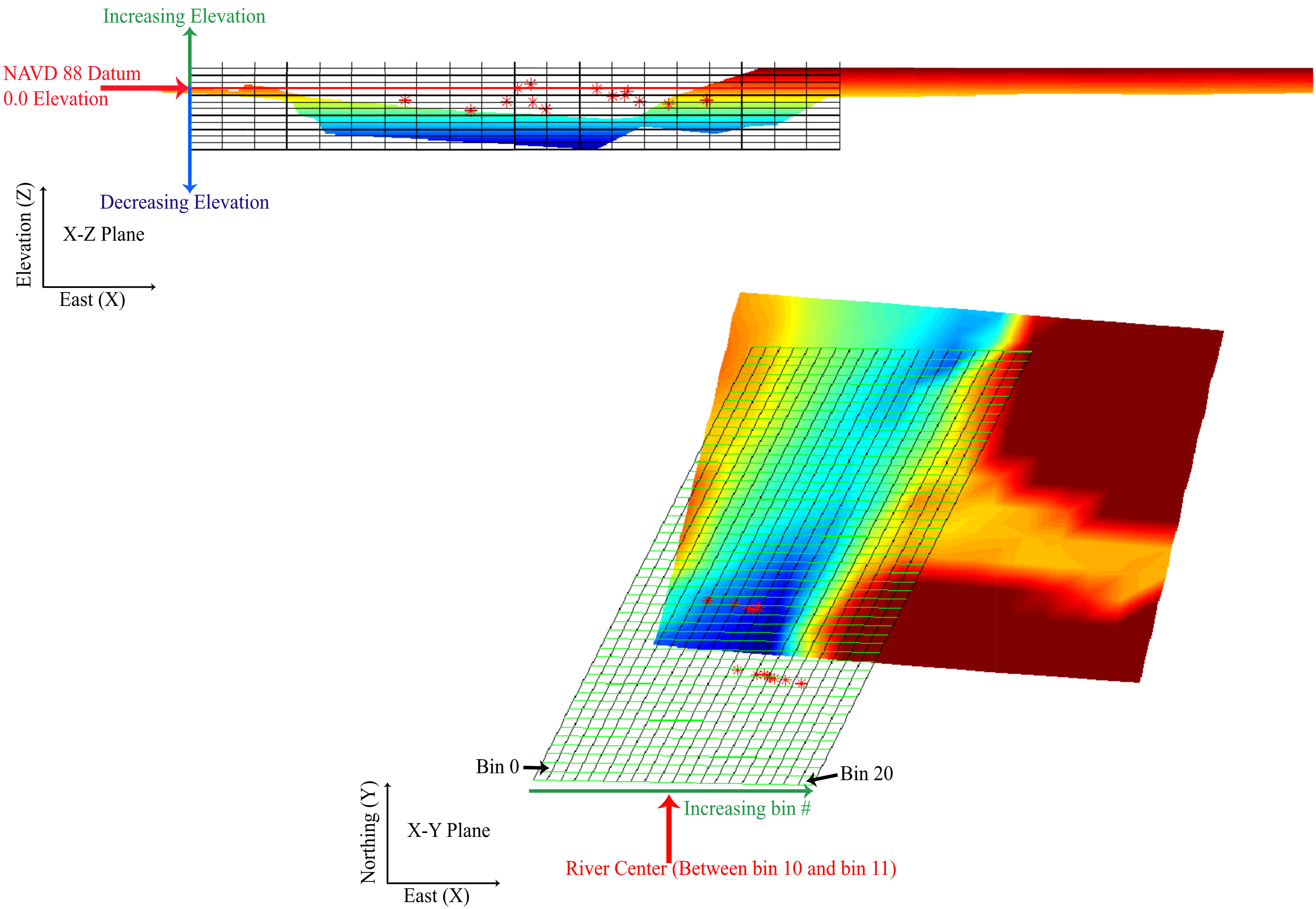
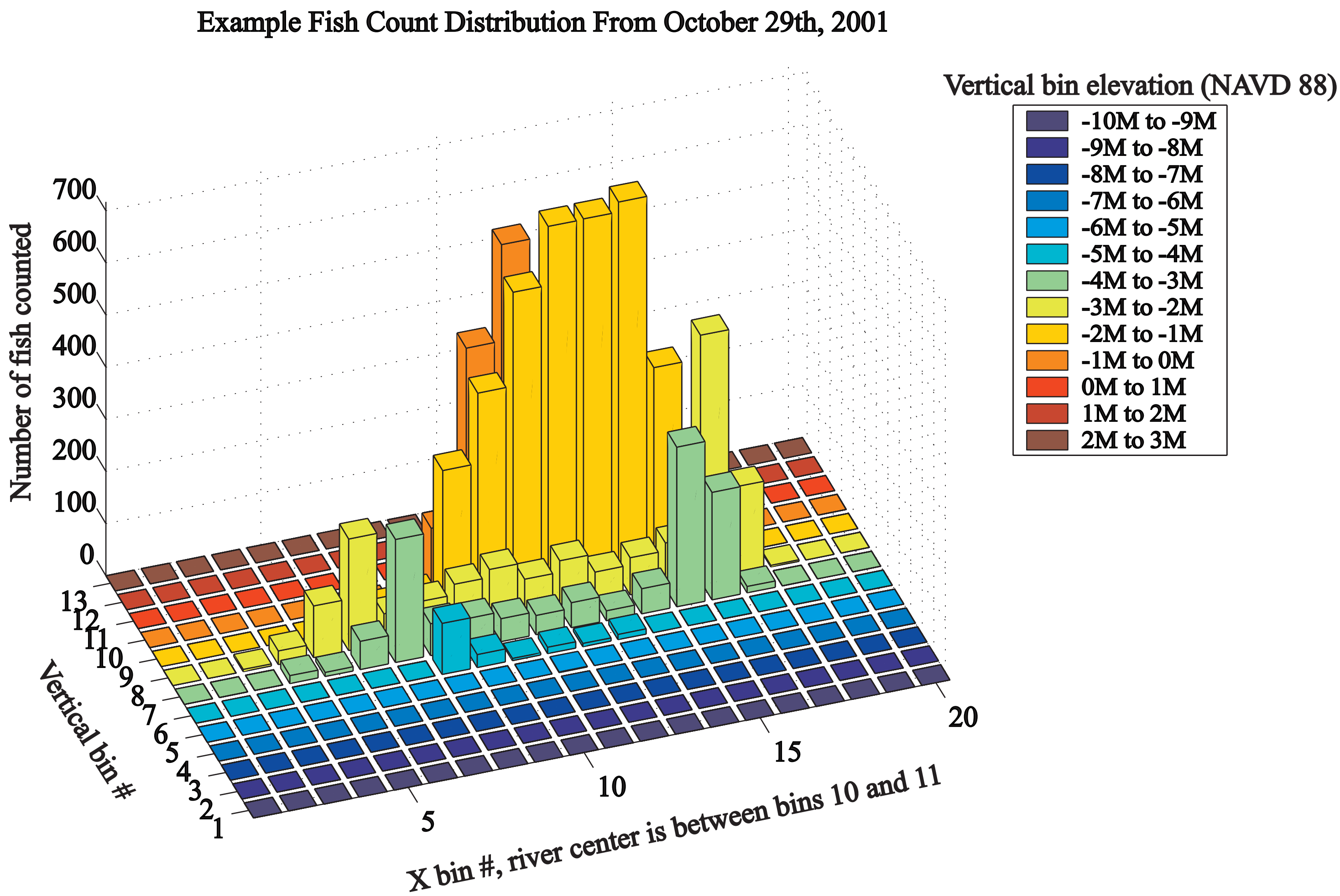


Figure 14. Example fish count distribution.



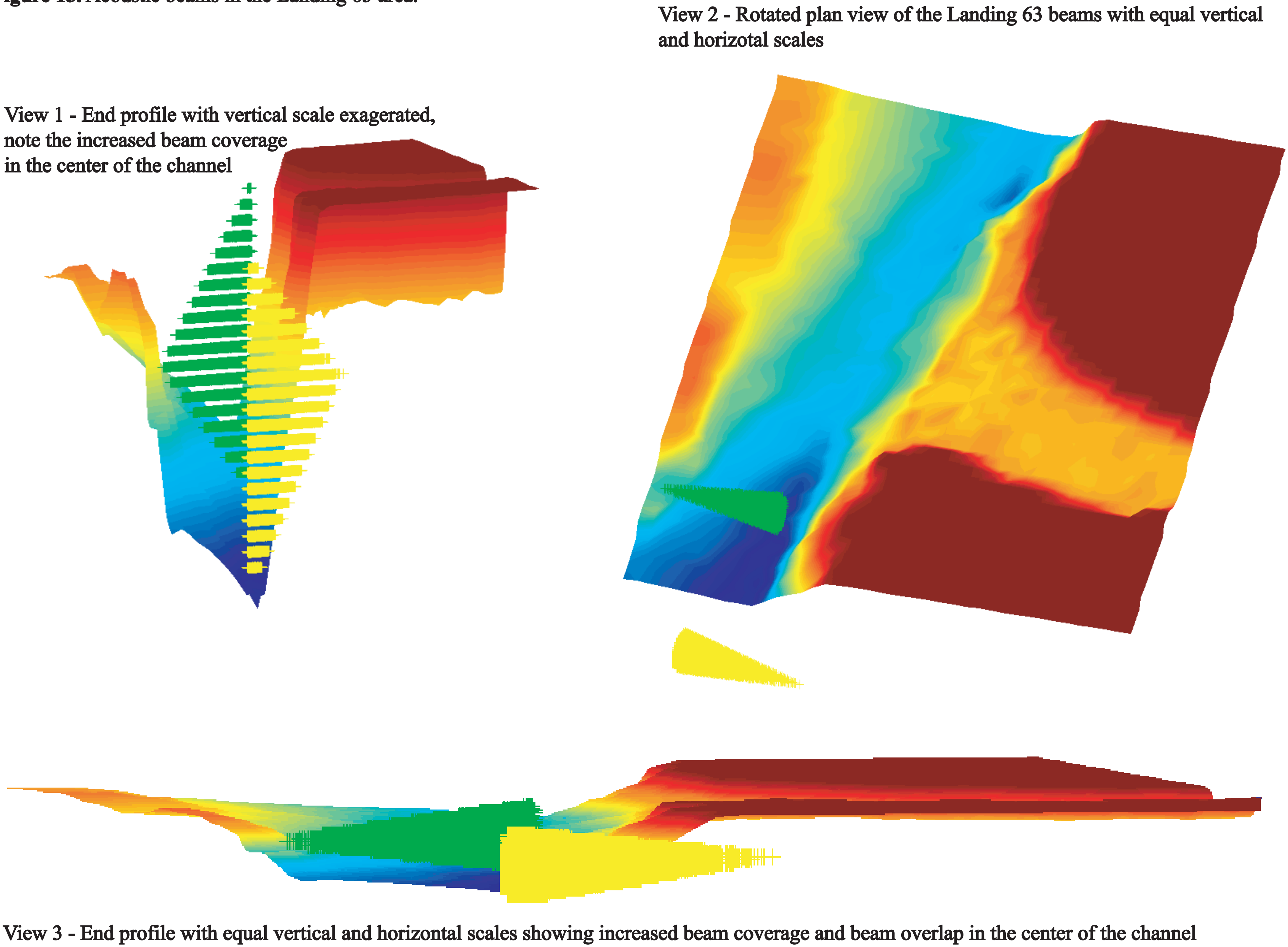


Figure 15. Acoustic beams in the Landing 63 area.

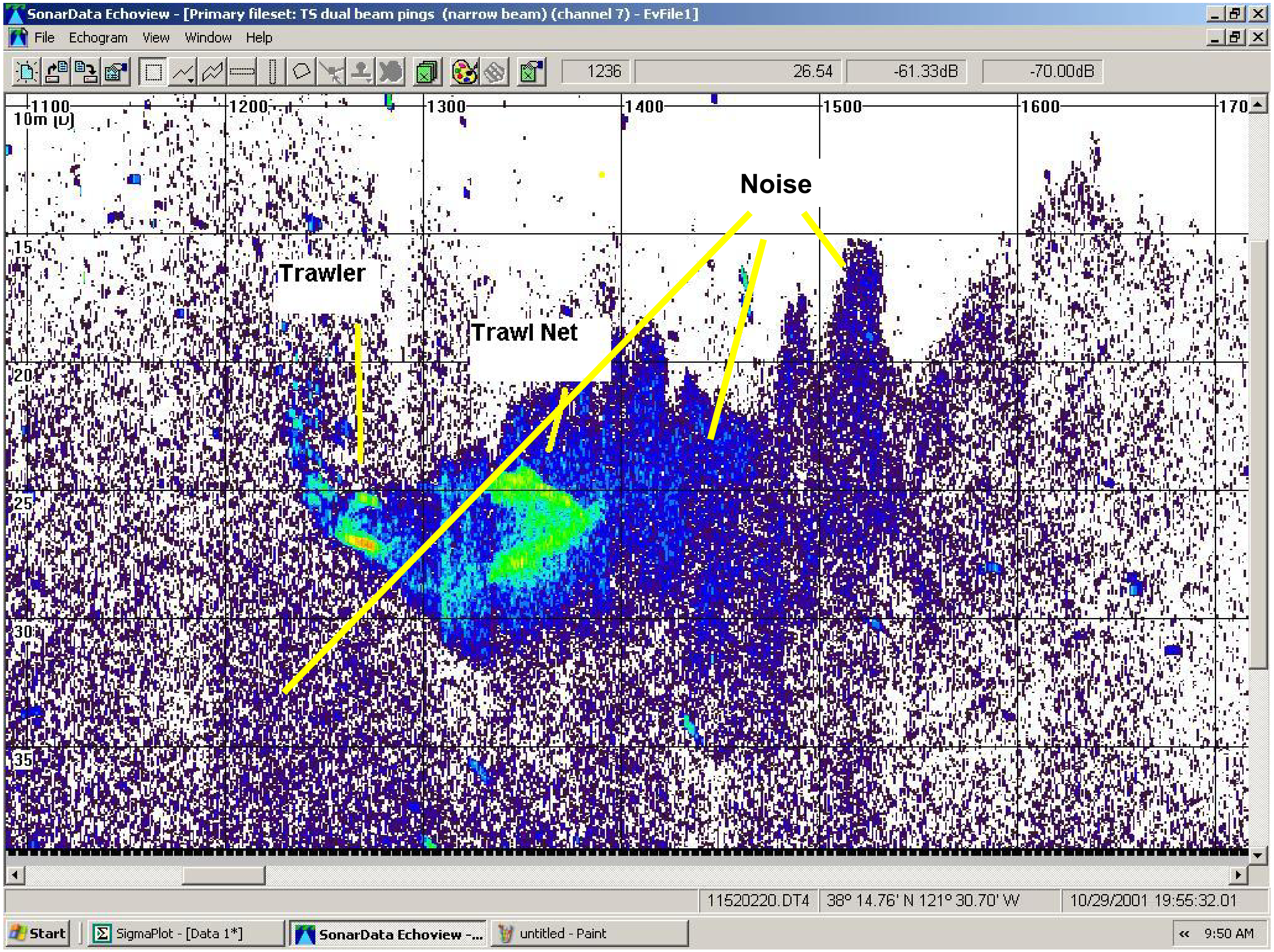


Figure 16. Illustration of Biosonics Visual Acquisition Software screen showing acoustic noise masking fish tracking data.

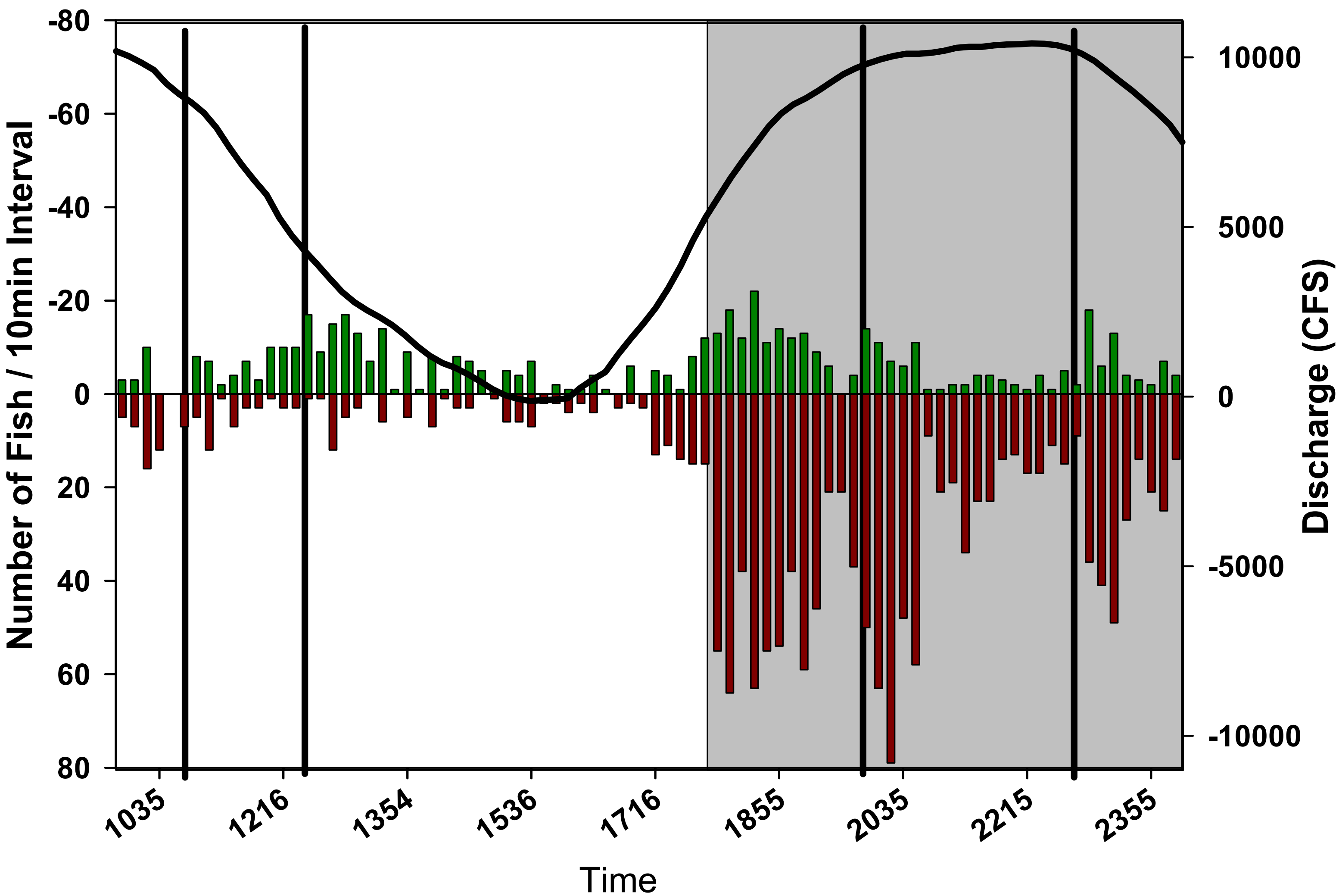


Figure 17. Diel fish passage past the Jon Boat 1.5km upstream of the DCC on October 29, 2001. Vertical black bars denote approximate times for drifter arrival at the Jon Boat.

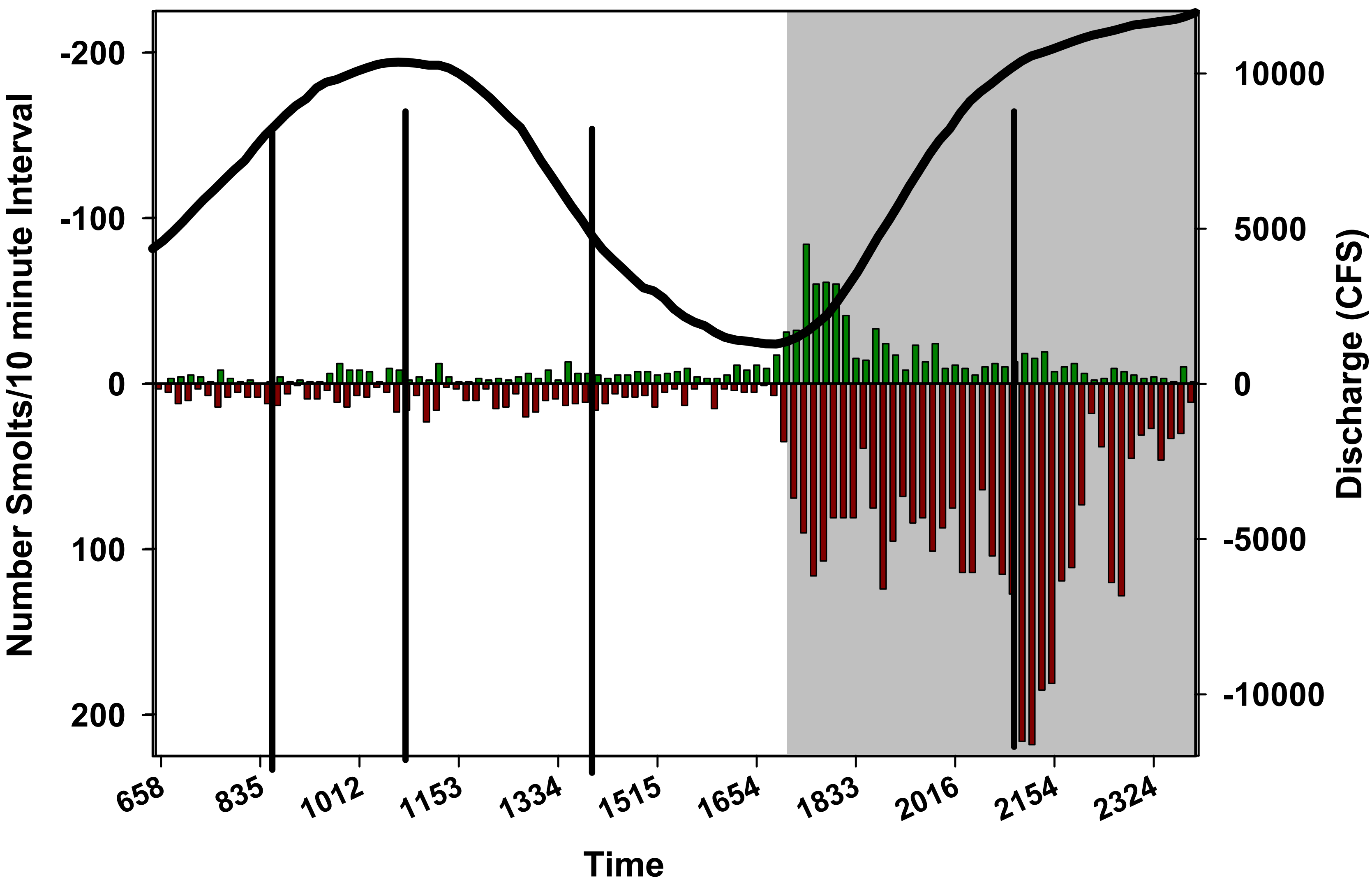


Figure 18. Diel fish passage past the Jon Boat 1.5km upstream of the DCC on November 1, 2001. Vertical black bars denote approximate times for drifter arrival at the Jon Boat.

Figure 19. Distribution of targets detected at the Jon Boat site 1.5 km upstream of the DCC.

