Modeling Estuarine Habitat in the Bay Delta

Unifying One and Three Dimensional Approaches to Modeling X2 and the Low Salinity Zone[1]

Estuarine Habitat and the Low Salinity Zone

Estuaries are coastal areas where rivers mix with seawater in semi-enclosed basins. The San Francisco Bay/Sacramento-San Joaquin Delta Estuary (Bay Delta) is the largest estuary on the west coasts of North and South America, draining 40% of California's land area and encompassing the 478-square mile Bay, and the 1,153-square mile Delta[2]. Hydrodynamic processes ensue when light freshwater meets heavy seawater, and these processes both concentrate suspended solids and aquatic organisms, and comprise the *estuarine habitat* that supports multiple life stages for a diversity of fishes.

The location and extent of estuarine habitat fluctuates in response to river flows, ocean tides, weather, and geographic features (e.g., levees, the depth and breadth of stream channels, connectivity to adjacent wetlands). The *low salinity zone* (LSZ) occurs at the inland edge of estuarine habitat where average daily salinities range from 1 to 6 practical salinity units (psu)[3]. The turbidity of the LSZ results from the concentration of suspended solids, phytoplankton, and zooplankton, and these turbid conditions both shelter and provide food for young fish[4].

Anthropogenic Changes and Current Conditions in the Delta and Suisun Bay

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Beginning in the 1850s, over 300,000 acres of tidal marshes in the Delta were diked, drained, and converted to agriculture[5]. Thus, the complex, shallow, and dendritic marshlands were replaced by simplified, deep, and barren channels (Figure 1). This hydrogeomorphic modification fragmented aquatic and terrestrial habitats, and decreased the quality and quantity of available estuarine habitat.

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[1] Drafted by Herbold and Vendlinski for the Technical Workshop on Estuarine Habitat (27 March 2012).

[2] The State of the Estuary: A Report on Conditions and Problems in the San Francisco Bay/Sacramento-San Joaquin Delta Estuary (SFEP, 1992).

[3] The UNESCO Practical Salinity Scale of 1978 (PSS78) is used to describe the concentration of dissolved salts in water and defines salinity in terms of a conductivity ratio. Salinity was formerly expressed in terms of parts per thousand (ppt) or by weight (parts per thousand or 0/00). That is, a salinity of 35 ppt meant 35 pounds of salt per 1,000 pounds of seawater. The salinity of freshwater is 0 psu and the salinity of the open ocean ranges from 32 to 37 psu. http://science.nasa.gov/glossary/practical-salinity-unit/

[4] Kimmerer, W. J., J. R. Burau, and W. A. Bennett. (1998). "Tidally oriented vertical migration and position maintenance of zooplankton in a temperate estuary." Limnology and Oceanography. 43(7): 1697-1709.

[5] Delta Ecosystem White Paper (October 2010), pages 4-5.