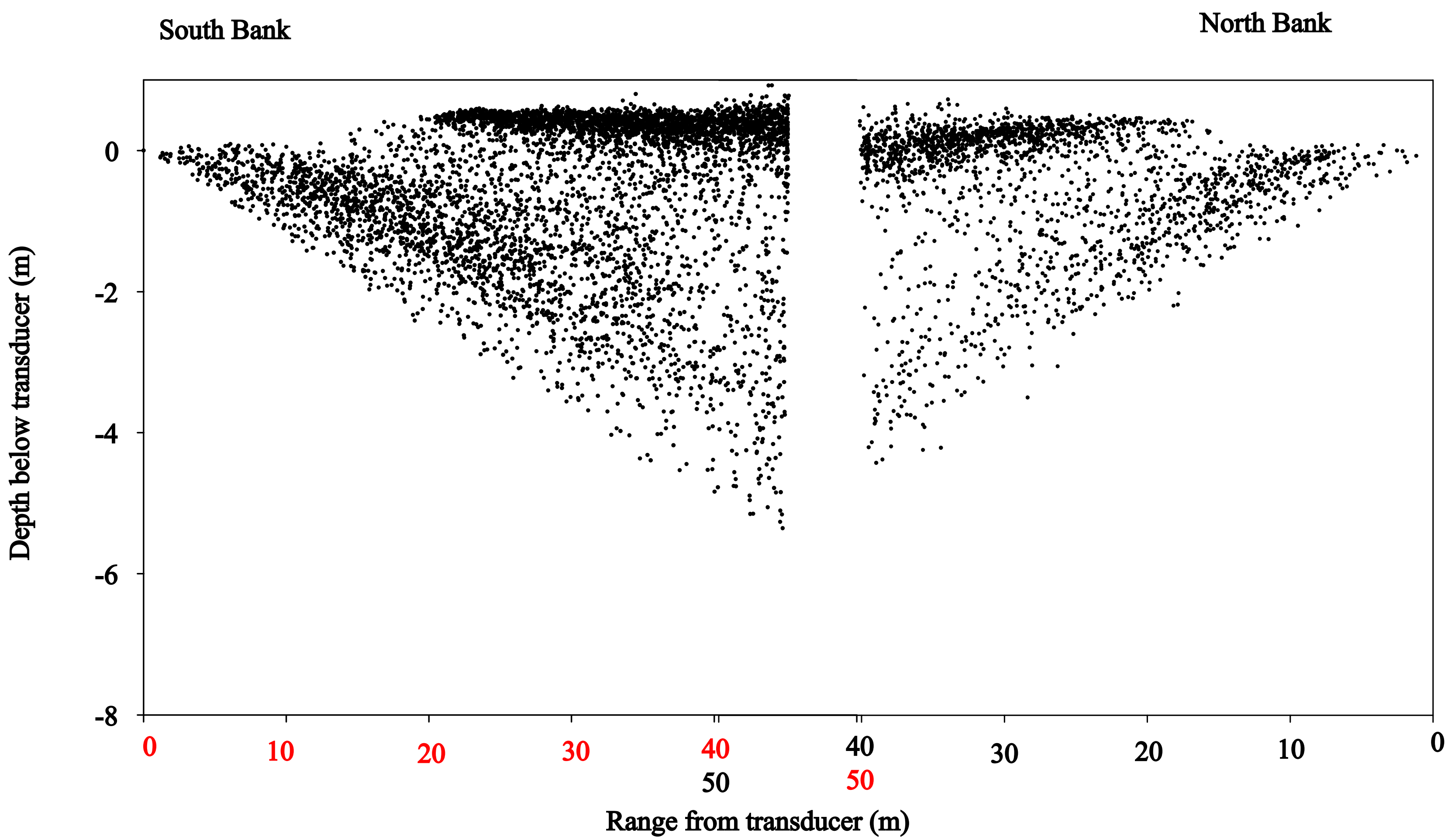


Figure 20. Spatial distribution of targets by release number for the Jon Boat site on October 29, 2001.

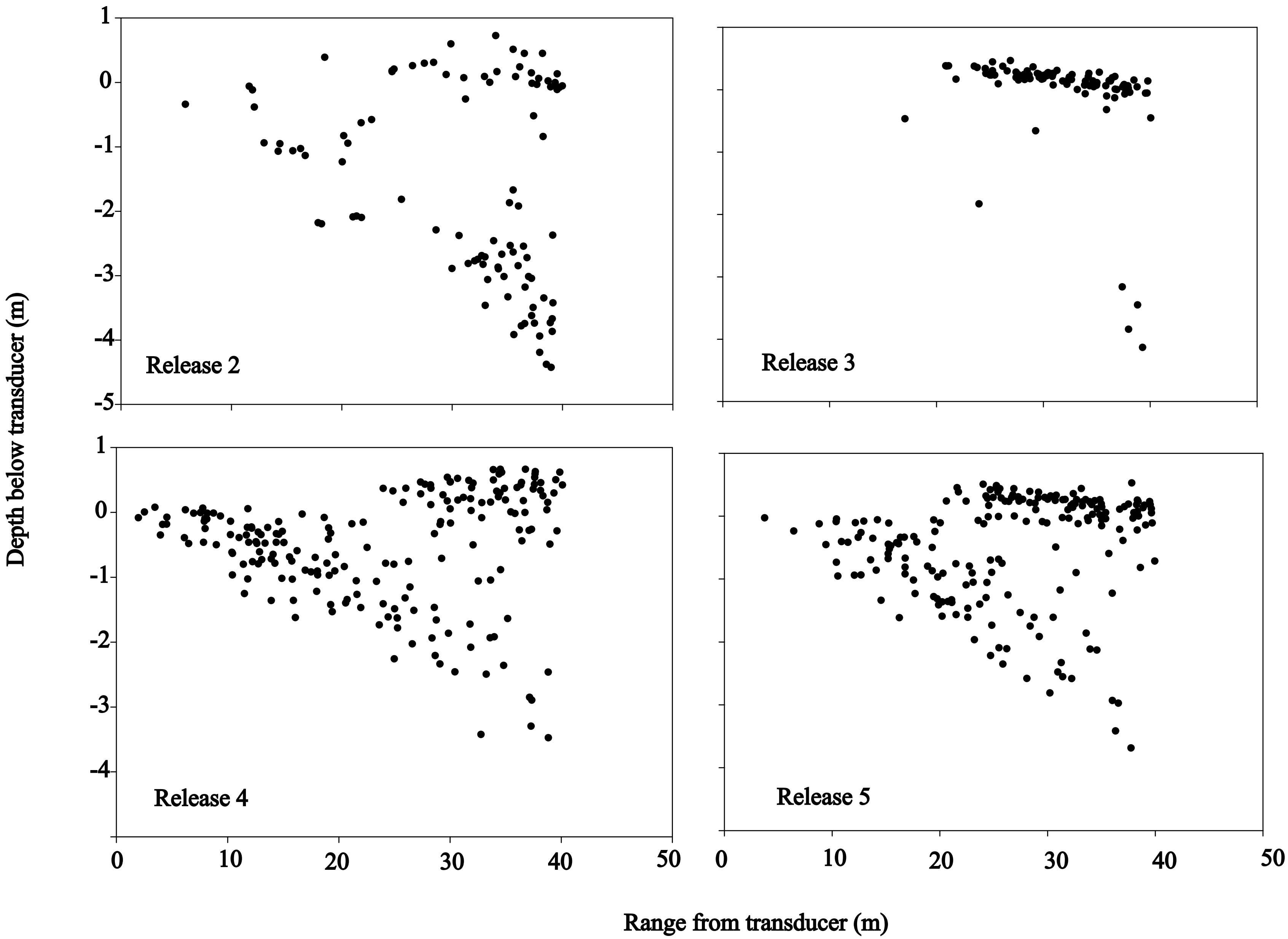


Figure 21. Spatial distribution of targets at the Jon Boat site comparing distributions from crepuscular periods and daytime periods.

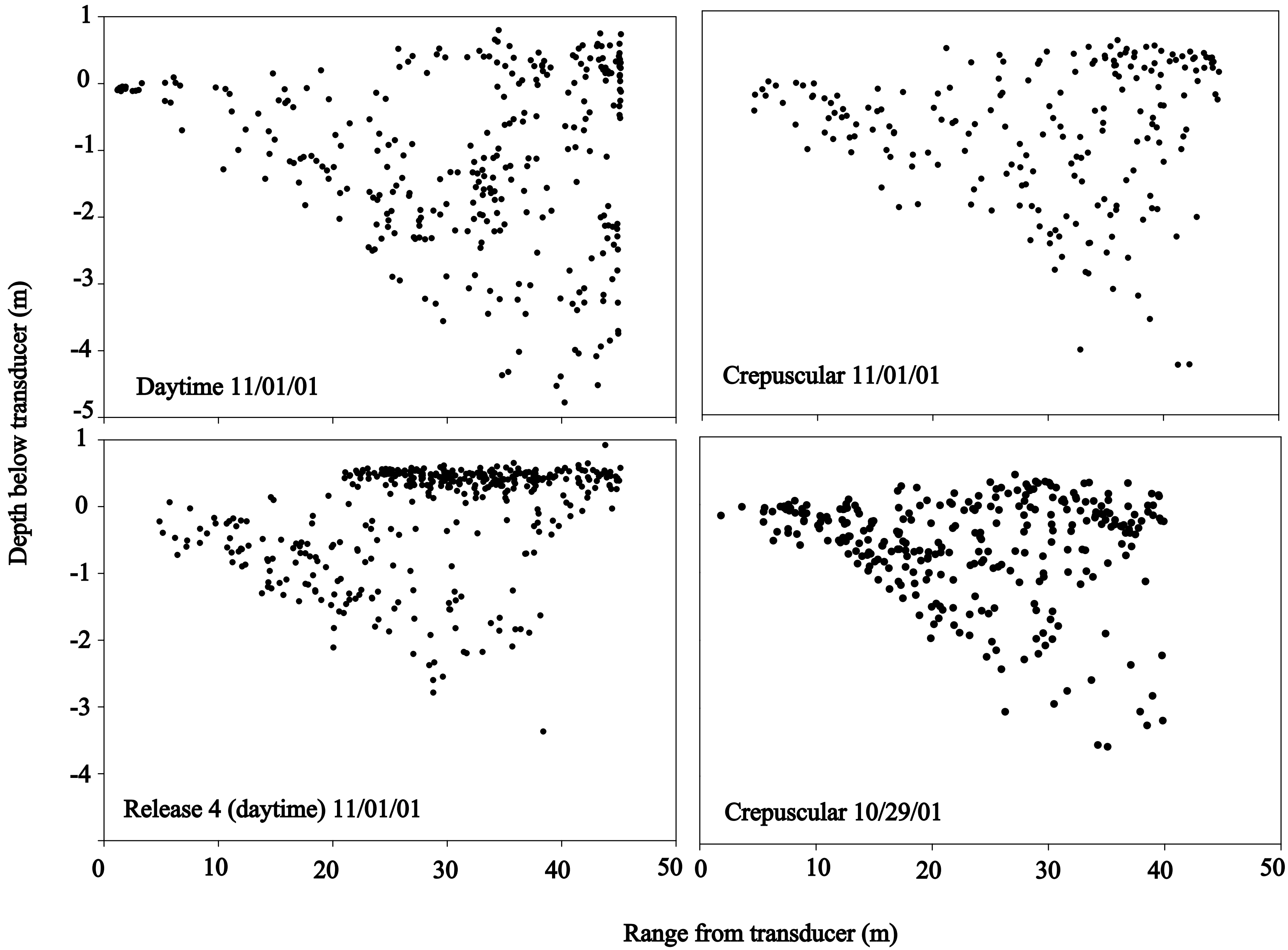


Figure 22. Diel fish passage past Landing 63 on October 29, 2001, as seen from the West bank of the Sacramento River. Vertical Black bars denote approximate times for drifter arrival.

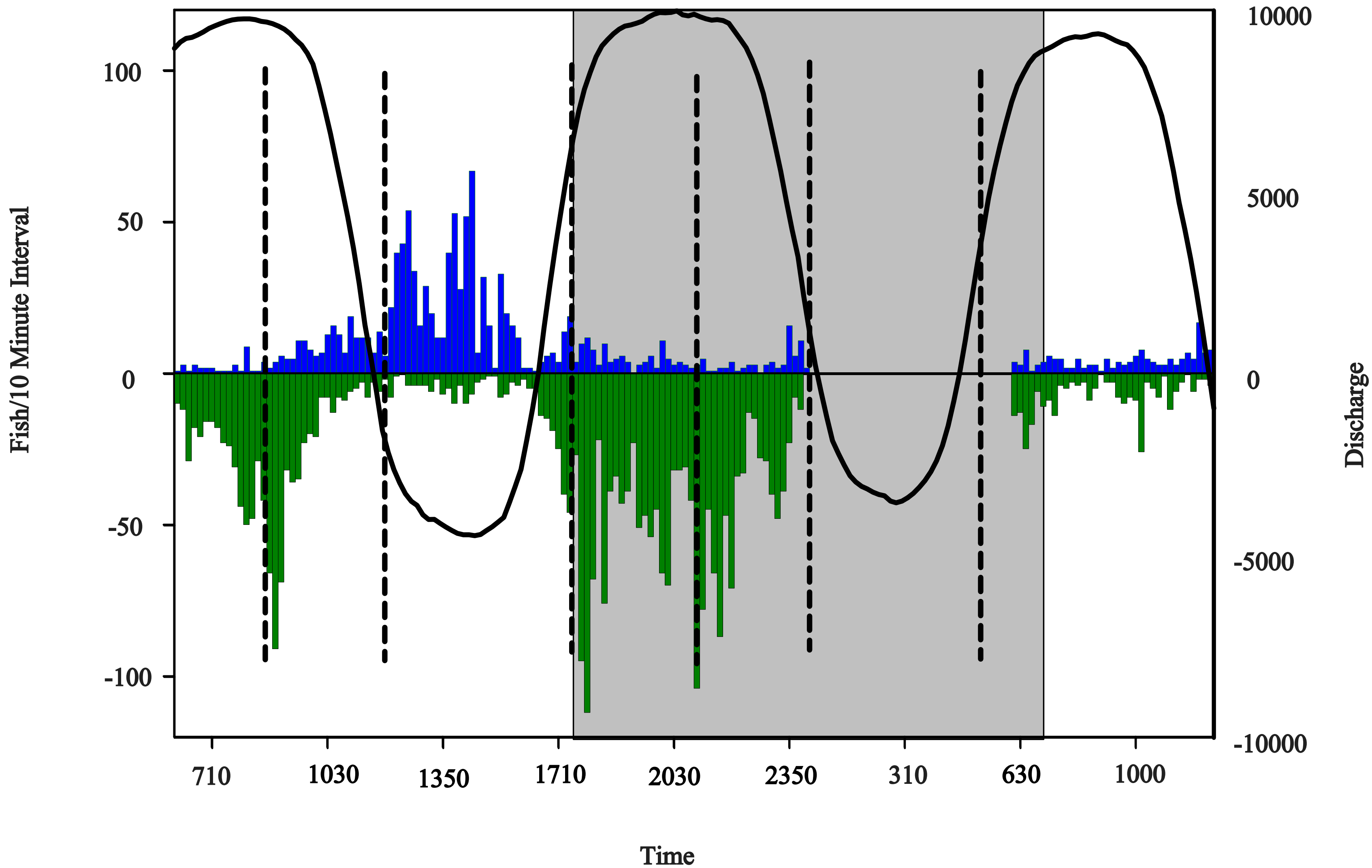


Figure 23. Diel fish passage past Landing 63 on October 29, 2001 as seen from the Eeast bank of the Sacramento River. Vertical Black bars denote approximate times for drifter arrival.

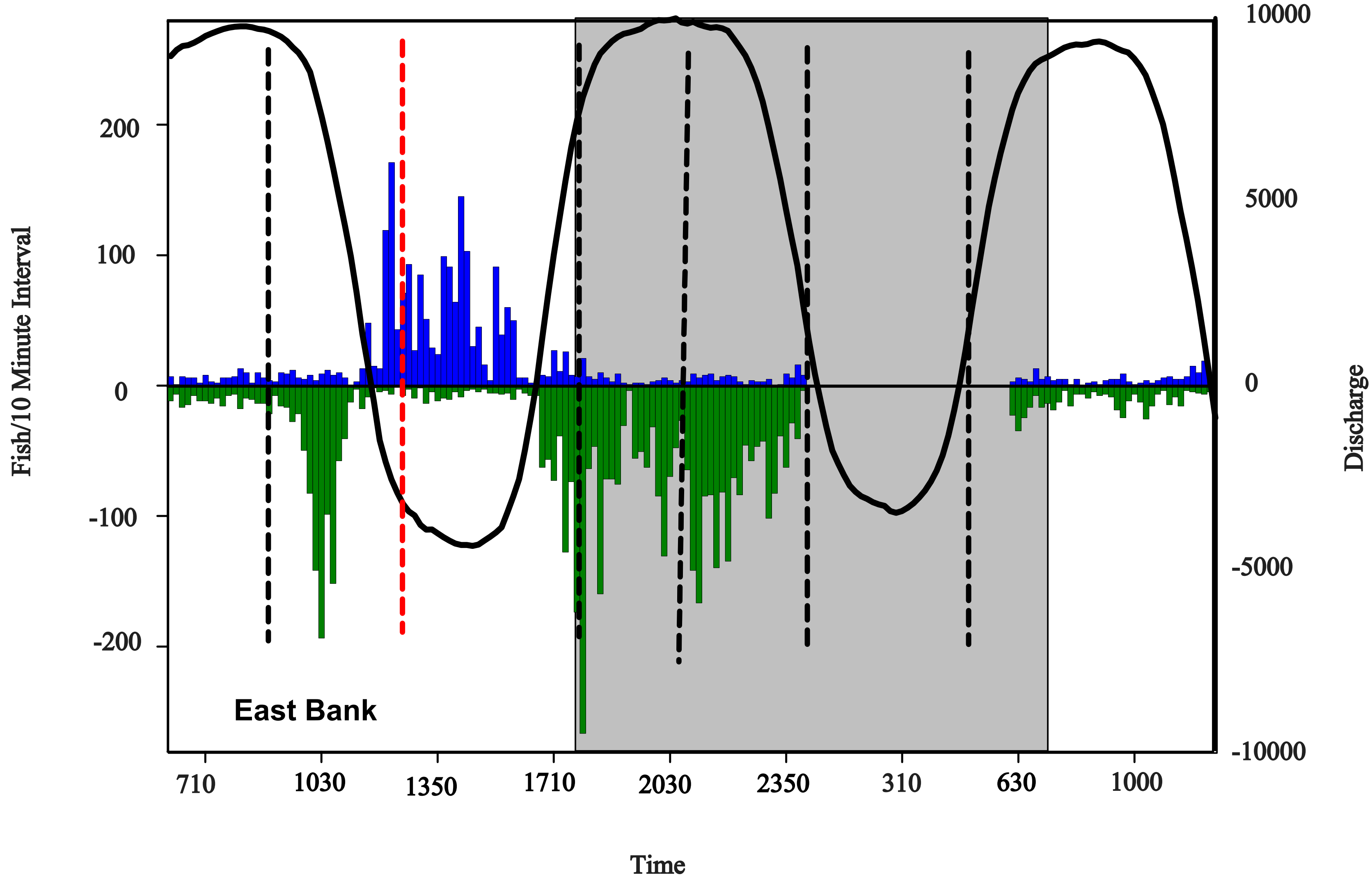


Figure 24. Group of targets moving along western bank of the Sacramento River downstream of the DCC early on October 29, 2001.

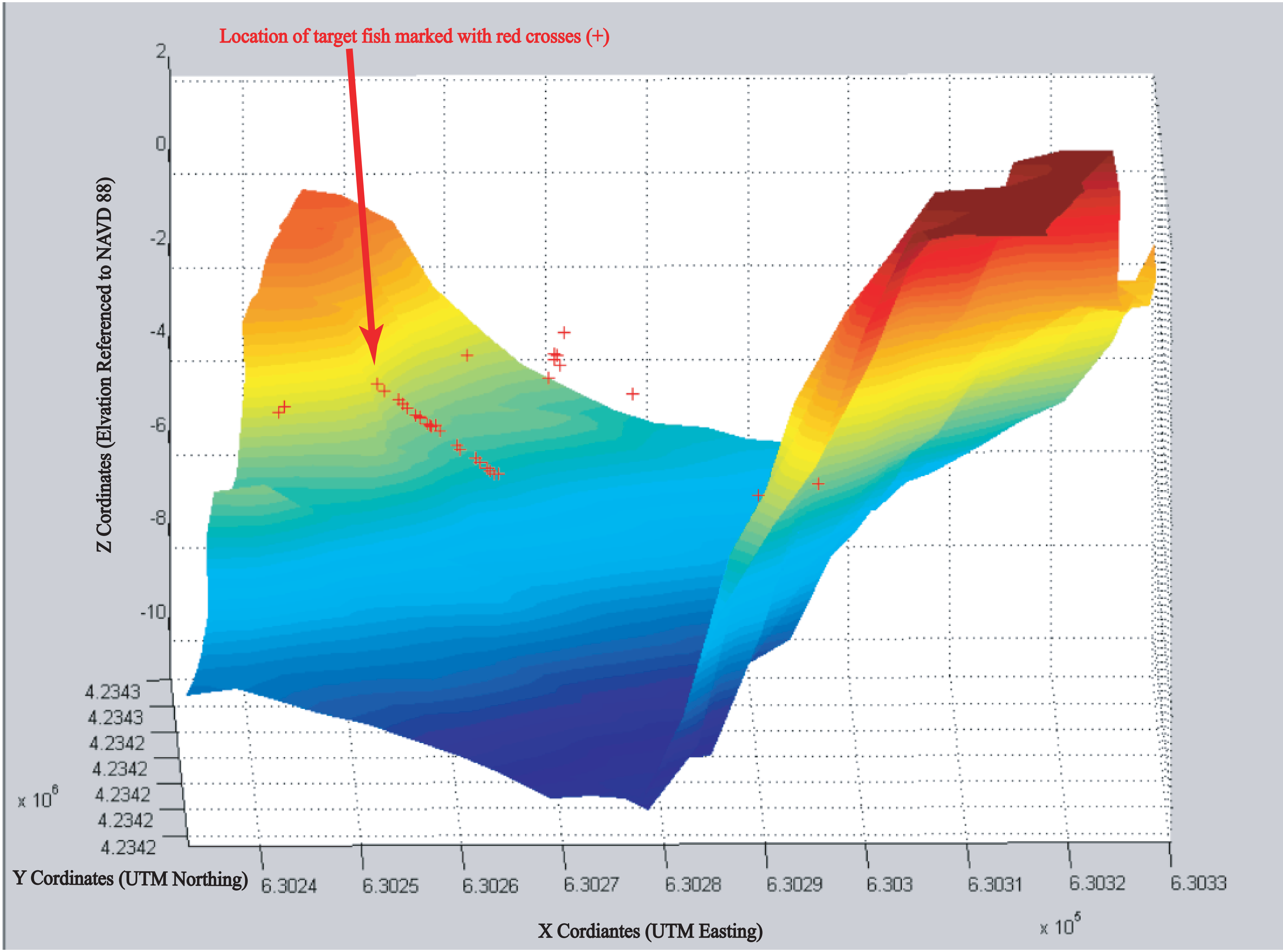


Figure 25. Group of targets moving along East bank of the Sacramento River downstream of the DCC early on October 29th, 2001.

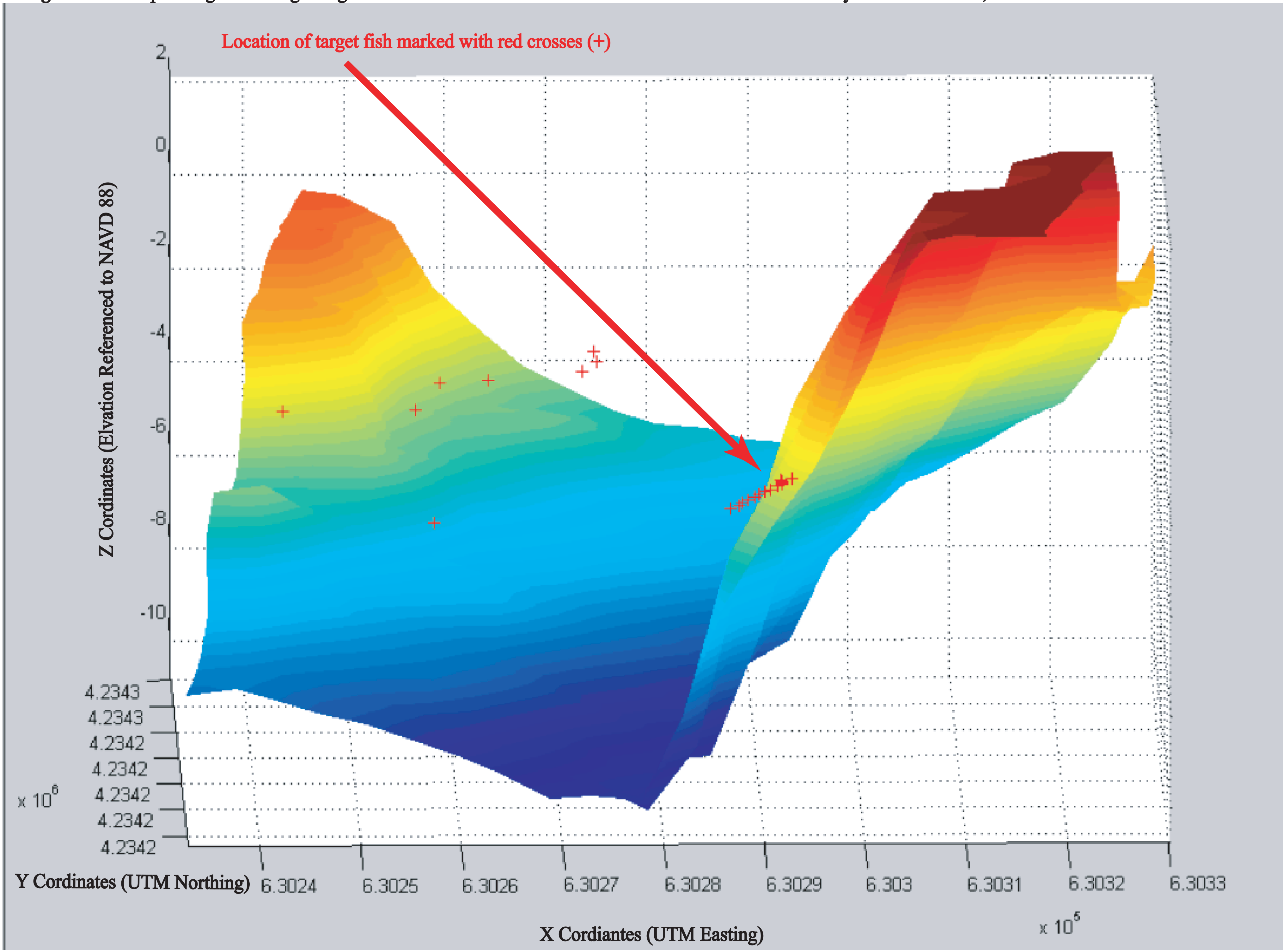


Figure 26. Trawl catches of CWT salmon and shad at Landing 63 and the DCC on October, 29, 2001.

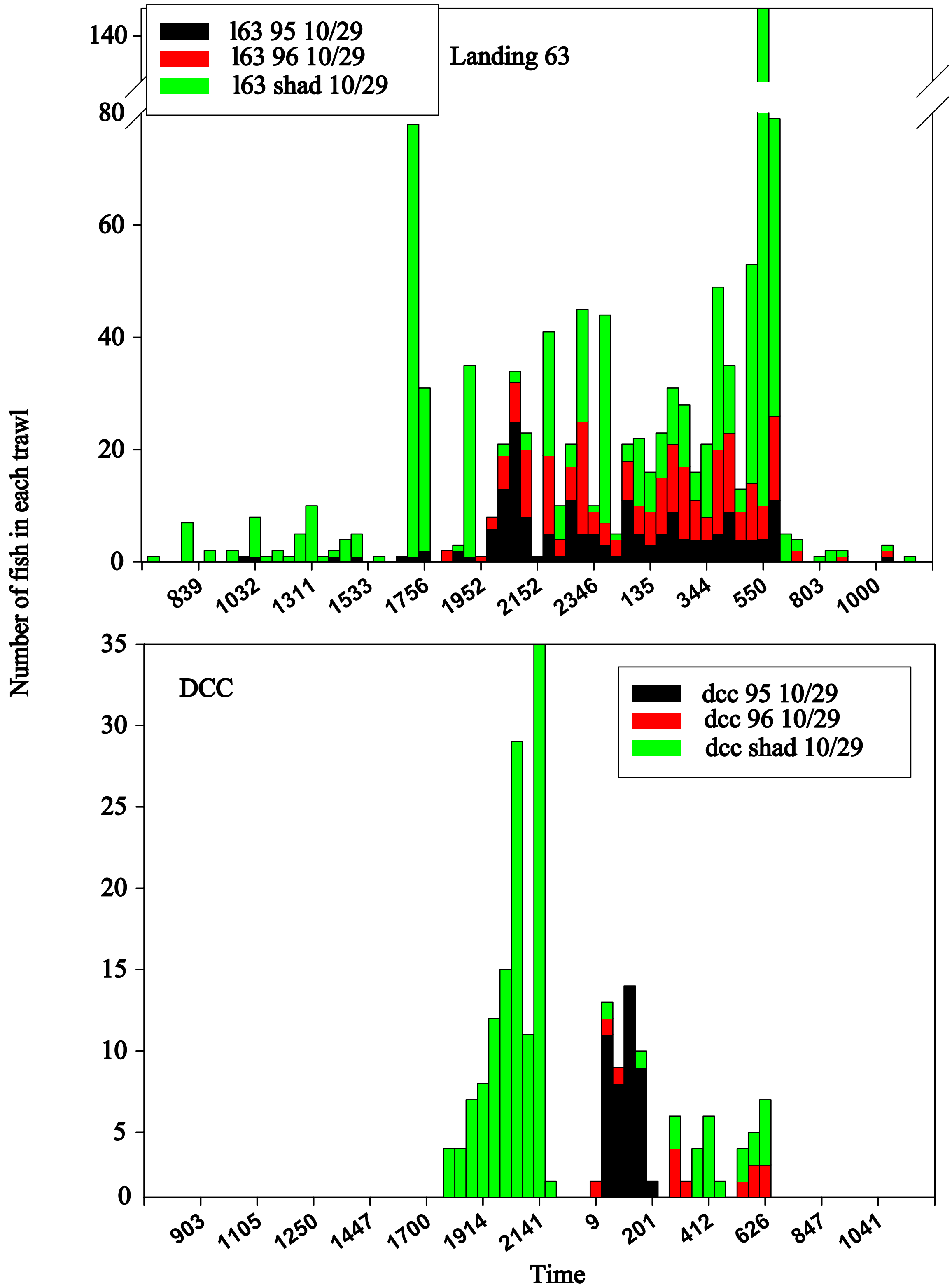


Figure 27. Diel fish passage past Landing 63 on November 1, 2001, as seen from the East bank of the Sacramento River. Vertical black bars denote approximate times for drifter arrival.

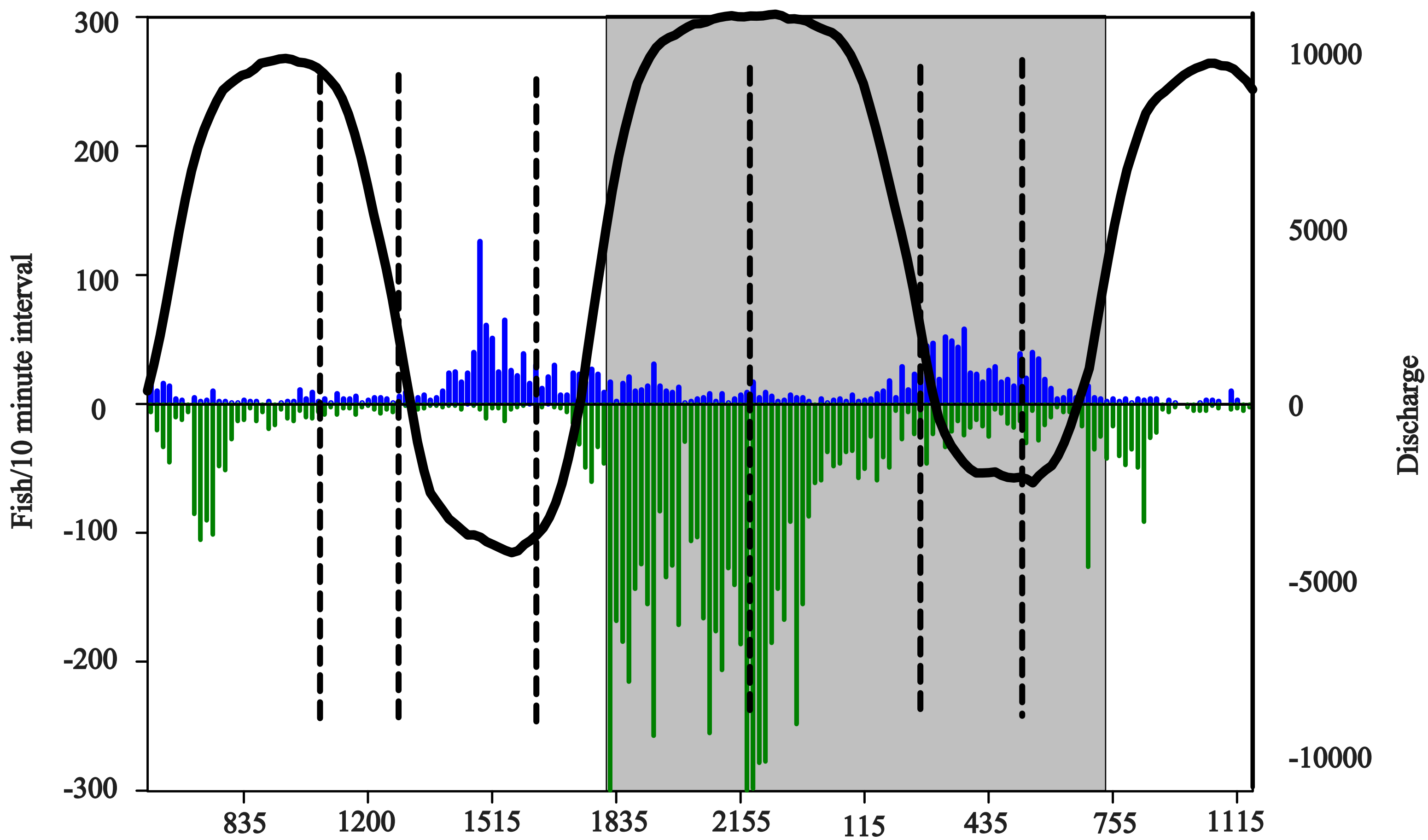


Figure 28. Diel fish passage past Landing 63 on November 1, 2001, as seen from the West bank of the Sacramento River. Vertical black bars denote approximate times for drifter arrival.

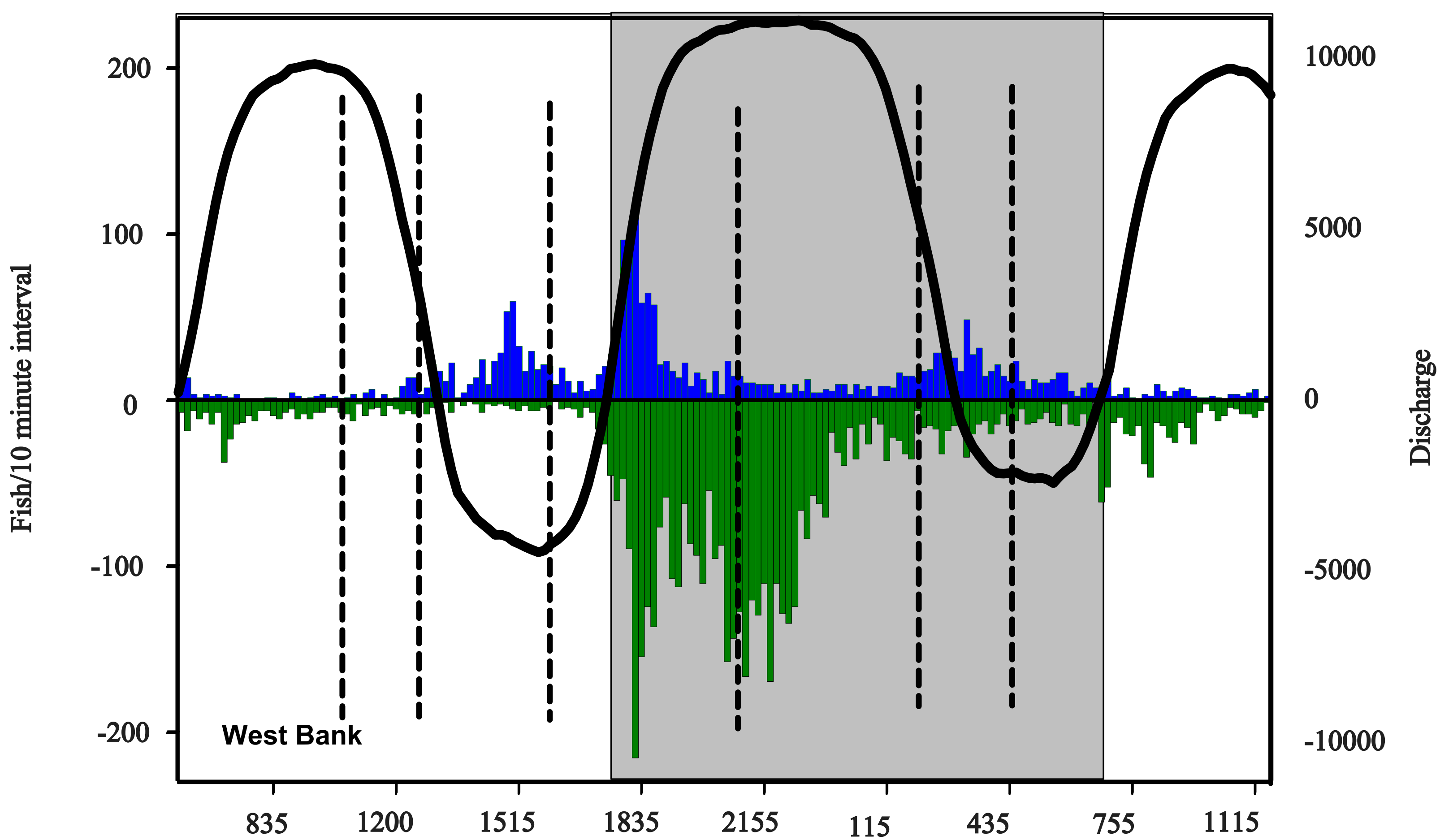


Figure 29. Trawl catches of CWT salmon and shad at Landing 63 and the DCC on November 1, 2001.

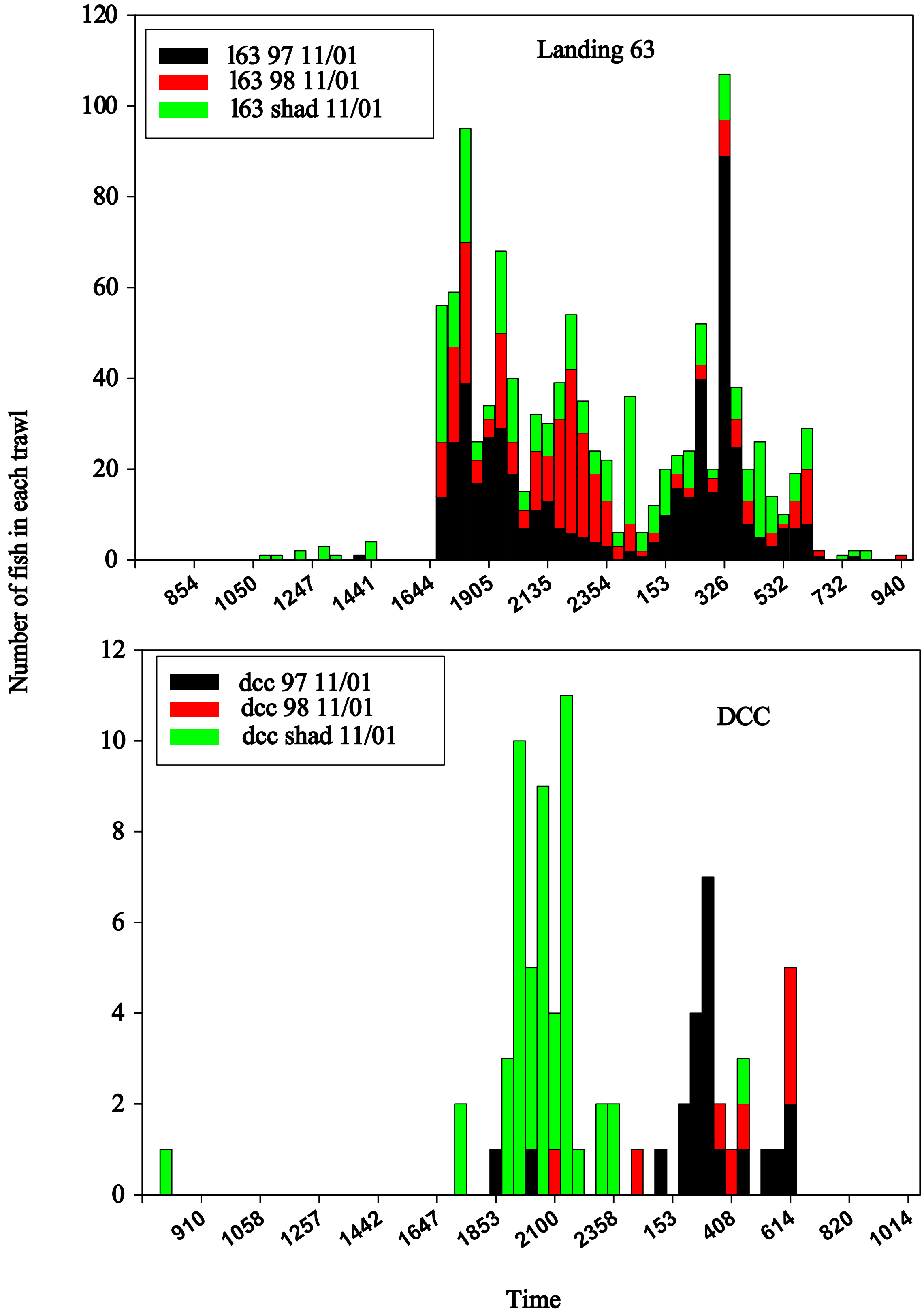


Figure 30. Sacramento River bypassing the DCC (Peak ebb).

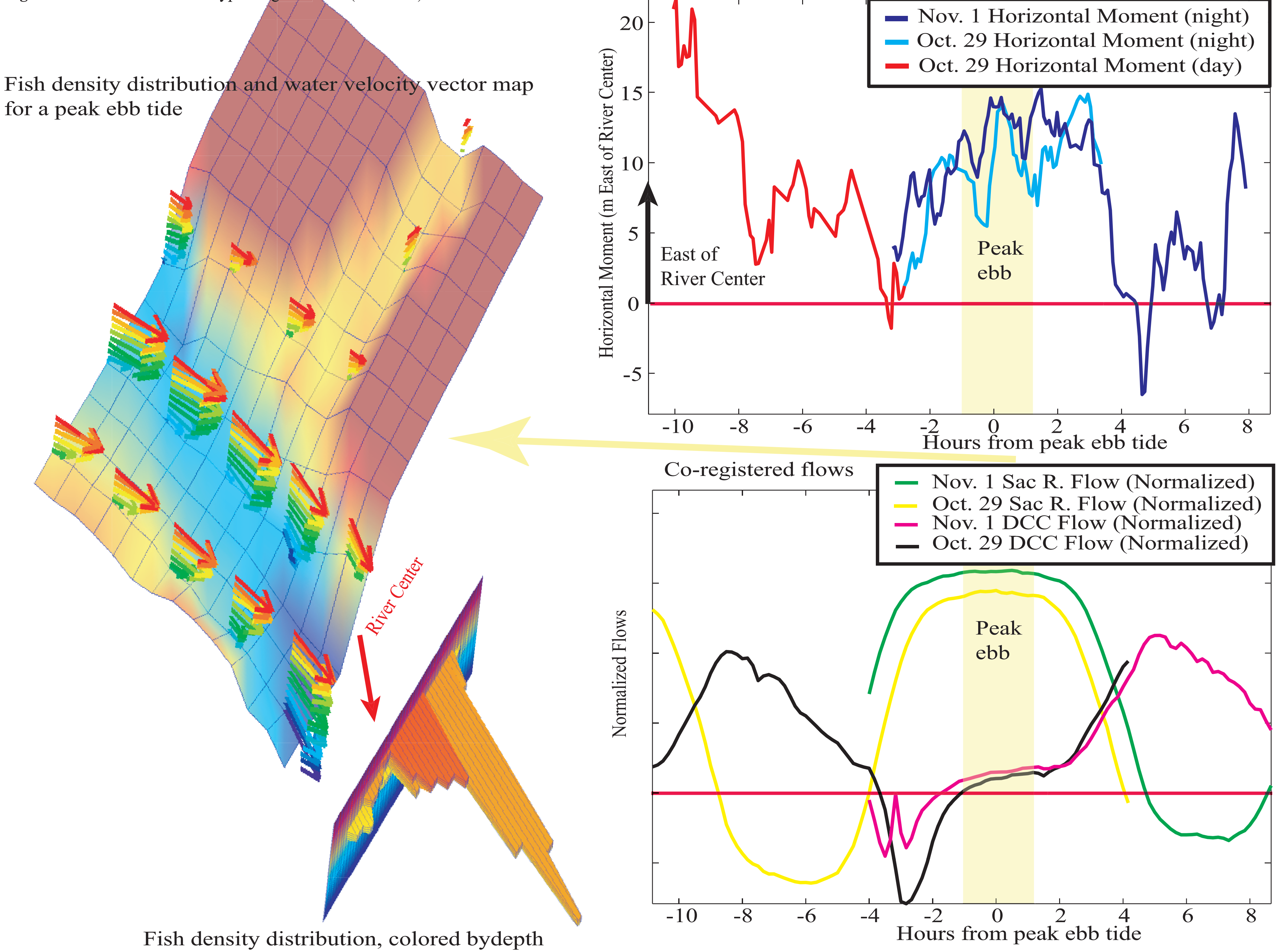


Figure 31. Fish passage through the DCC on October 29, 2001.
Vertical black bars denote approximate times for drifter arrival.