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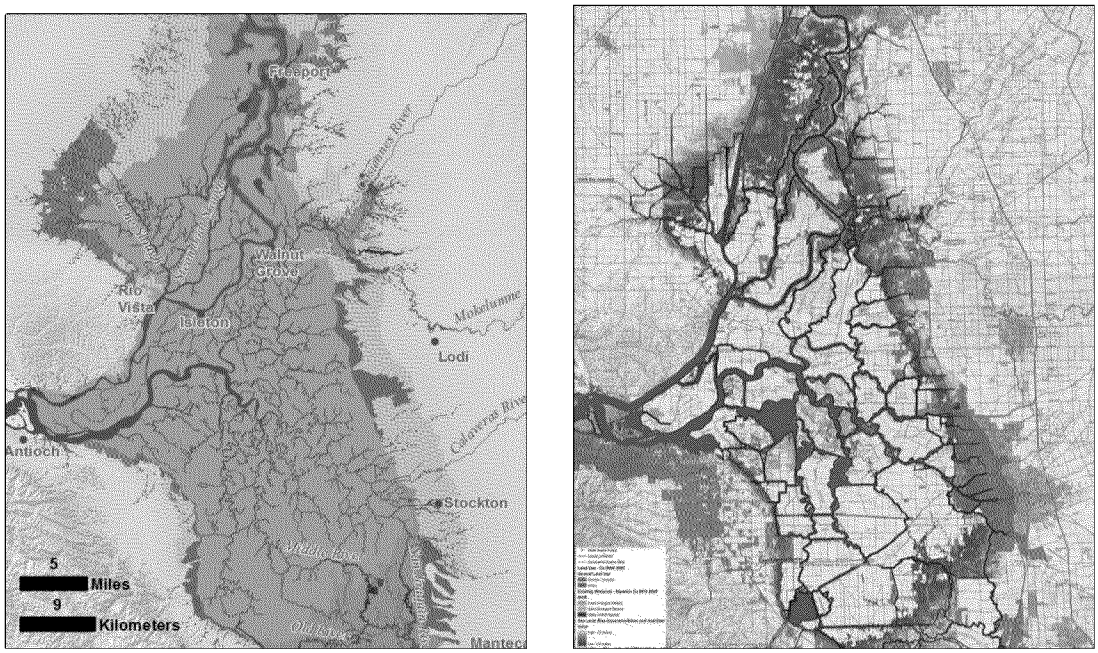

Figure 1: The Delta before and after diking and draining. The draft map of the Delta in the early 1880s on the left is courtesy of Grossinger and Whipple, SFEI (2012). The map of the post-modification, modern day Delta on the right was drawn from USBR-ESRI[6].

Since the year 2000, the position of the LSZ has been frequently fixed in the western Delta throughout the summer and fall until the first storms arrive. As a result, estuarine habitat is located in deep river channels for a large fraction of the year and exposed to a variety of stressors[7]. Fishes that follow the LSZ into this area face an increased risk of predation and entrainment resulting from a lack of cover and foraging habitat caused by the simplification of geographic features, and by the design and operation of water supply infrastructure. By contrast, when the LSZ occupies Suisun Bay, the estuarine habitat spreads out across the expansive shallows of Grizzly and Honker bays and into the large adjacent tidal marsh (Figure 2).

While the form and function of the marsh have been greatly altered, the remnant wetlands still bear a resemblance to the habitat that once characterized both the Suisun Marsh and the western Delta. Most of the wetland acres within Suisun Marsh are managed for waterfowl, but there remain many dendritic sloughs lined with extensive fringing tidal wetlands. Suisun Marsh

[6] USBR-ESRI: The California Delta—Ecosystem Restoration Targets and Levees at Risk.
In comparing their maps of the early 1880s Delta with the early 2000s Delta (the latter not pictured in this paper), Grossinger and Whipple found the maps revealed a reduction in historical tidal channel complexity with the damming of smaller waterways, channel widening, meander cuts, and straight connecting canals. The mapping done by USBR-ESRI led them to conclude that subsidence and anticipated sea level rise have limited restoration opportunities for aquatic and terrestrial habitats. This would apparently exclude the western Delta from consideration as a restoration target, however, USGS has demonstrated that subsided islands in the western Delta are restorable, and the subsidence reversible, through carbon farming with tule-based wetlands.

[7] For the purposes of this paper, the "western Delta" refers to the area around Sherman Island at the confluence of the Sacramento and San Joaquin rivers, river km 81 to 90.

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continues to shelter a number of aquatic species that are rarely found elsewhere in abundance.

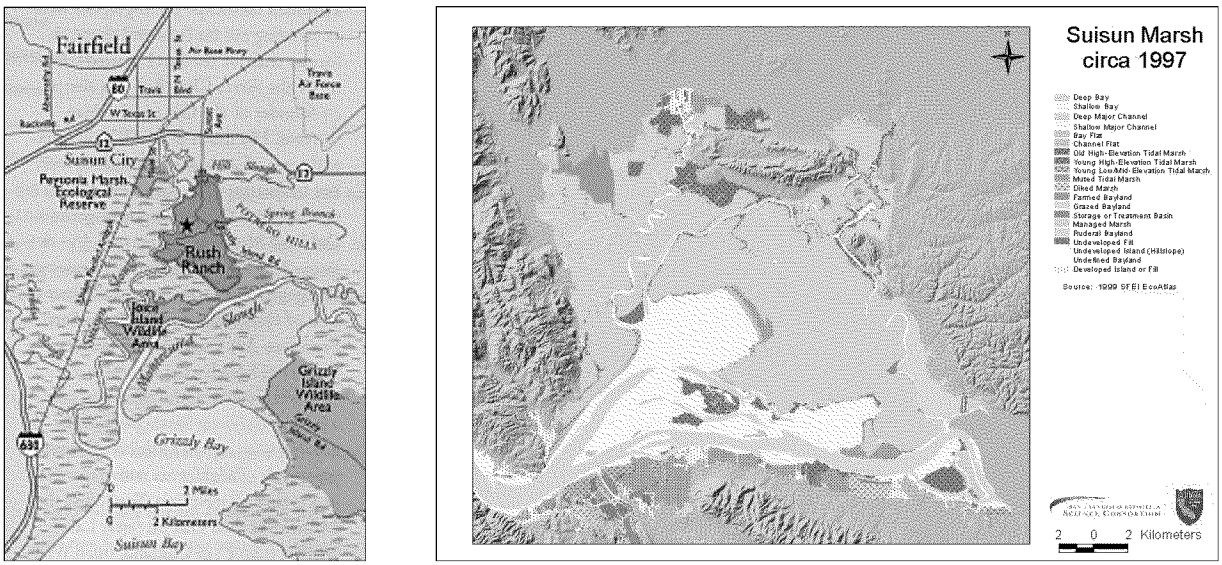

Figure 2: Suisun Bay and Marsh comprise the only area upstream of San Pablo Bay where shallow embayments are contiguous with significant, remnant patches of tidal marsh. Here, optimal estuarine habitat can be created by using Delta outflows to co-locate the LSZ with these geographic features. Map on left from Bay Nature (2001); map on right from CDFG's Suisun Marsh Atlas.

A number of species that often reside in the LSZ (e.g., delta smelt, longfin smelt, young striped bass), and a number of species that move in concert with the LSZ but are associated with higher salinities downstream (e.g., Pacific herring, starry flounder, and native shrimp species) show a greater abundance and survival when the LSZ shifts downstream from the western Delta and toward Suisun Bay. With the exception of delta smelt, the aforementioned species show a relatively straightforward, positive relationship between the westward locations of the springtime LSZ, and their greater survival as young fishes, or abundance as adults[8].

A Brief History of X2

An *isohaline* is a line that connects all points of equal salinity in an estuary. Isohalines generally move in parallel with each other and in response to ocean tides, freshwater inflows, and, to some extent, atmospheric pressure. The abundance and survival of most of the aforementioned Bay Delta species are correlated with the location of the 2 ‰ (parts per thousand) salinity isohaline -- as measured in kilometers from the Golden Gate (Figure 3). In the early 1990s, scientists

[8] Kimmerer, W. J. 2002. Effects of freshwater flow on abundance of estuarine organisms: physical effects or trophic linkages? Marine Ecology Progress Series

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designated this parameter as *X2*[9], and since then, scientists have sought to understand the mechanisms behind the relationships of X2 with aquatic resources, and the changes in those relationships through time. Despite its statistical association with a variety of aquatic resources, the one-dimensional nature of the X2 parameter does not reveal the ecological processes that underlie those associations.