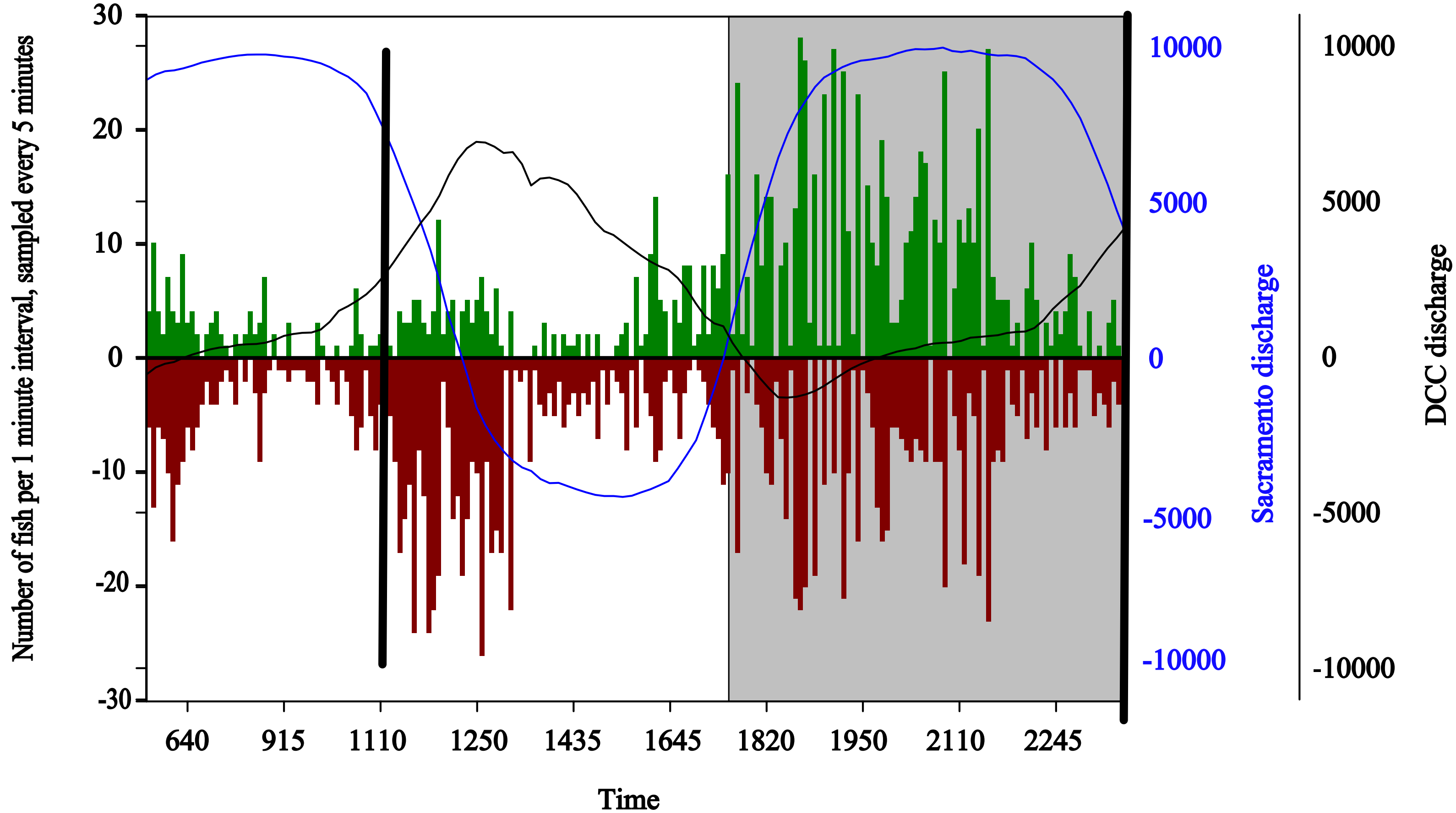


Figure 32. Fish moving towards and into the DCC on a strong flood tide, October 29, 2001.

Map of water velocity vectors (blue) and fish velocity vectors (red)
Fish vectors are shown at an increased scale for emphasis

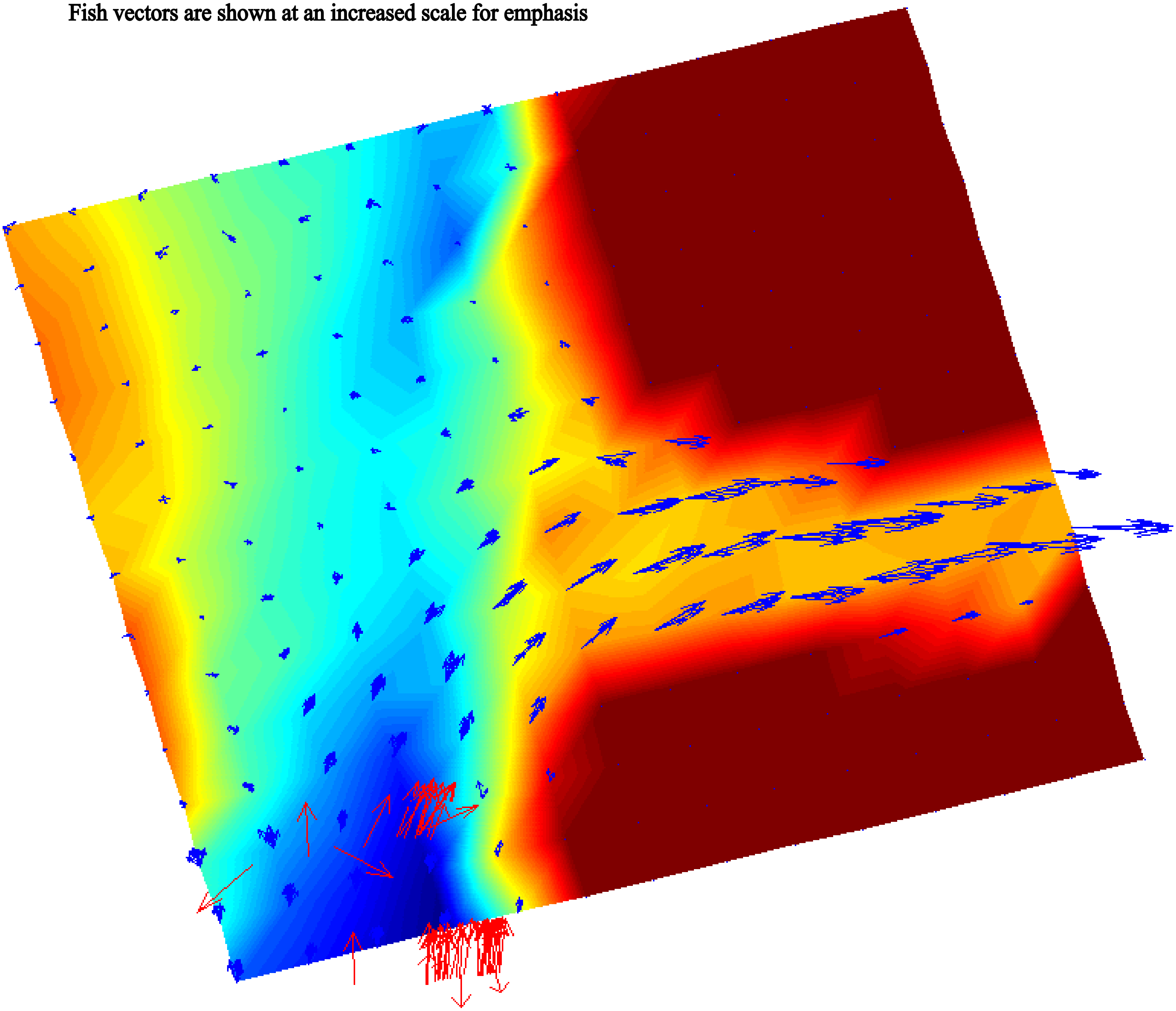


Figure 33. Spatial distribution of targets observed in the DCC during the day and night.

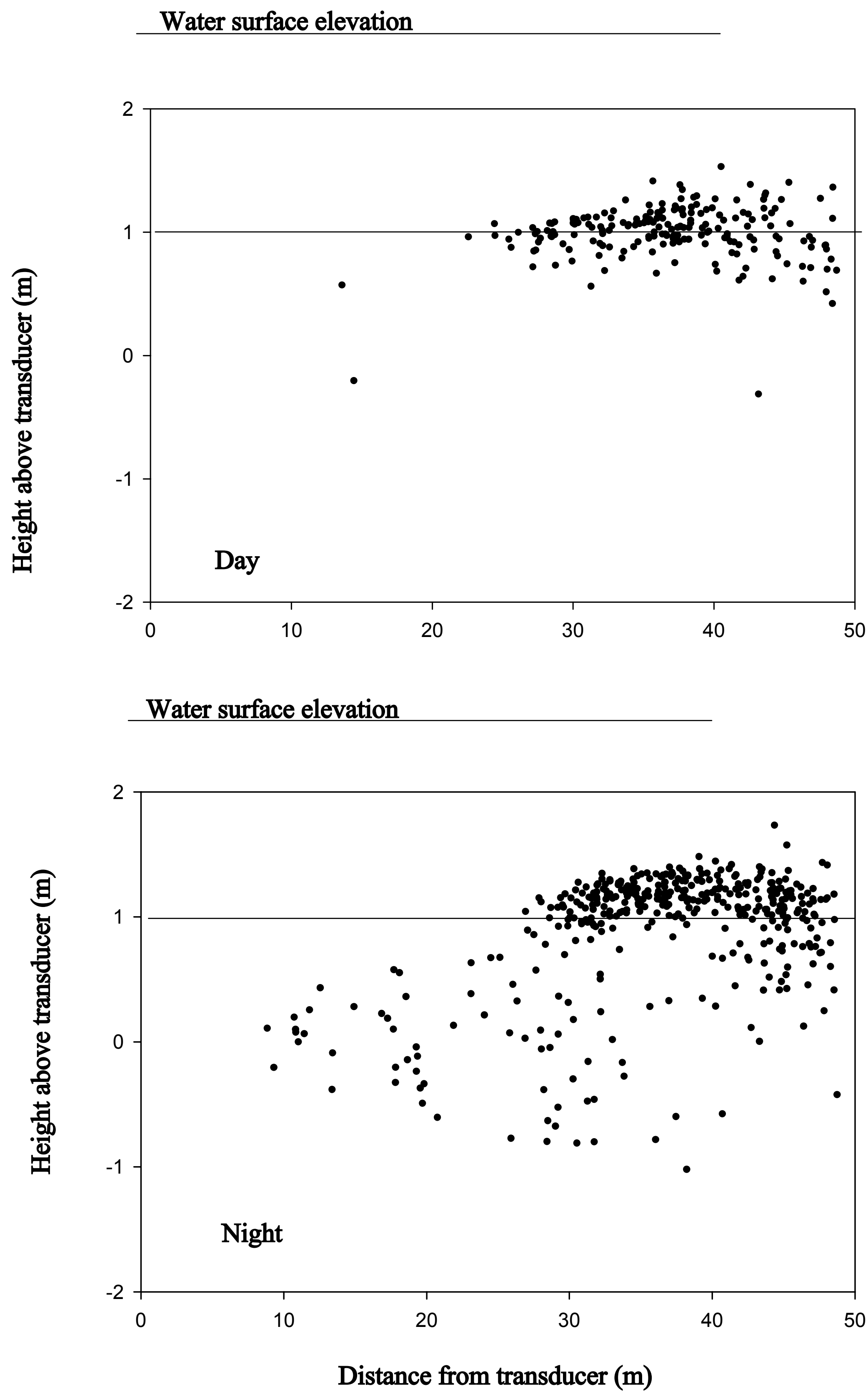


Figure 34. Biosonics Visual Acquisition Software screen showing milling behavior of fishes.

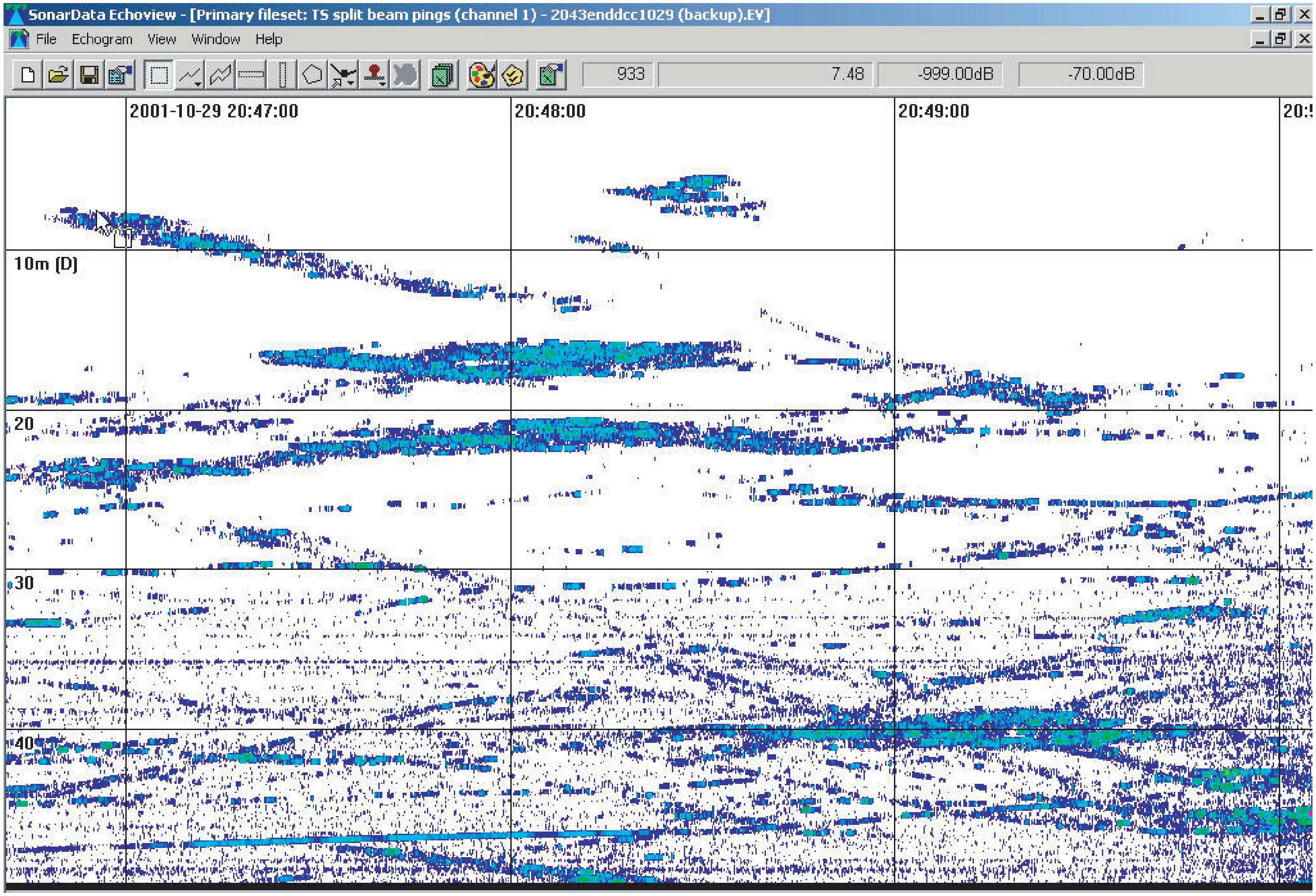


Figure 35. Diel fish passage through the DCC on November 1, 2001.
Vertical black bars denote approximate times for drifter arrival.

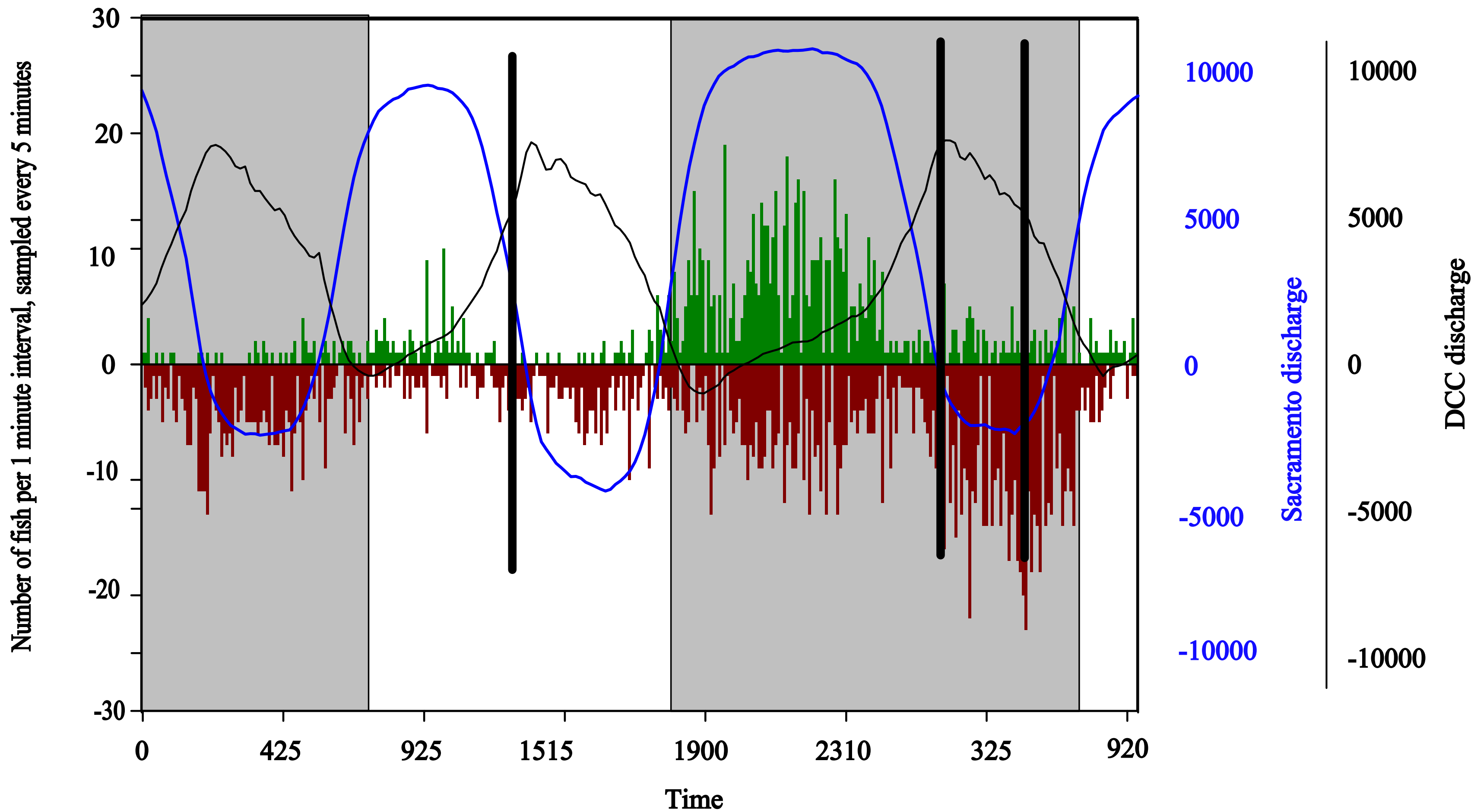


Figure 36. Diel fish passage through Georgiana Slough on October, 29, 2001
Vertical black bars denote approximate times for drifter arrival.

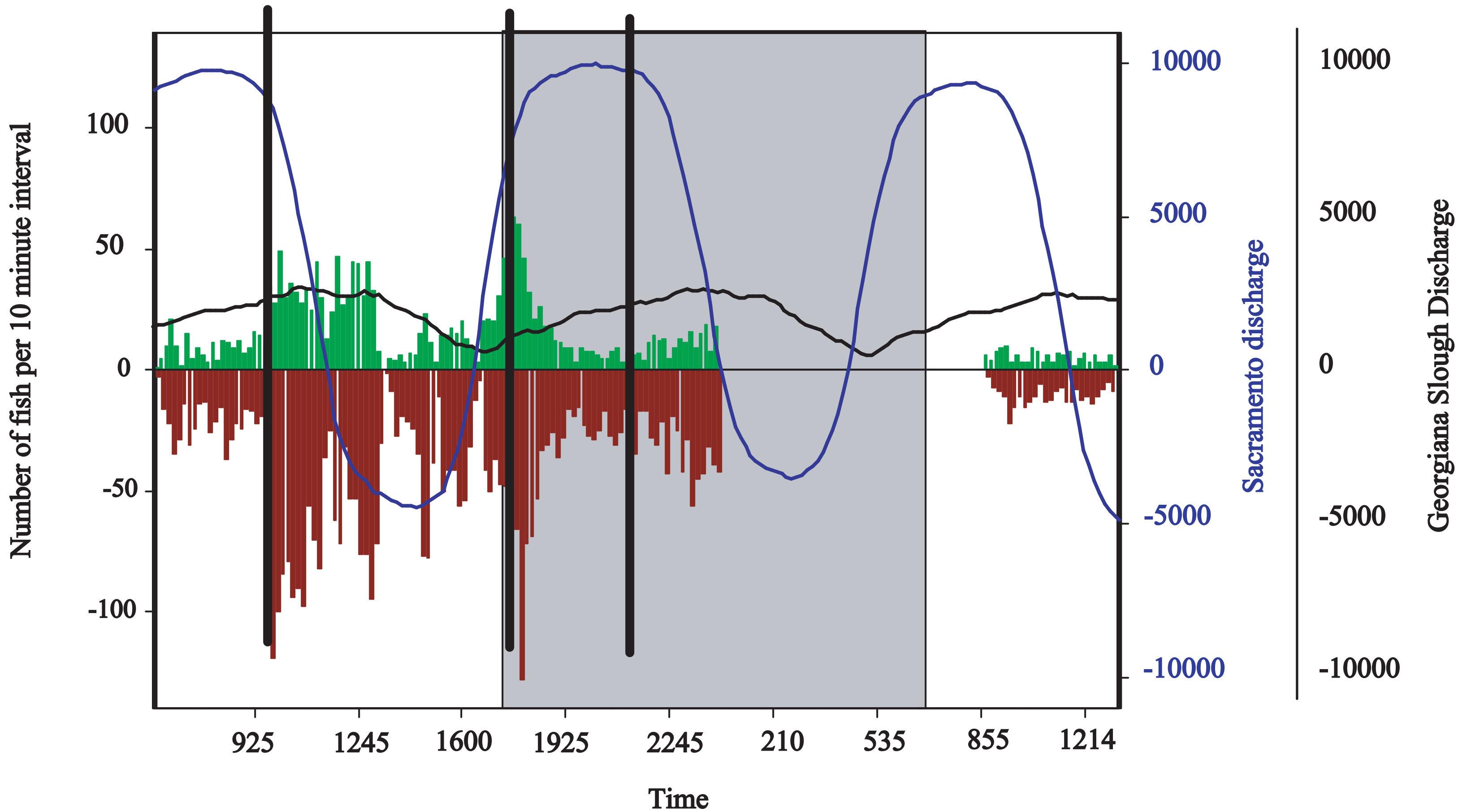


Figure 37. Spatial distribution of targets for release one passing through Georgiana Slough, October 29, 2001.