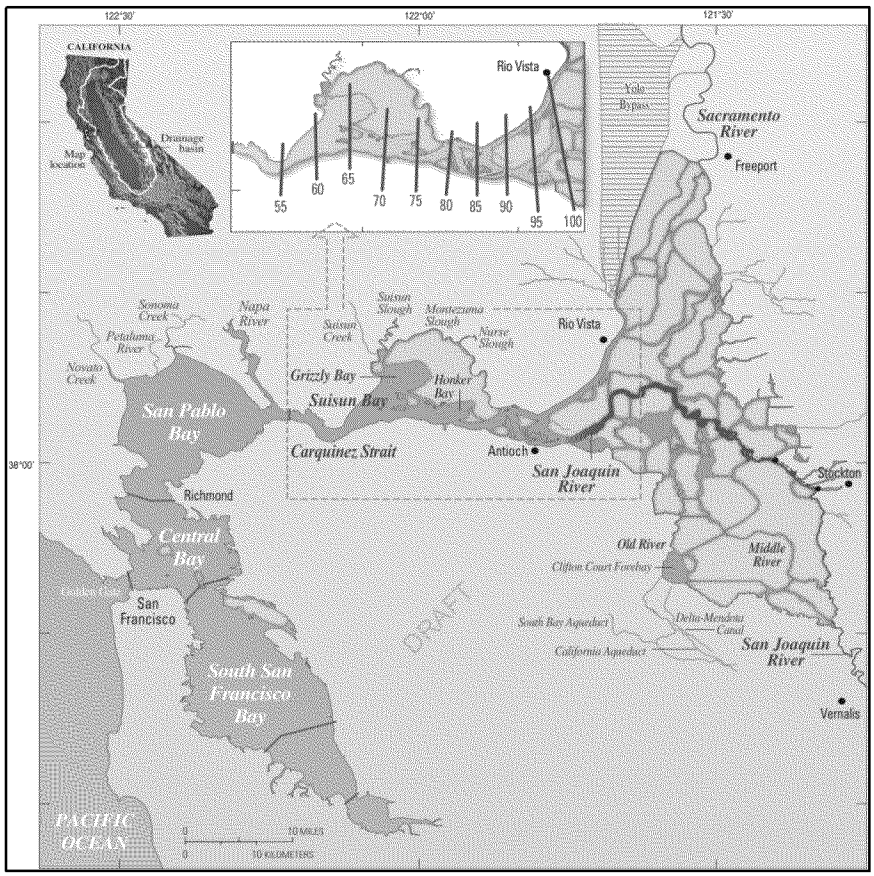

Figure 3. Isohaline positions (X2) measured at nominal distances (in kilometers) from the Golden Gate Bridge along the axis of the estuary. New map by DeLio (2011) adapted from Jassby et al. (1995). Kimmerer and Monismith developed *the X2 model* to predict the location of X2 based on the preceding location of the isohaline and the present value of delta outflow[10], while Denton developed *the G model* to predict salinity at a particular location (intakes for drinking water) based on previous salinity conditions at that location and present delta outflow[11]. Today, X2 positions are interpolated from measurements of salinity at four locations in the Bay Delta and reported daily.

The Translation of X2 into Water Quality Standards

[9] Jassby et al. 1995 Isohaline Position as a Habitat Indicator for Estuarine Populations. Ecological Applications 5: 272-289.

[10] Wim Kimmerer (SFSU) and Stephen Monismith (Stanford University) developed the "X2 Model." Historical X2 is included in the DAYFLOW dataset, and calculated using this model.

[11] The "G Model" developed by Richard Denton of Contra Costa Water District.

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In 1995, the State Water Resources Control Board (State Board) adopted X2 as a water quality standard to help restore the relationship between springtime precipitation and the geographic location and extent of estuarine habitat. The regulatory requirements for this springtime (February through June) standard are indexed to monthly flows into reservoirs on the eight largest rivers draining into the Bay Delta[12]. This requires water managers to position X2 further downstream in wet months than in dry months either by increasing reservoir releases or, more commonly, decreasing exports from the Delta. Compliance is achieved by positioning X2 downstream of one of three locations: Roe Island (65 km), Chipps Island (74 km), or the confluence of the Sacramento and San Joaquin rivers (81 km). The State Board did not set standards for managing the location of X2 during other times of the year.

Following the State Board's implementation of the X2 standard under the 1995 Water Quality Control Plan, more characteristic springtime flows prevailed in the Delta, and migratory and resident fishes responded with modest yet significant increases in abundance. By 1999, increases in the population of delta smelt nearly achieved the criteria for delisting set forth in the federal recovery plan for native fishes in the Delta[13]. Moreover, populations were rebounding for both threadfin shad and longfin smelt, and populations of adult striped bass returned to levels not seen since the 1970s. However, beginning in the early 2000s, populations of delta smelt and other pelagic species experienced unexpected and dramatic declines, and this phenomenon became known as the *pelagic organism decline* (POD)[14] .

Modeling X2 and the Low Salinity Zone with 3D models

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The LSZ is a three dimensional (3D) volume of estuarine habitat that changes its shape depending on its location in the Bay Delta. New models allow for the 3D characterization of the LSZ in terms of its average depth, width, and river kilometer, and can depict the dispersion of the LSZ over short time steps.

These models include the UnTRIM San Francisco Bay-Delta model (UnTRIM) that the Delta Modeling Associates adapted for use in the Bay Delta. Other models include the SUNTANS model developed by researchers at Stanford and U.C. Berkeley, and a public domain model being developed by DWR[15]. All of these models can, or have the potential to, characterize the hydrodynamics of the Bay Delta in a fine geographical scale and with small time steps that more closely mimic real world conditions than the aforementioned X2 and G models.

The following is not intended to be an endorsement of the UnTRIM model per se, but rather an

[12] Eight largest rivers draining into the Bay Delta and their corresponding Reservoirs:
American River (Folsom Lake), Feather River (Lake Oroville), Merced River (Lake McClure), Sacramento River (Lake Shasta), San Joaquin River (Millerton Lake), Stanislaus River (New Melones Reservoir), Tuolumne River (Don Pedro Reservoir), and Yuba River (Engelbright Lake).
[13] FWS: Recovery Plan for the Sacramento/San Joaquin Delta Native Fishes (1996).
[14] Baxter, R., R. Breuer, L. Brown, M. Chotkowski, F. Feyrer, M. Gingras, B. Herbold, A. Mueller-Solger, M. Nobriga, T. Sommer, and K. Souza. 2008. Pelagic organism decline progress report: 2007 synthesis of results. Interagency Ecological Program for the San Francisco Estuary, Technical Report 227.

[15] Stanford Unstructured Nonhydrostatic Terrain-following Adaptive Navier-Stokes Simulator (SUNTANS)

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exploration of the potential advantages of using a 3D approach toward characterizing the LSZ of the Bay Delta. EPA became aware of the UnTRIM model during the regulatory review of the proposed Sacramento Deep Water Ship Channel project proposed by the Corps of Engineers and the Port of West Sacramento.

The UnTRIM model was calibrated using data collected in the Bay Delta about water levels, flow, velocity, and salinity. The model provides a 3D hydrodynamic characterization of conditions from the Pacific Ocean eastward through the entire Sacramento-San Joaquin Delta. Predicted water levels were compared to observed water levels at monitoring stations administered by DWR and NOAA in San Francisco Bay, and those administered by DWR and USGS in the Delta. Large grid cells were used to characterize the Pacific Ocean, and these cells gradually transition to finer grid resolution for the small channels of the Delta (Figure 4). This approach allows for detailed analysis of local hydrodynamics, while still incorporating the overall hydrodynamics of the larger estuary in a single model.