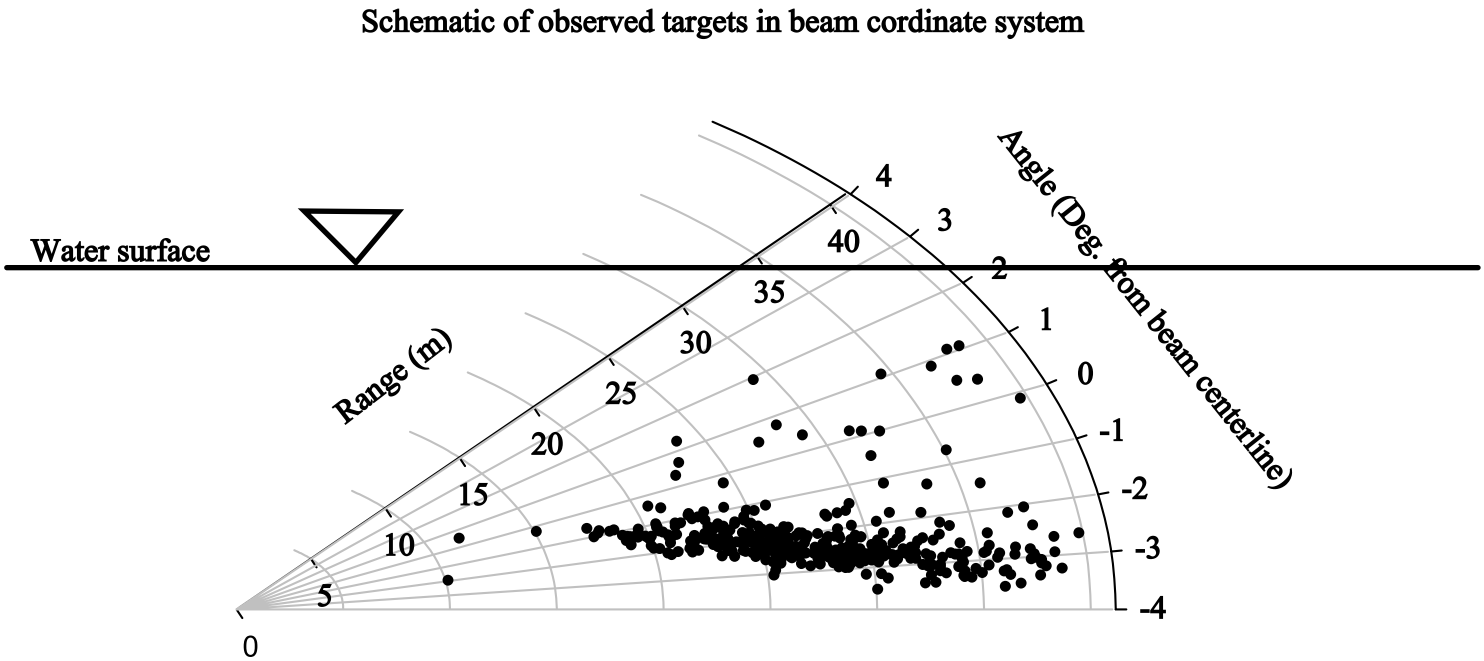


Figure 38. Diel fish passage through Georgiana Slough on November 1,2001.
Vertical black bars denote approximate times for drifter arrival.

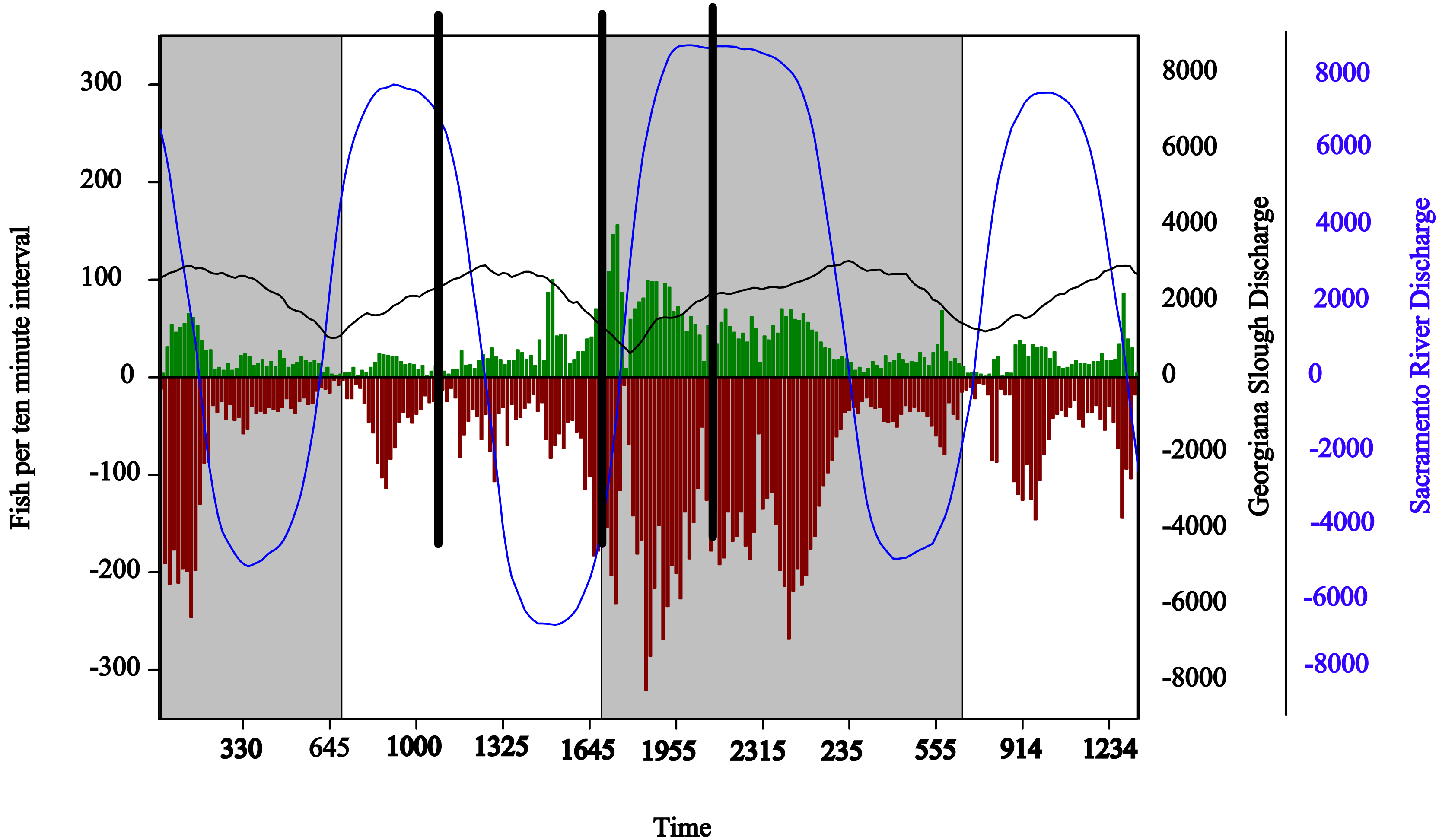


Figure 39. Time periods from the October 29, 2001 data set used for juvenile distribution analysis.

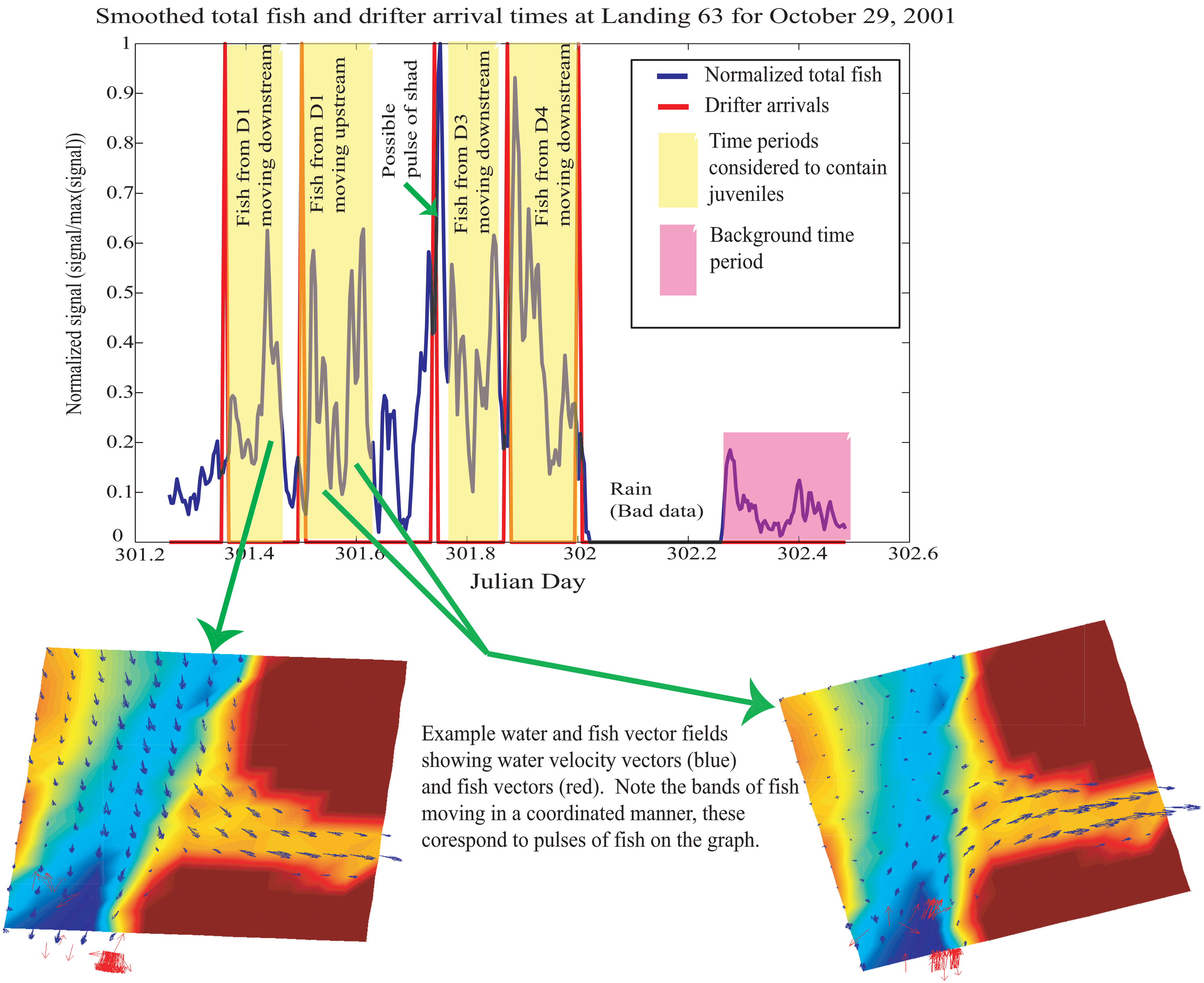


Figure 40. Time periods from the November 1, 2001 data set used for juvenile distribution analysis.

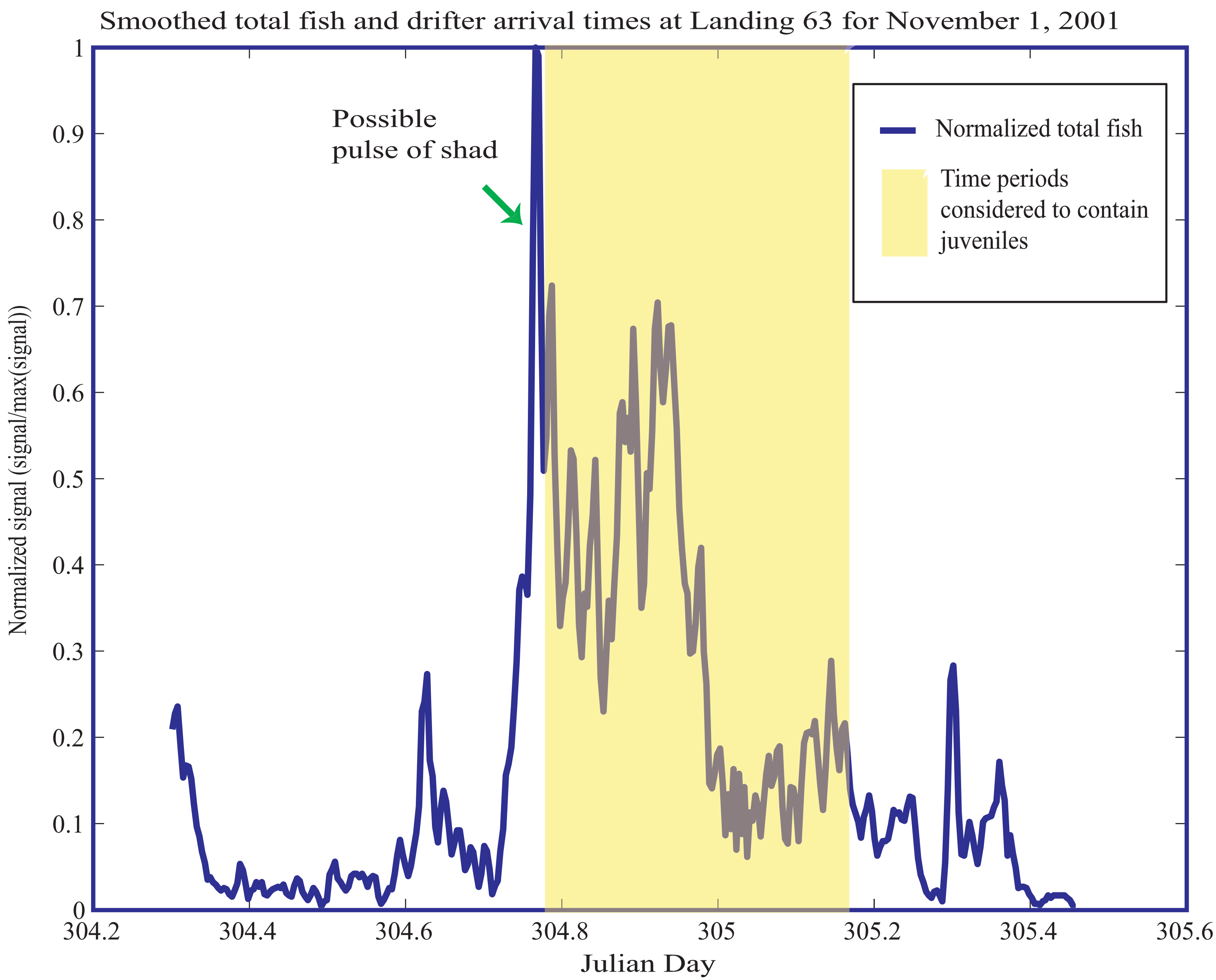
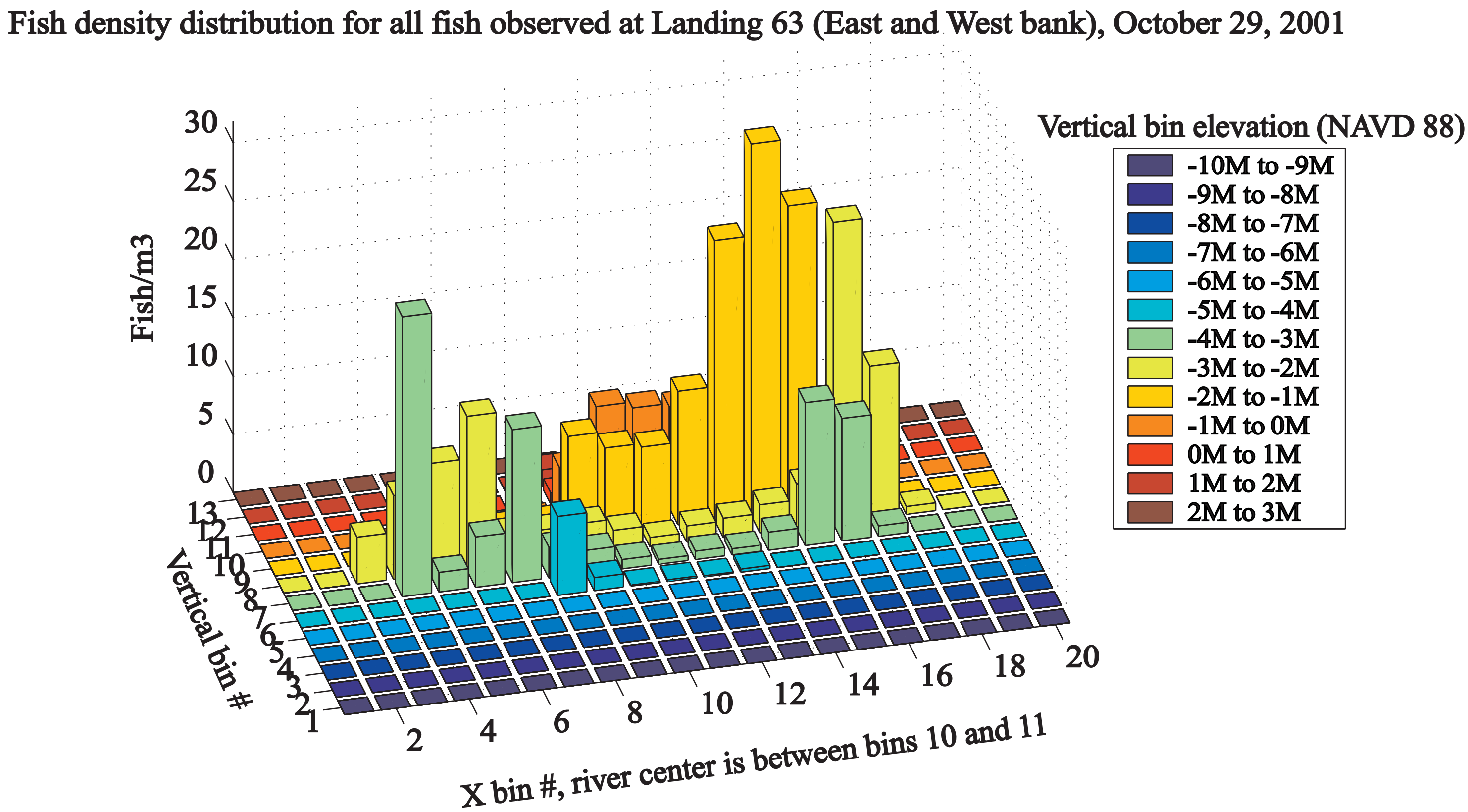


Figure 41. Overall fish density distributions for the October 29th and the November 1st studies.



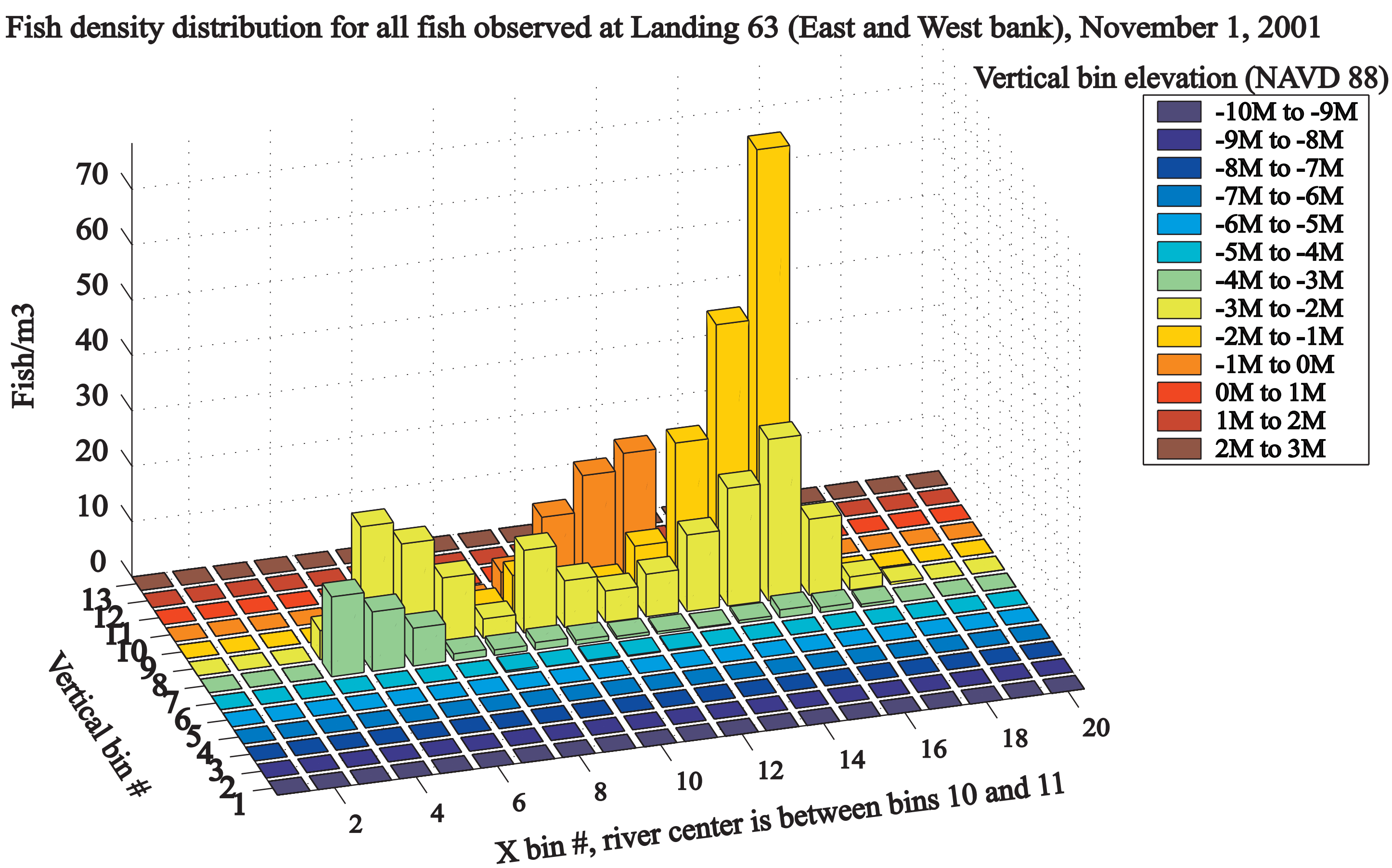


Figure 42. Qualitative comparison of juvenile time period fish density distributions and background fish density distribution.
Note the difference in shape between the background distribution and the two juvenile distributions.

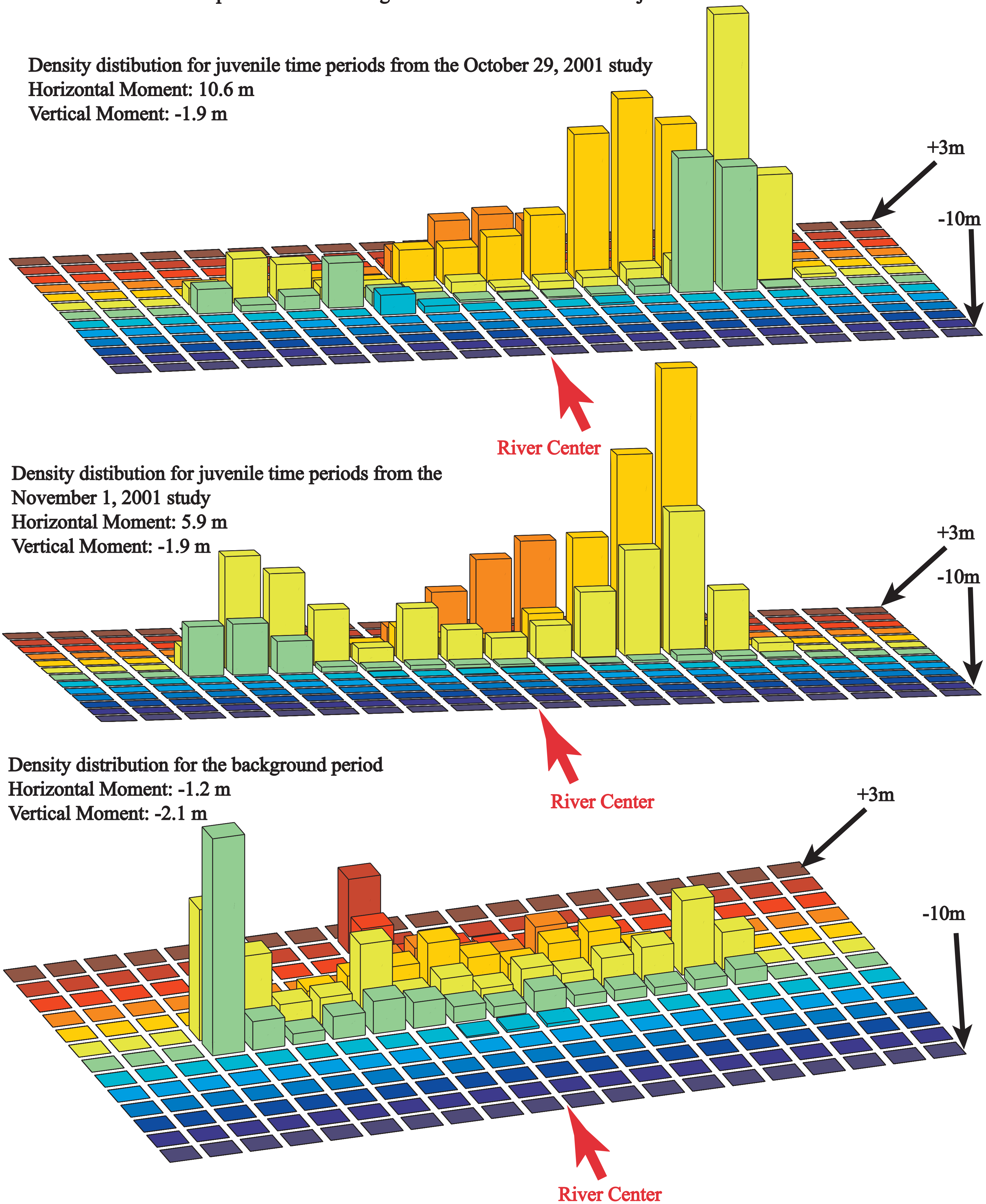


Figure 43. Combined horizontal moment signal.

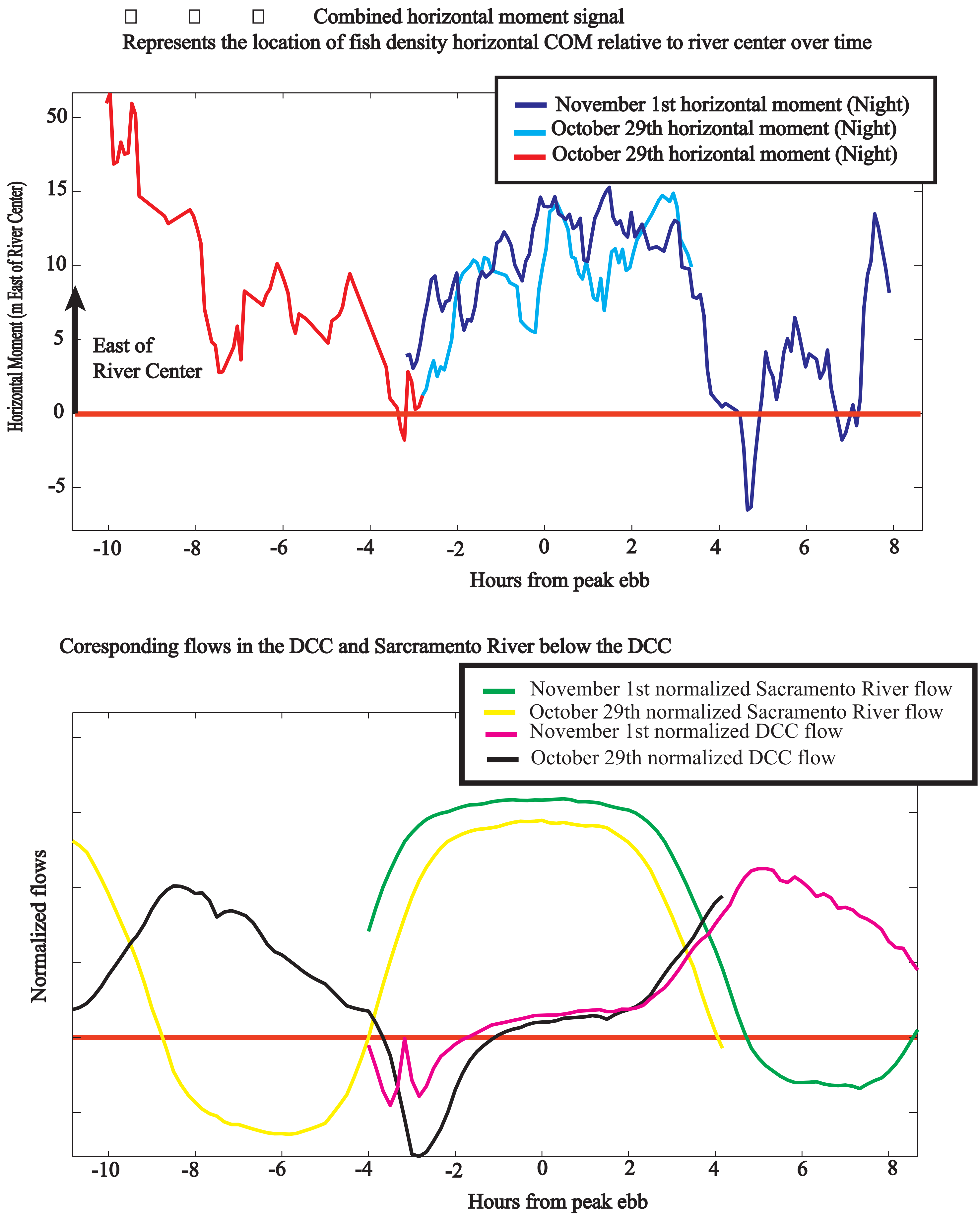


Figure 44. Milling fish in the slack water below the DCC, November 1st, 2001.

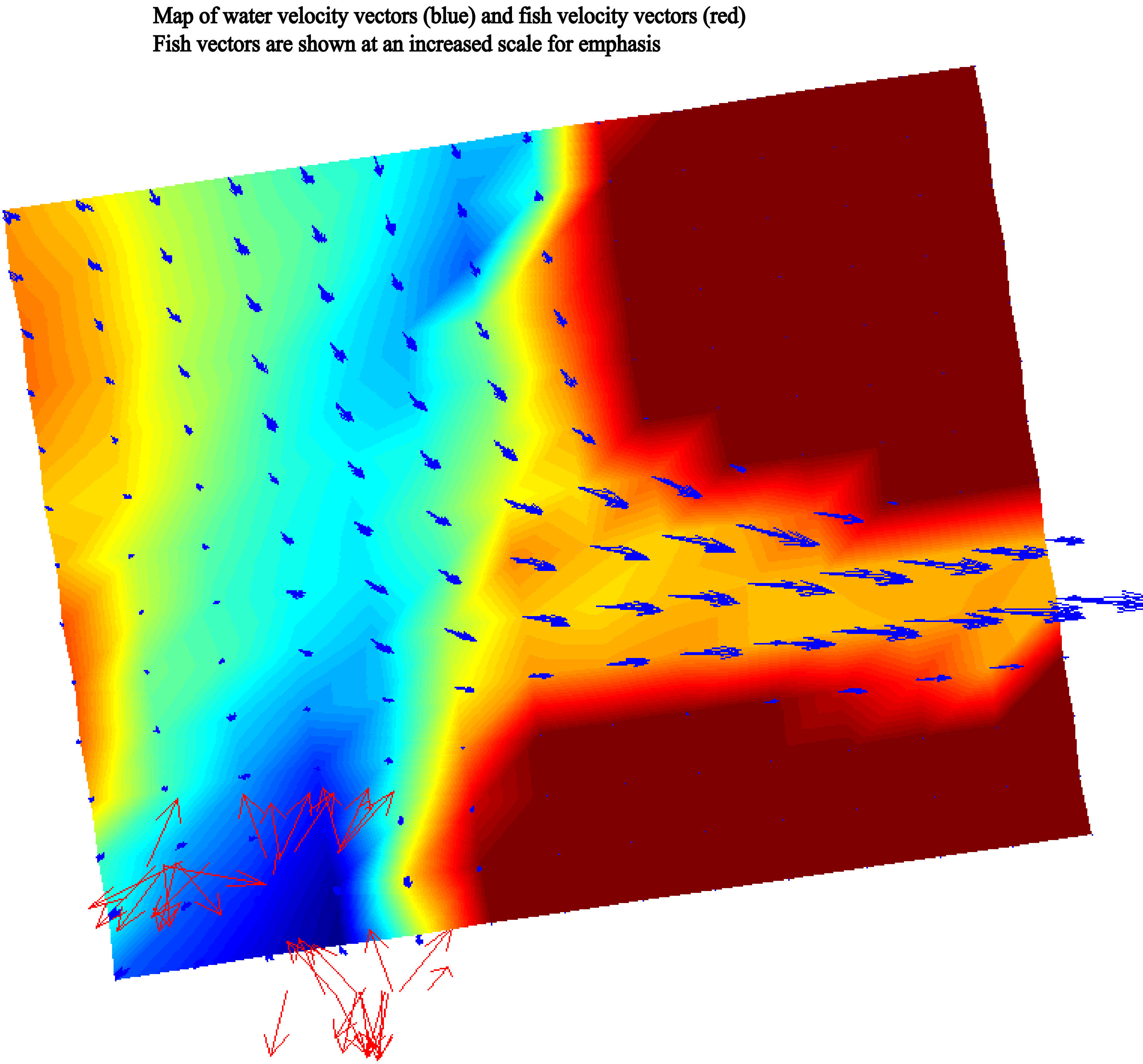


Figure 45. Large pulse of fish moving along the East bank of the Sacramento River below the DCC on an ebb tide, October 29, 2001.

Map of water velocity vectors (blue) and fish velocity vectors (red)
Fish vectors are shown at an increased scale for emphasis

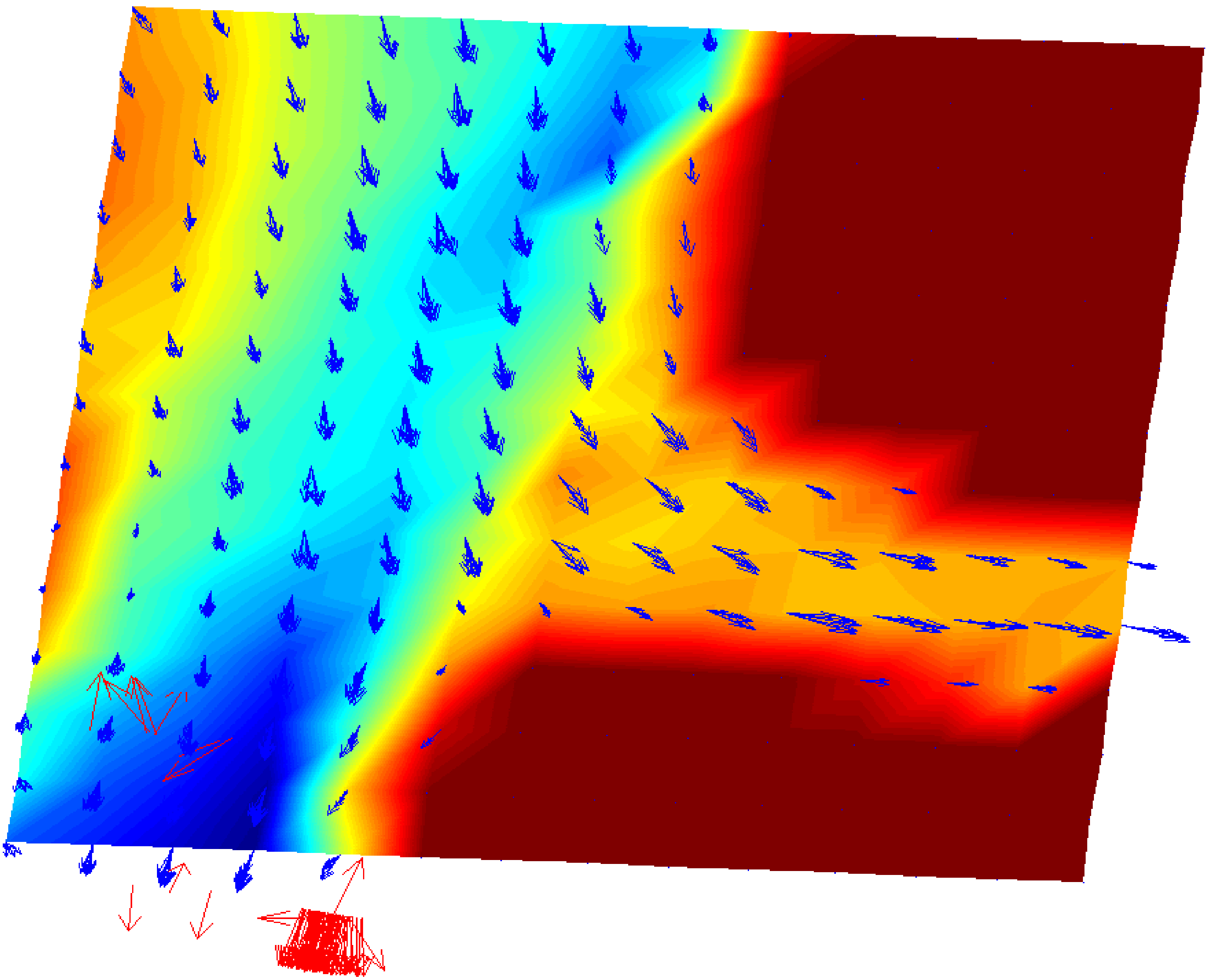
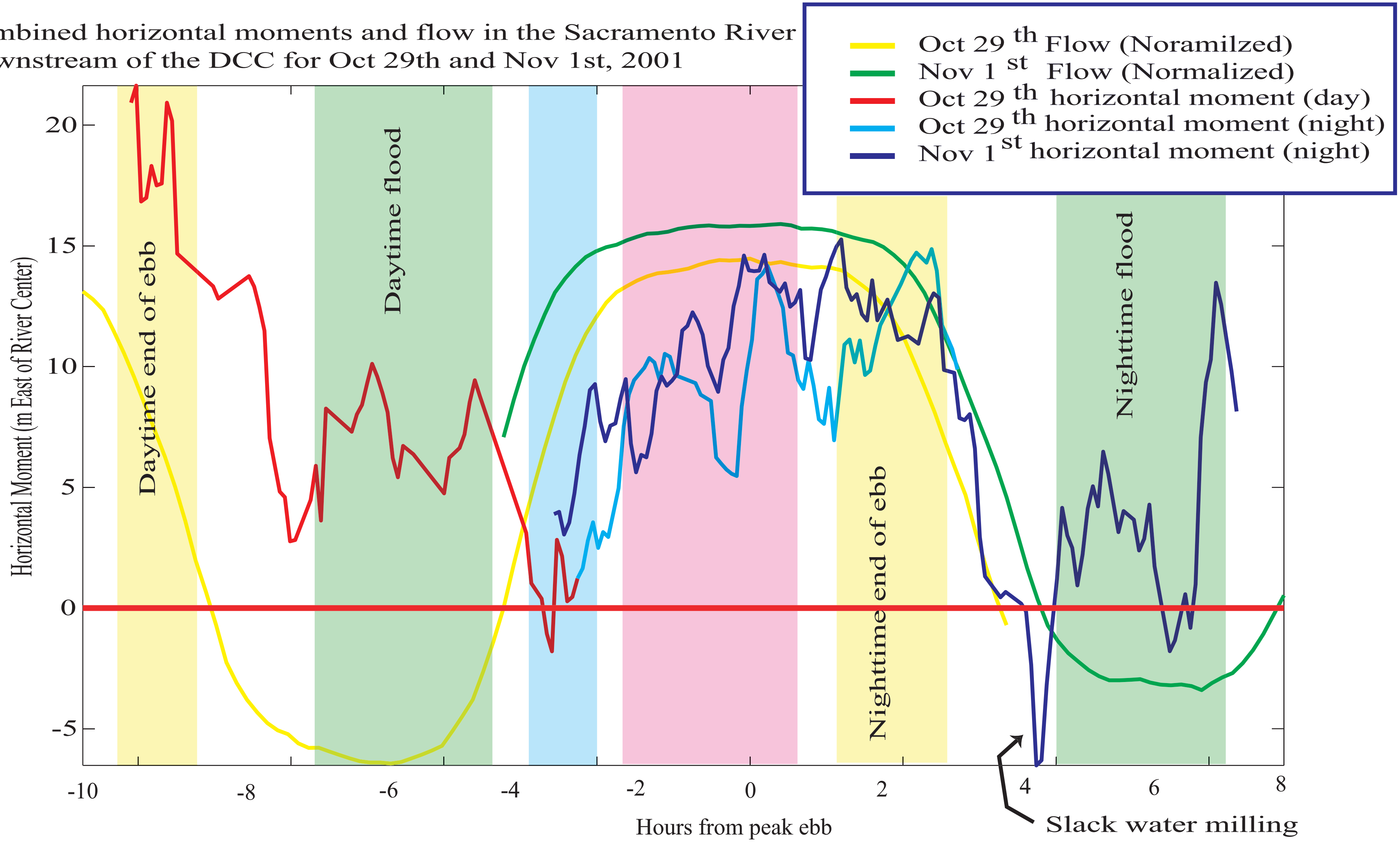


Figure 46. Features in the horizontal moments signal that correspond to the tidal phase in the Sacramento River.



Increase in horizontal moment at the end of a Sacramento River ebb tide (Most positive during daytime)

Horizontal moment slightly east of river center on a full flood tide

Horizontal moment west of river center (negative) as DCC empties into the Sacramento River at the flood-ebb transition

Horizontal moment increases throughout the Sacramento River ebb tide

Figure 47. Sacramento River upstream entering the DCC on the end of an ebb tide.

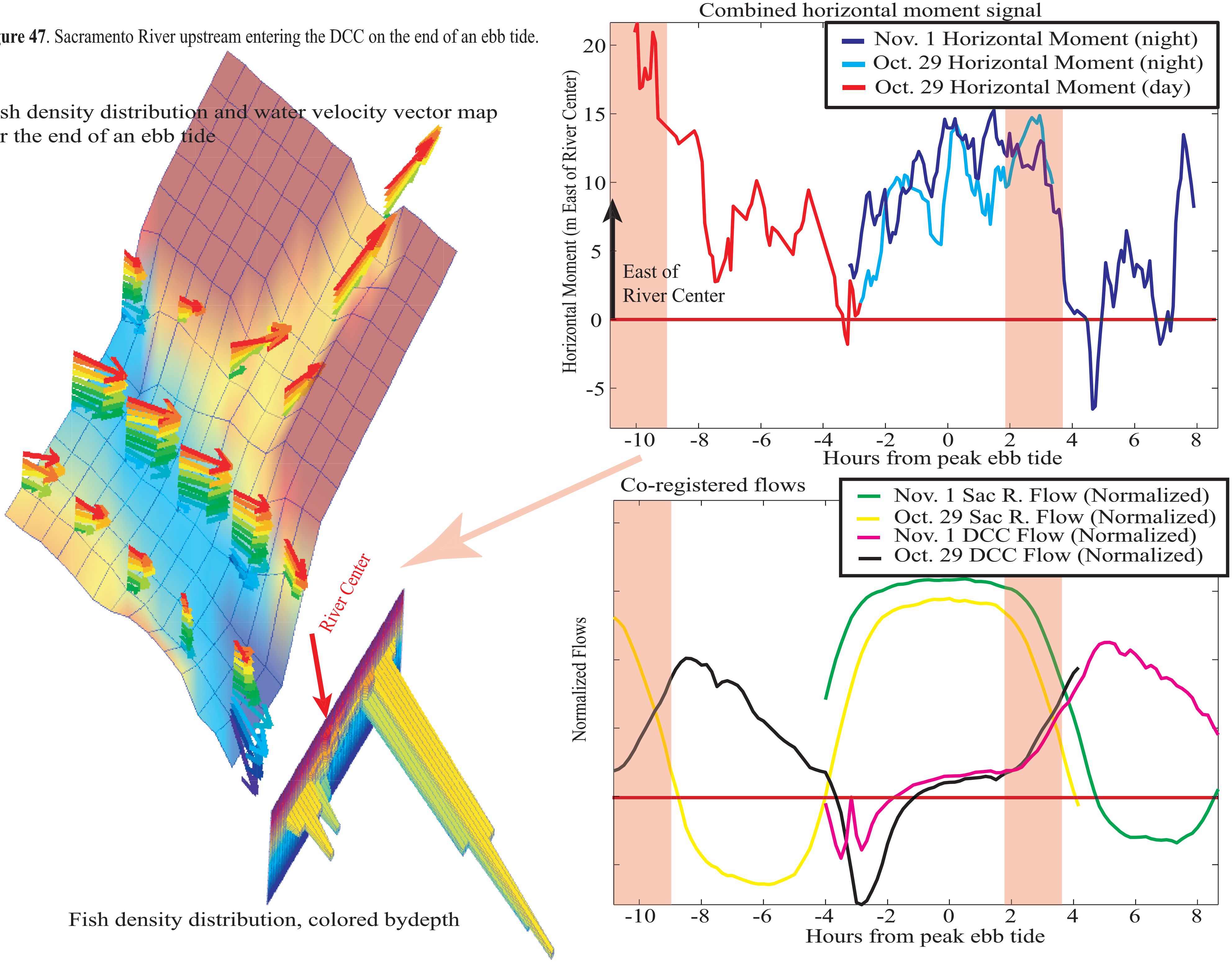


Figure 48. Sacramento river downstream entering the DCC on a flood tide.

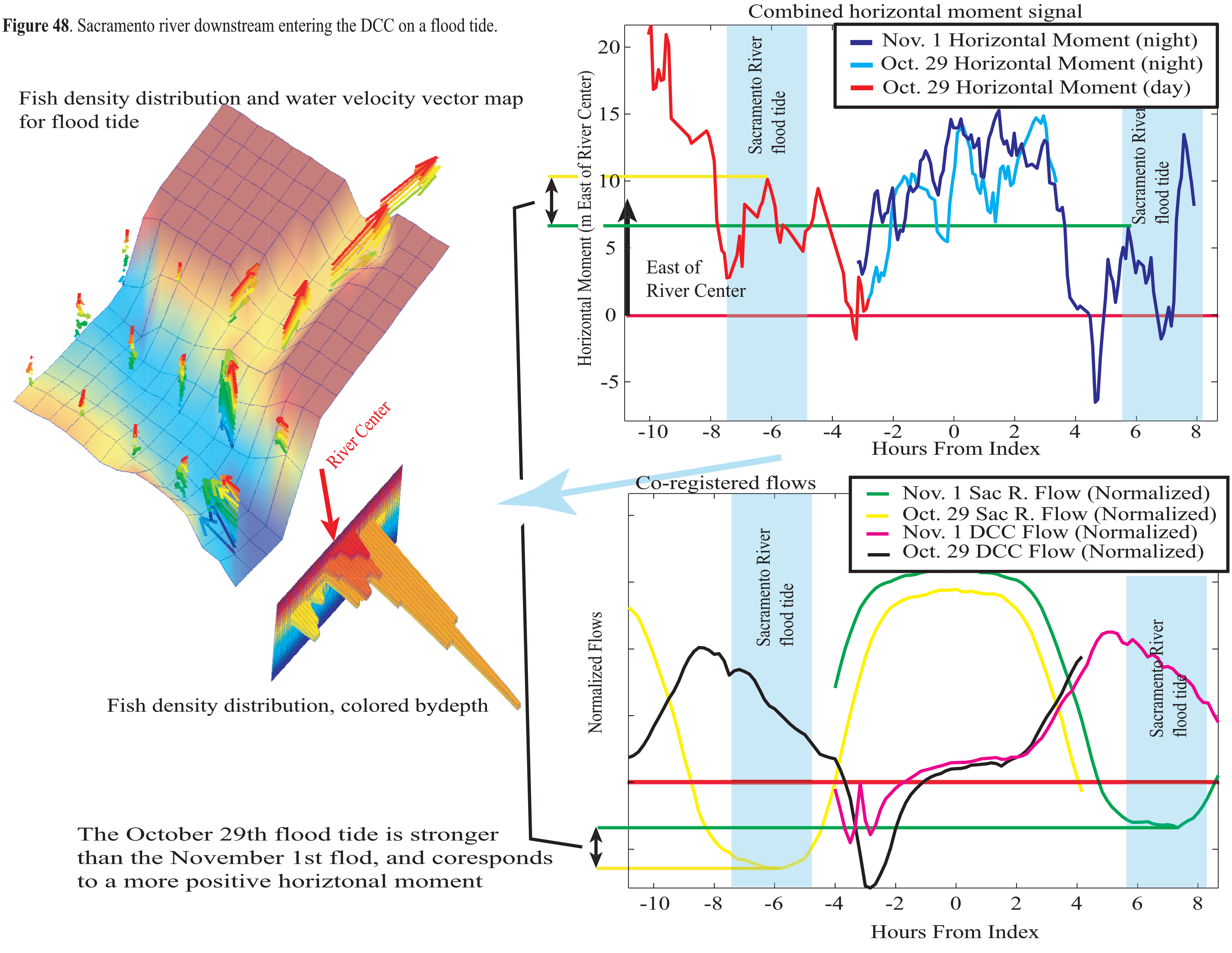


Figure 49. Fish density distribution for beginning of ebb tide flow pattern on November 1, 2001
Horizontal Moment: -4.5m Vertical Moment: -2.0m Number of fish: 2,519

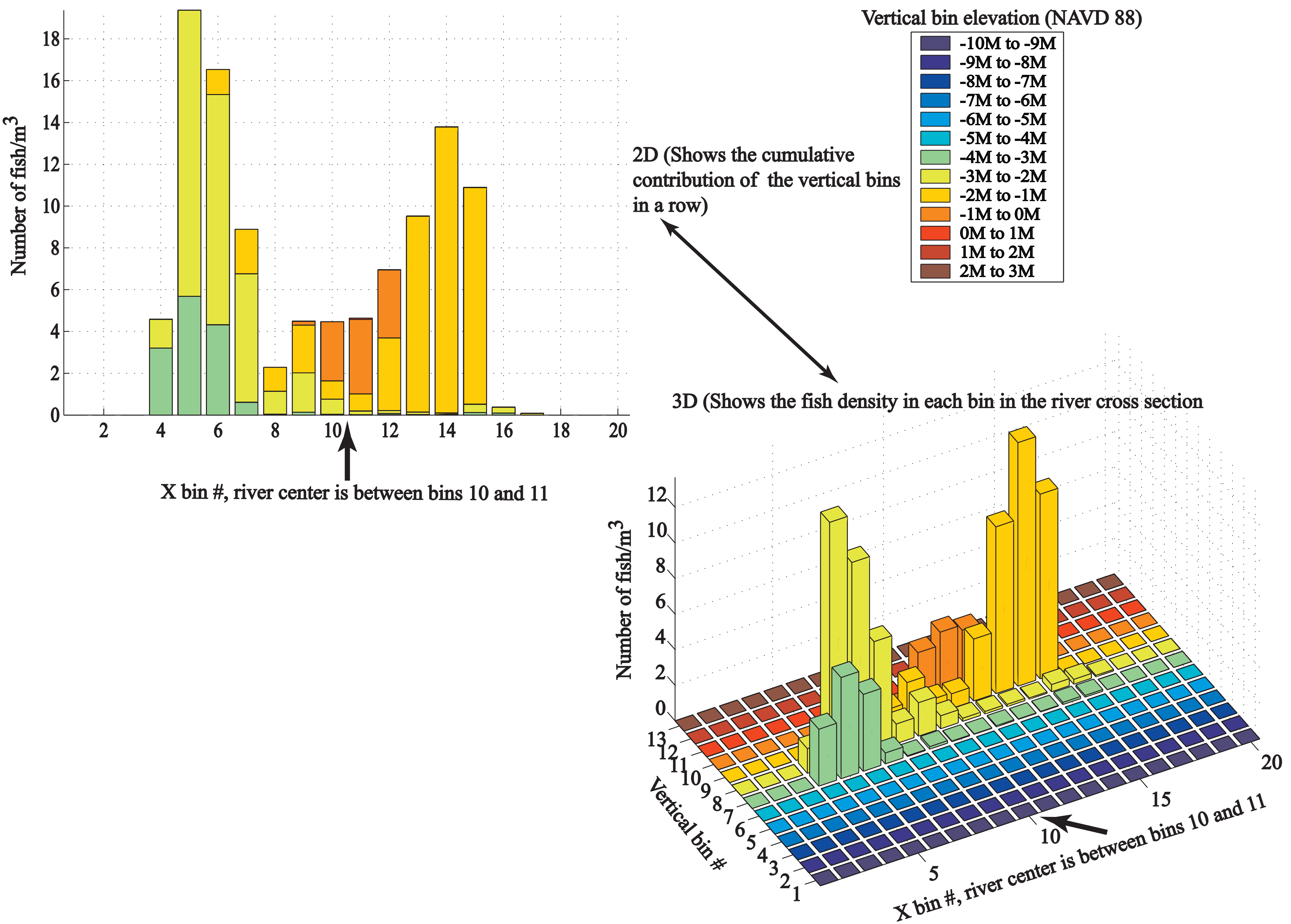


Figure 50. Fish density distribution for beginning of ebb tide flow pattern on October 29th, 2001
Horizontal Moment: +4.4m Vertical Moment: -1.4m Number of fish: 745

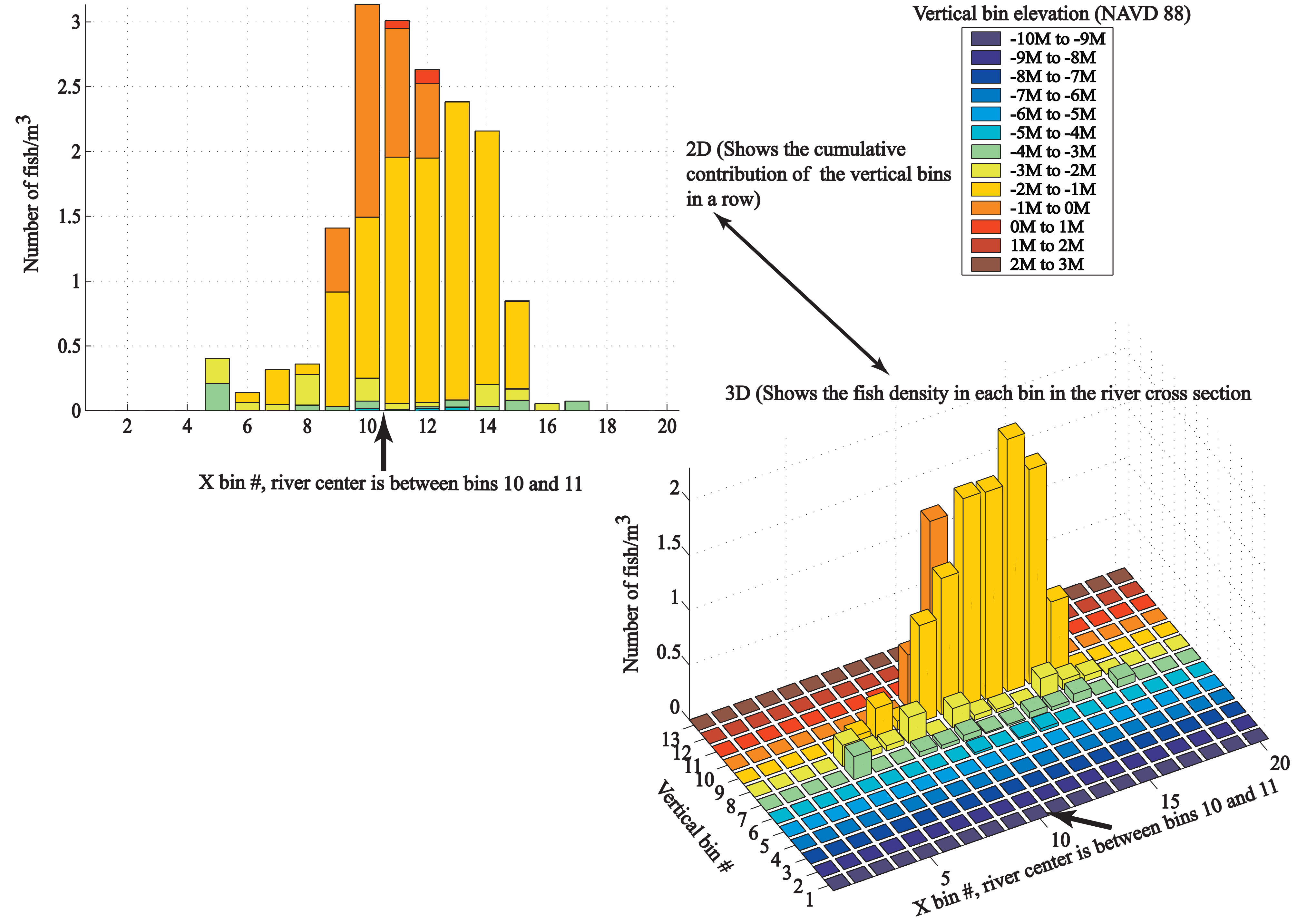


Figure 51. DCC flowing into the Sacramento River on an early ebb tide.

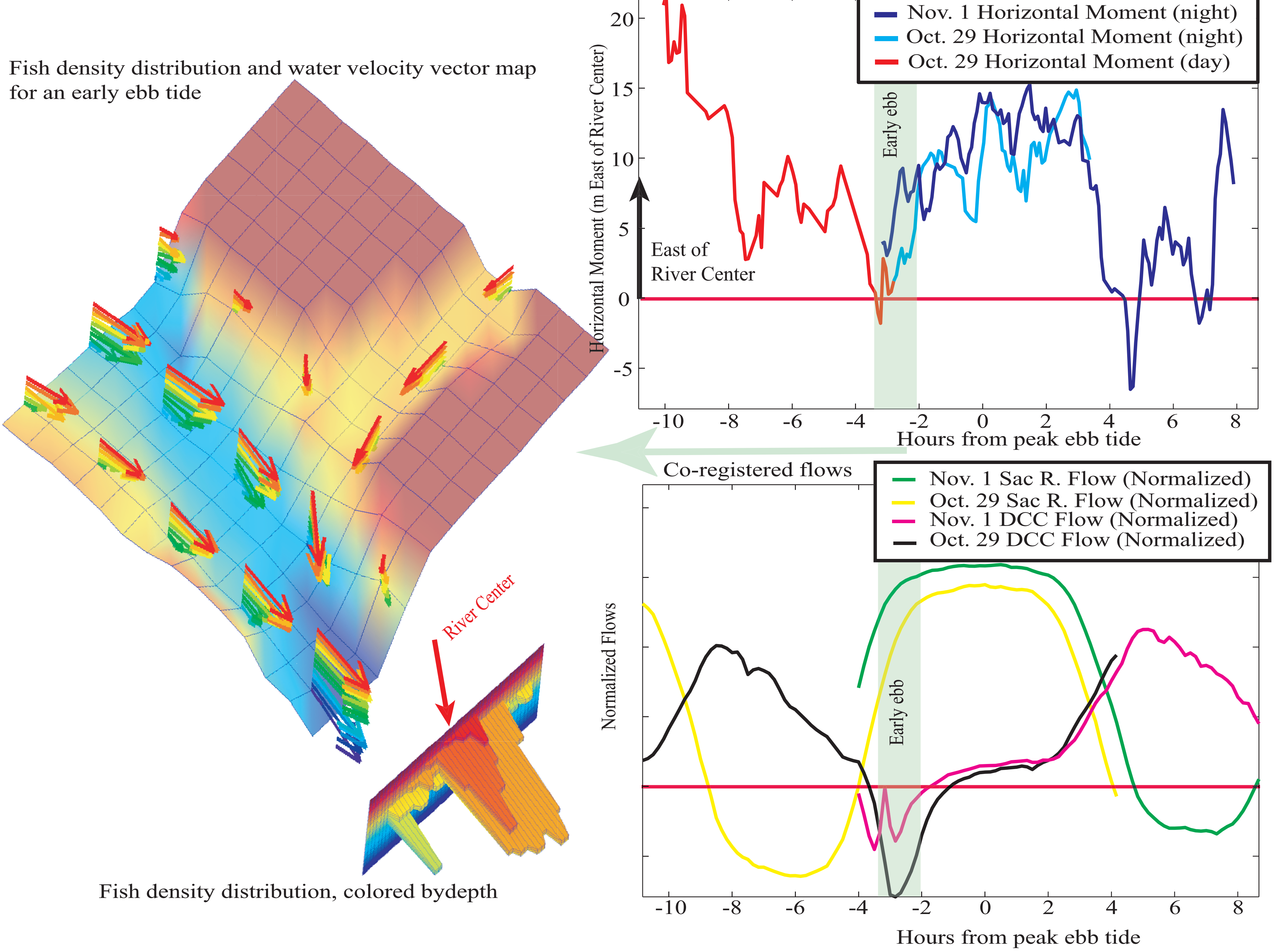


Figure 52. Fish density distribution for full ebb tide flow pattern on October 29th, 2001.
Horizontal Moment: +9.5m, Vertical Moment: -1.5m, Number of fish: 1,431.0, Nighttime

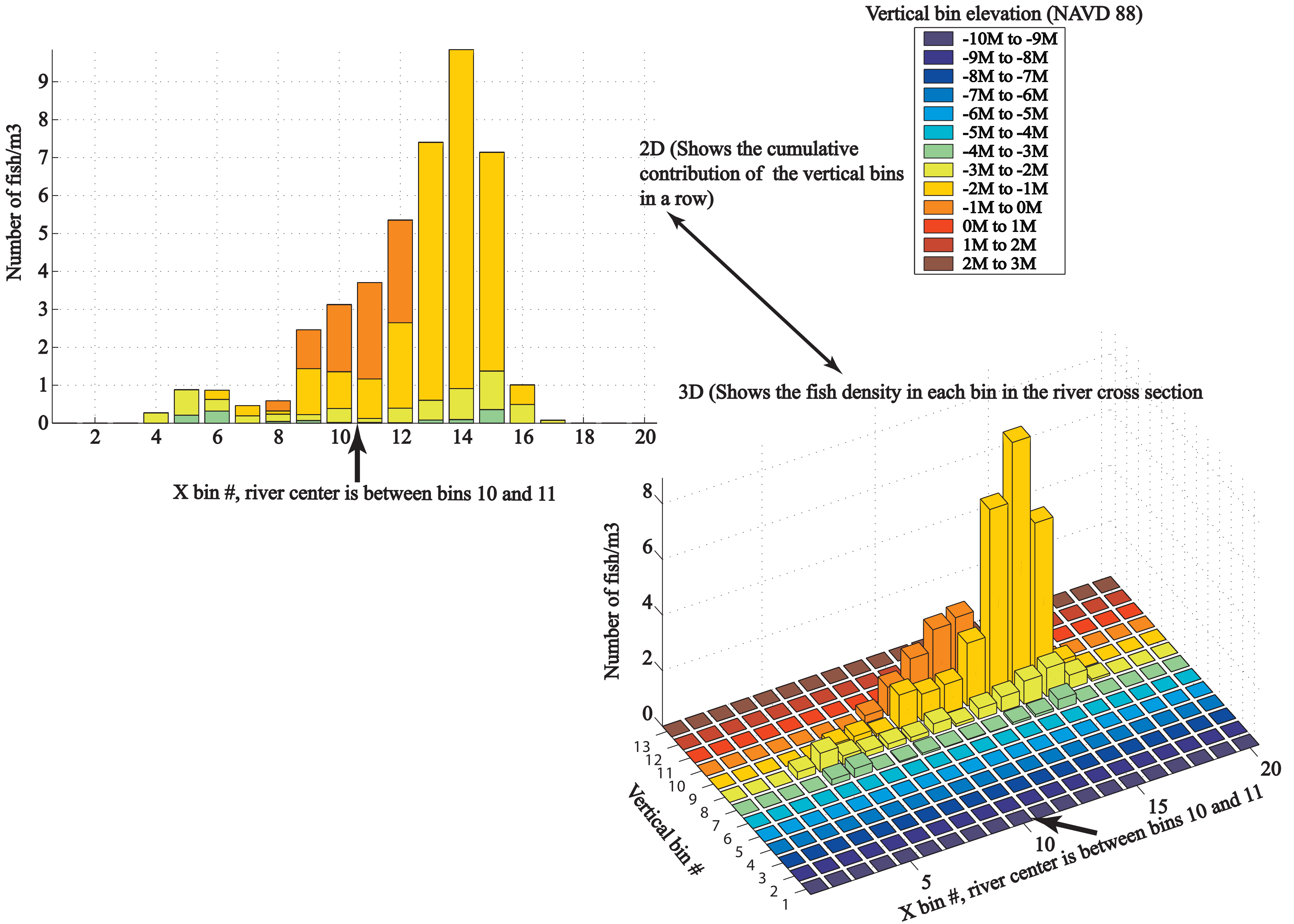


Figure 53. Fish density distribution for full ebb tide flow pattern on November 1st, 2001.
Horizontal Moment: +11.4m, Vertical Moment: -1.7m, Number of fish: 5,140.0, Nighttime

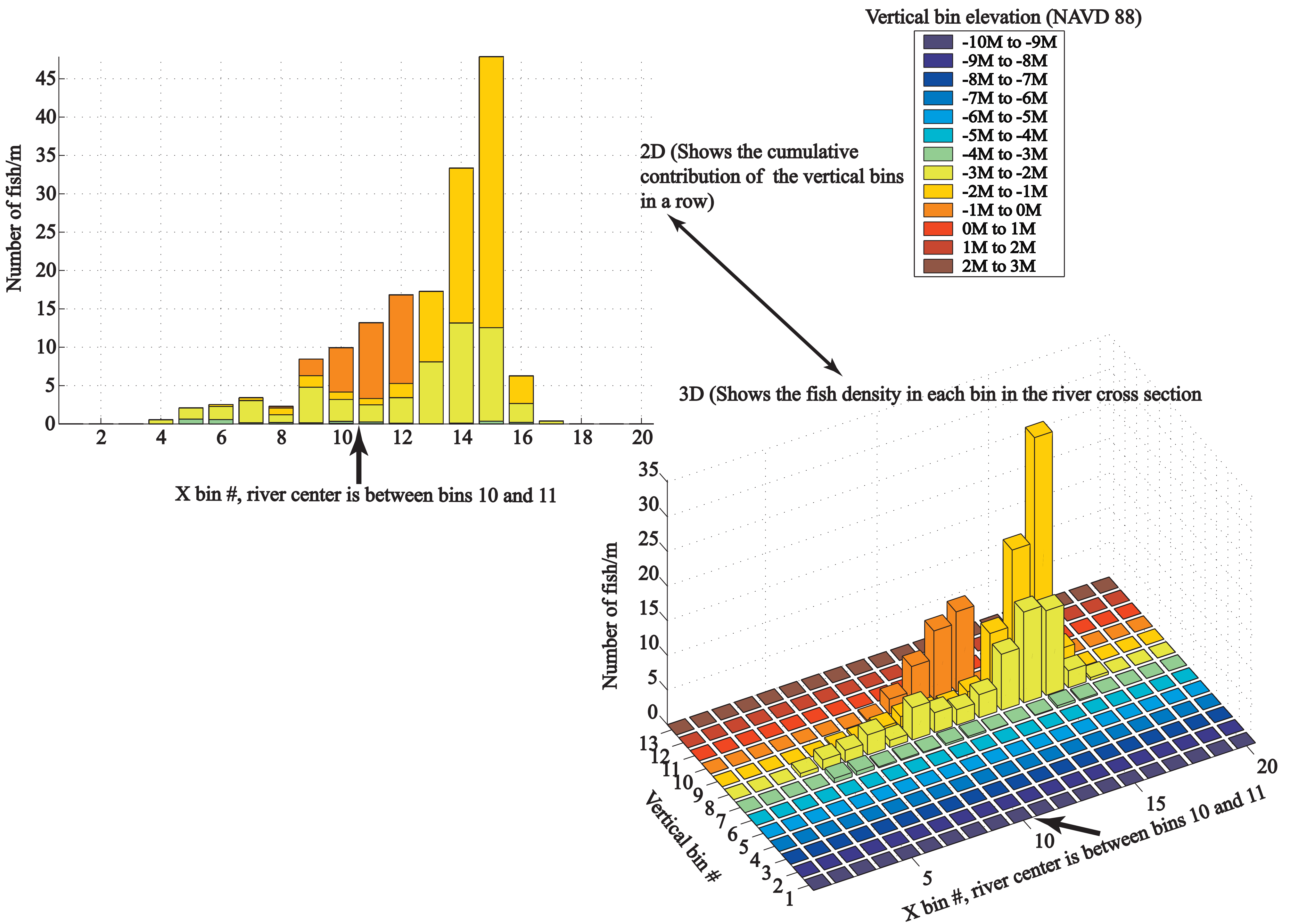


Figure 54. Fish density distribution for daytime juvenile periods on October 29, 2001.
Horizontal Moment: +16.9m Vertical Moment: -2.9m Number of fish: 1,046

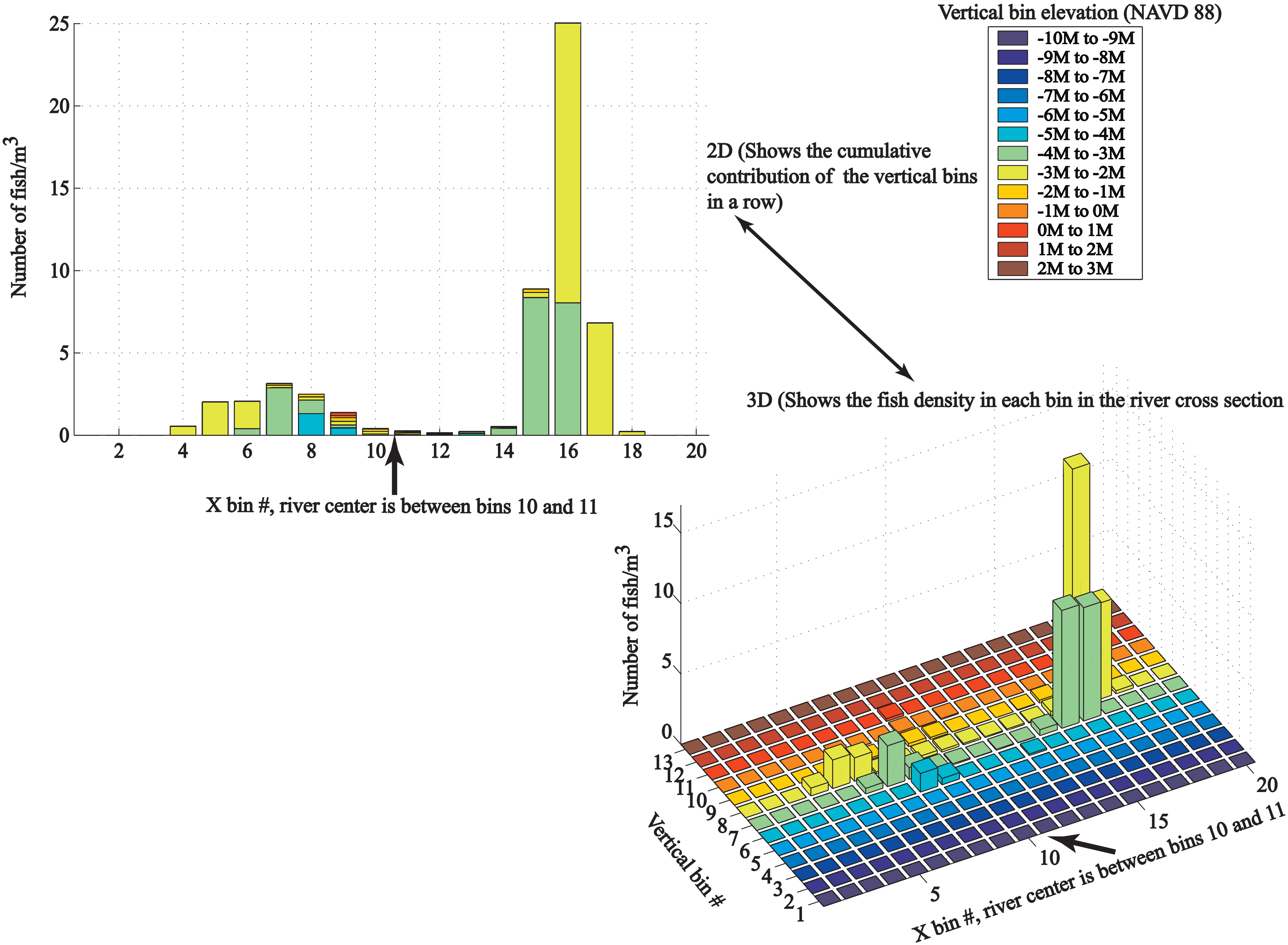


Figure 55. Fish density distribution for nightime juvenile periods on October 29, 2001.
Horizontal Moment: +7.8m Vertical Moment: -1.5m Number of fish: 2,340

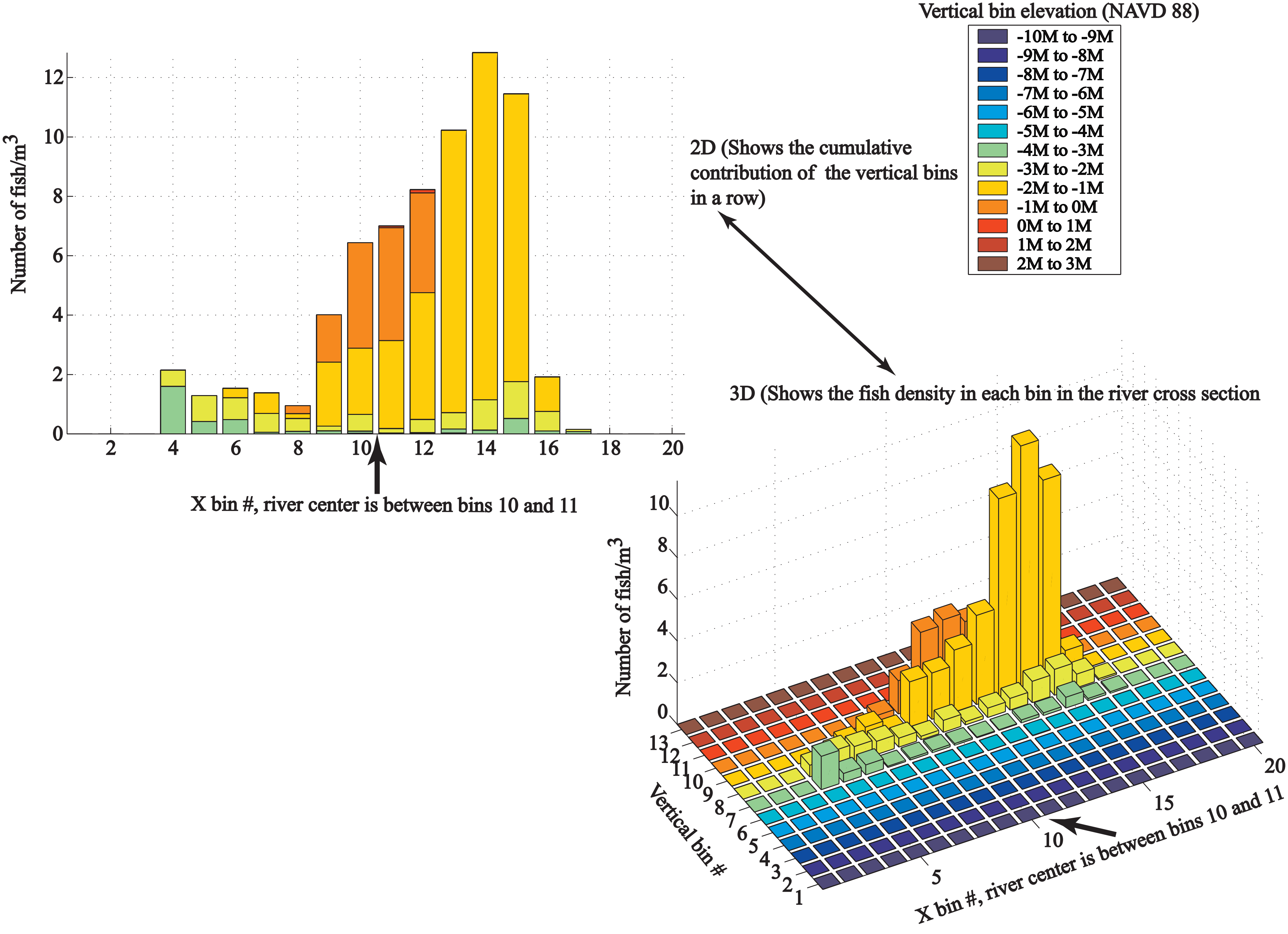


Figure 56. Vertical moments, trawl catch, and light for the October 29, 2001, and November 1, 2001 studies.

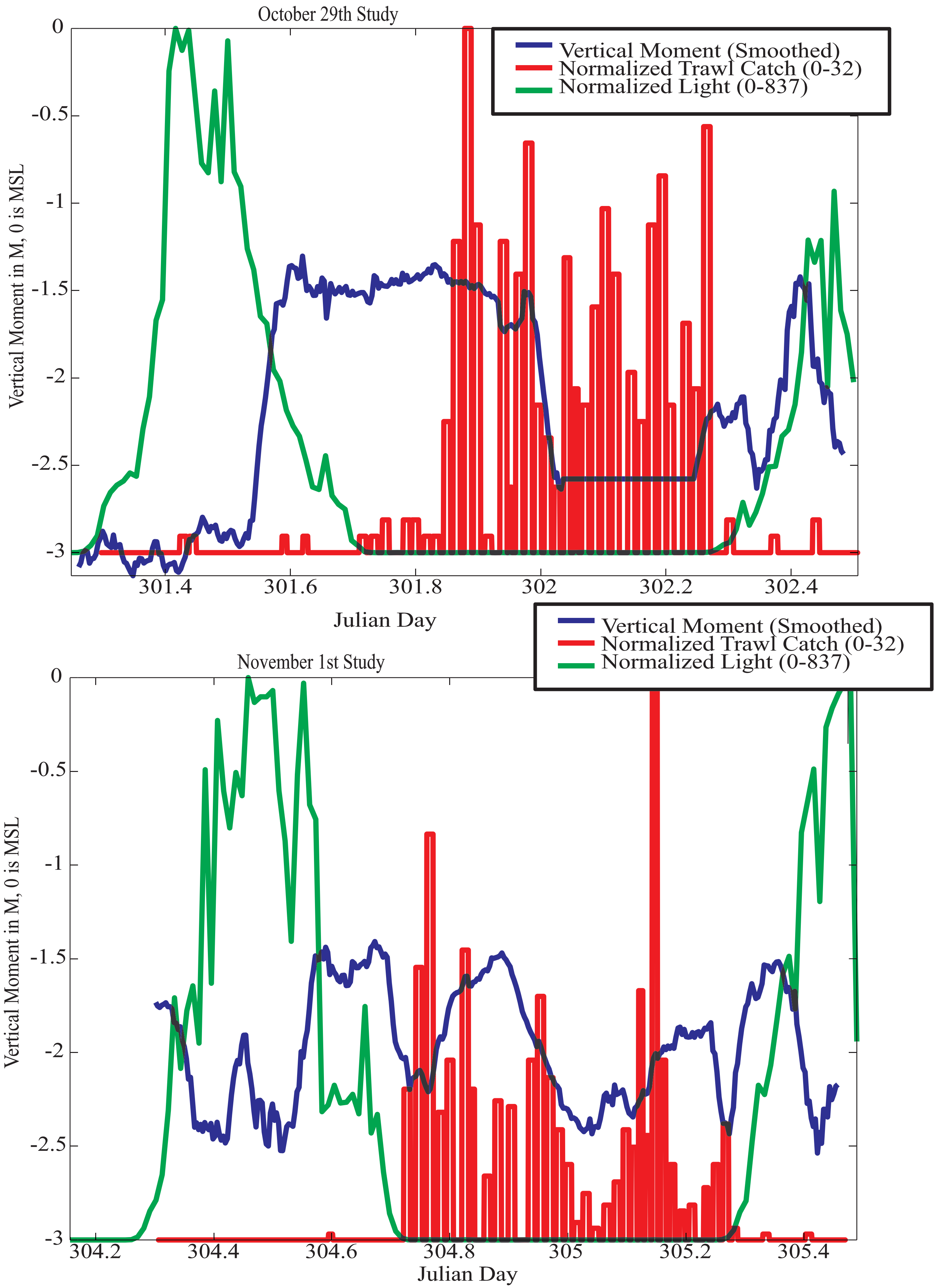


Figure 57. Possible triggers for diel migrations.

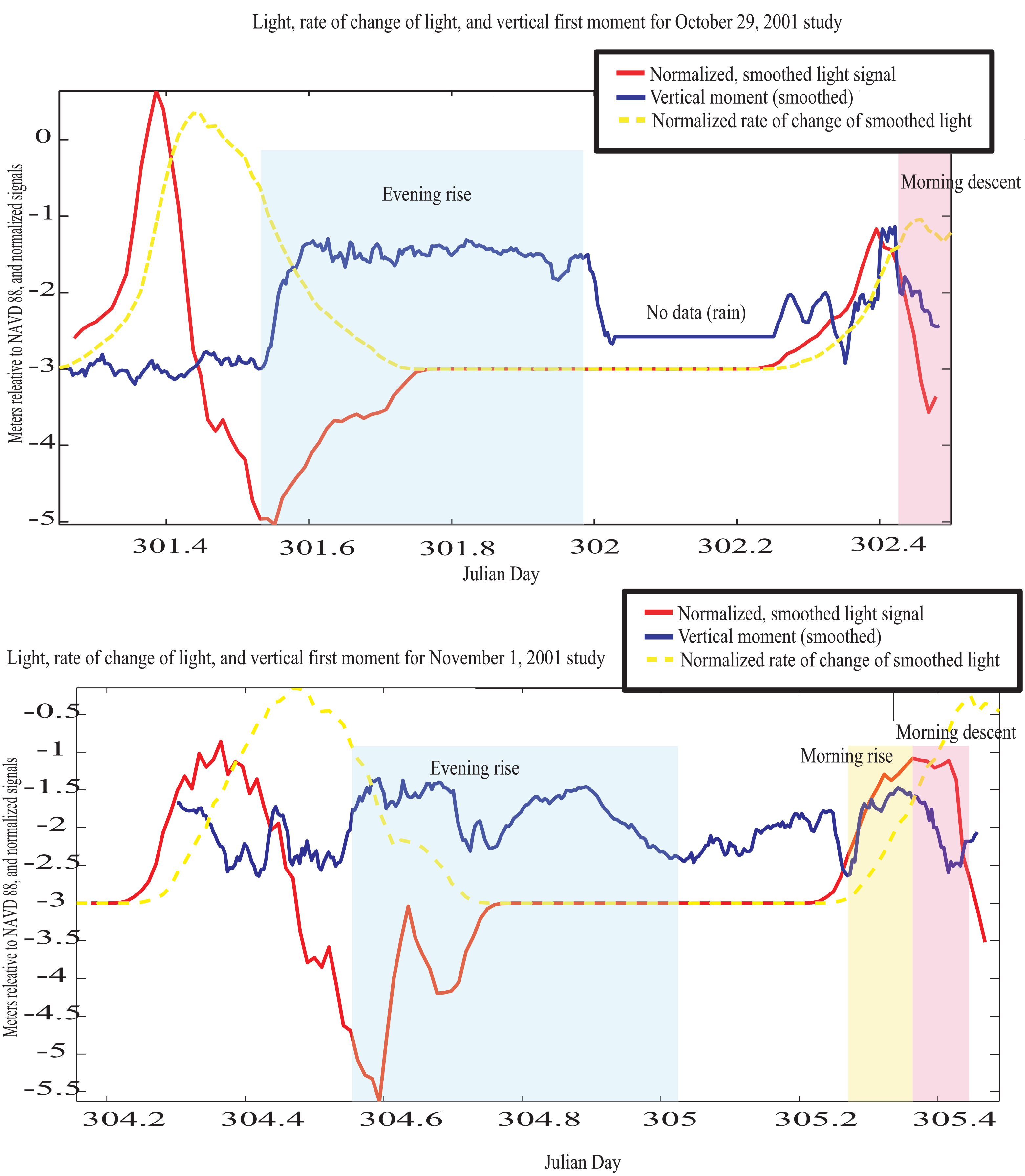


Figure 58. Fish density distribution from the night of November 1, 2001 which indicates possible entrainment in the DCC.

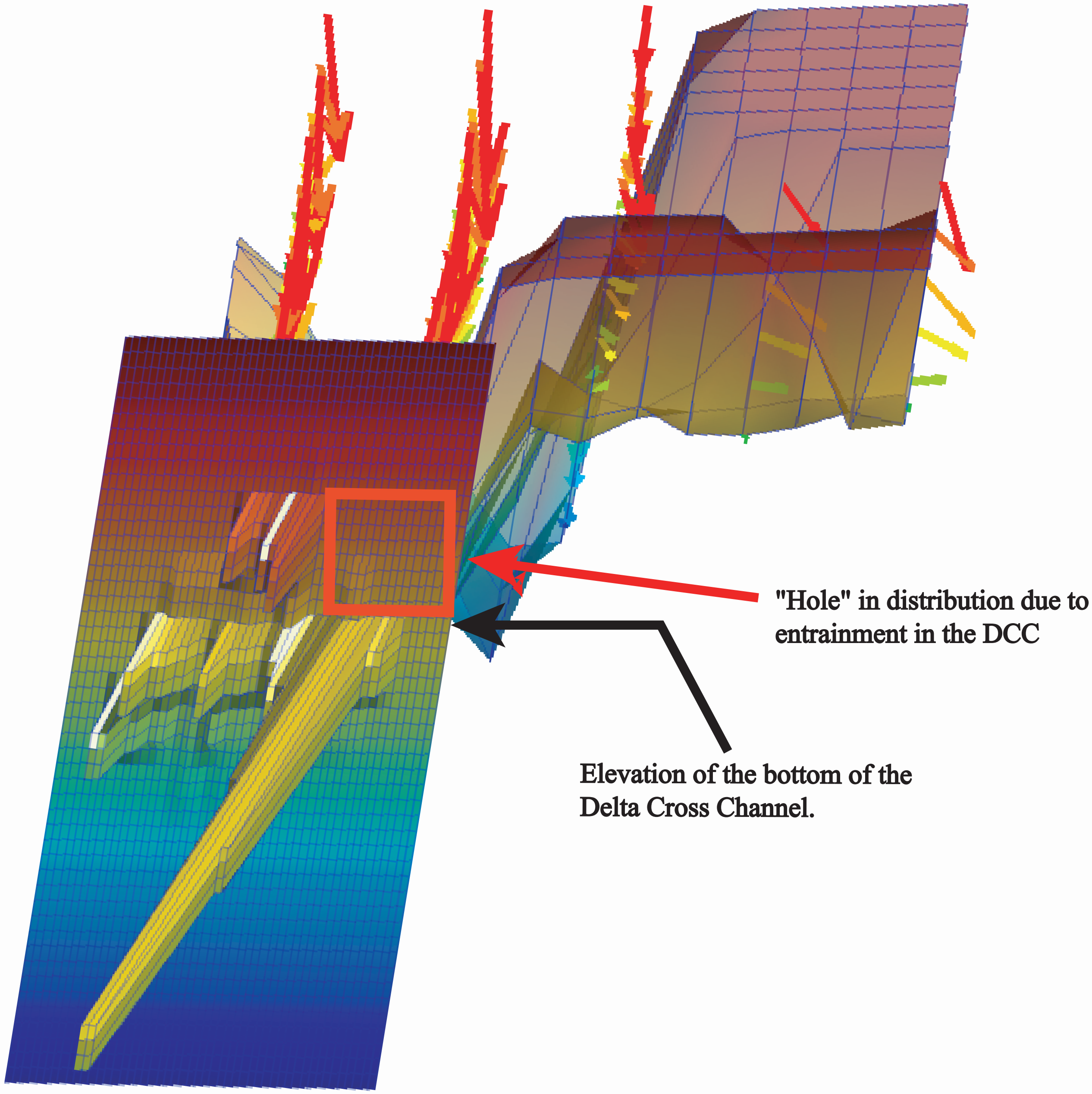
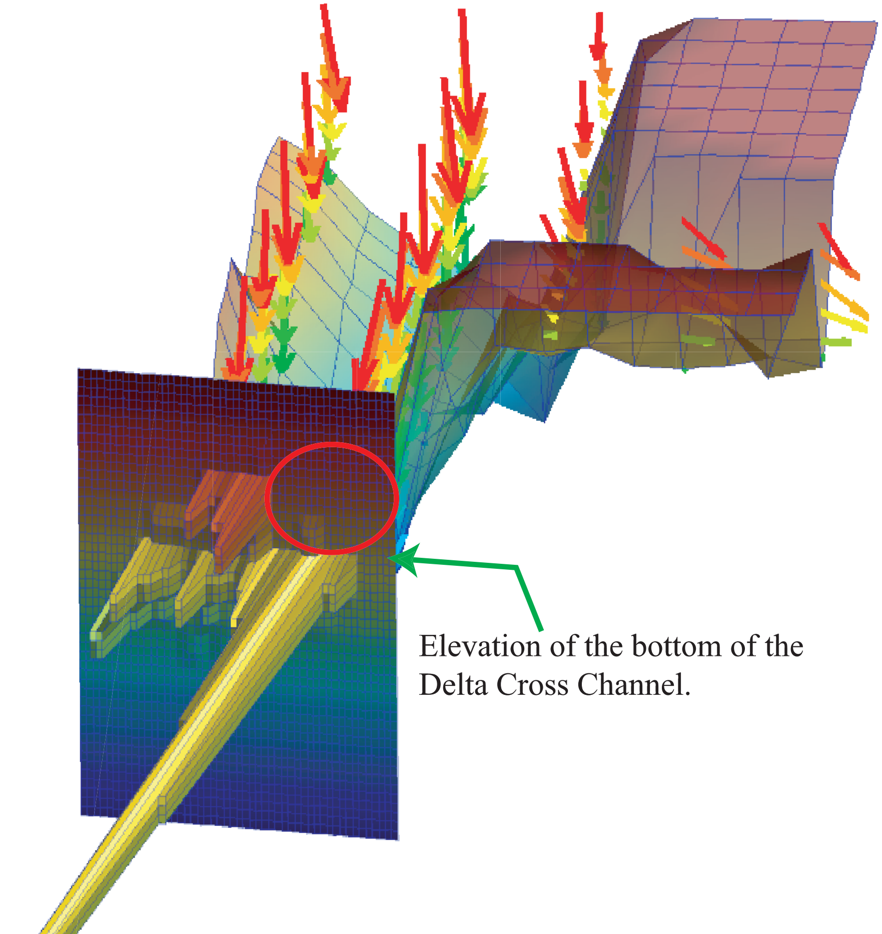


Figure 59. Illustration of entrainment zone concept.



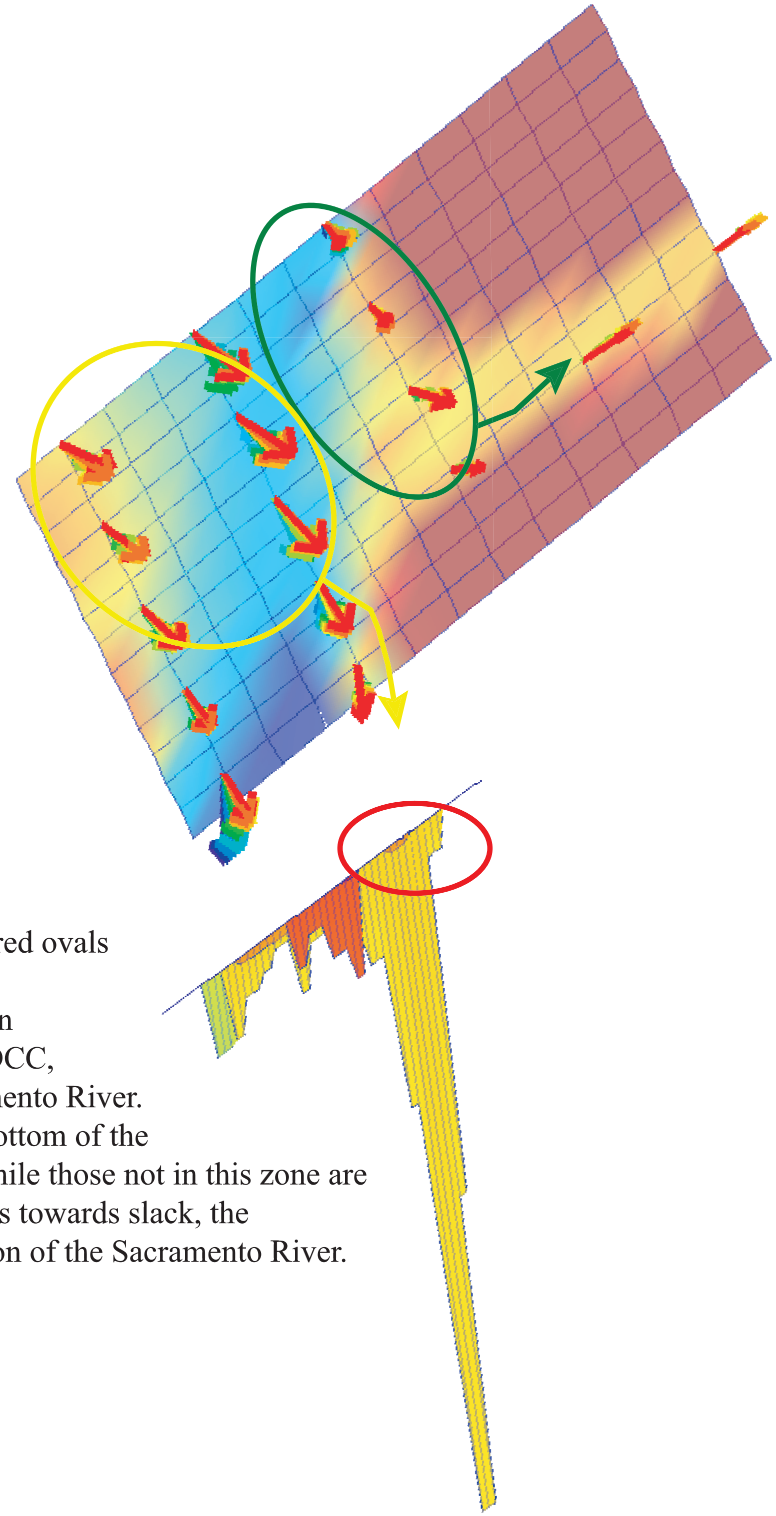


Figure A17 illustrates the concept of smolt entrainment zones. The red ovals on the fish density distributions indicate regions where no fish were detected due to upstream entrainment in the DCC. The green oval on the right hand flow map illustrates the xy entrainment zone for the DCC, and the yellow oval represents the entrainemtnt zone for the Sacramento River. Fish entering the DCC entrainment zone at an elevation above the bottom of the DCC have a very high probability of being entrained in the DCC, while those not in this zone are moved towards the outside bank. Note that as the ebb tide decreases towards slack, the DCC entrainment zone will expand to contain the entire upper portion of the Sacramento River.