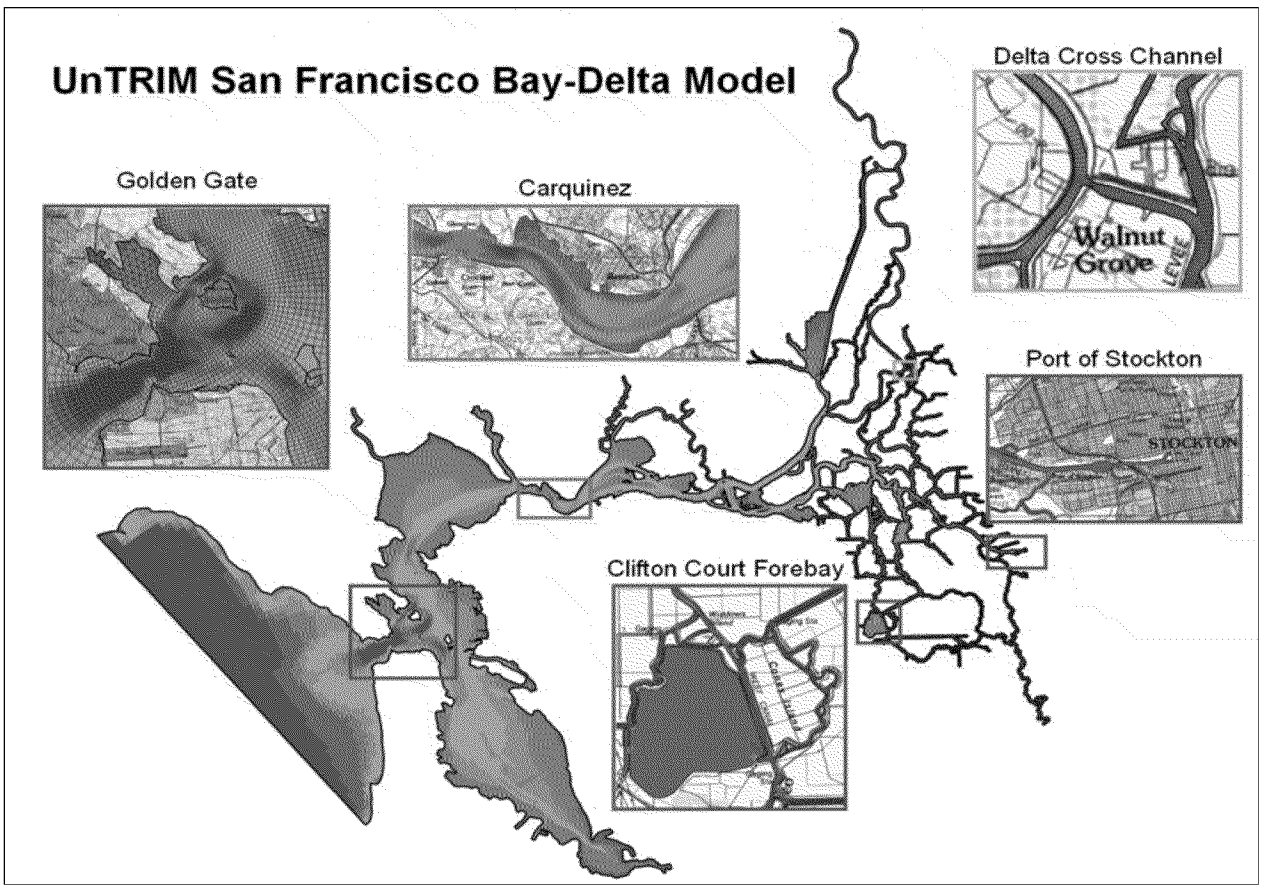

Figure 4. The domain and samples of the computational grid for the UnTRIM model.

Characterizing the LSZ in relation to X2 using the UnTRIM Model

In the figures below, the volumetric UnTRIM model was used to characterize: (i) the areal extent

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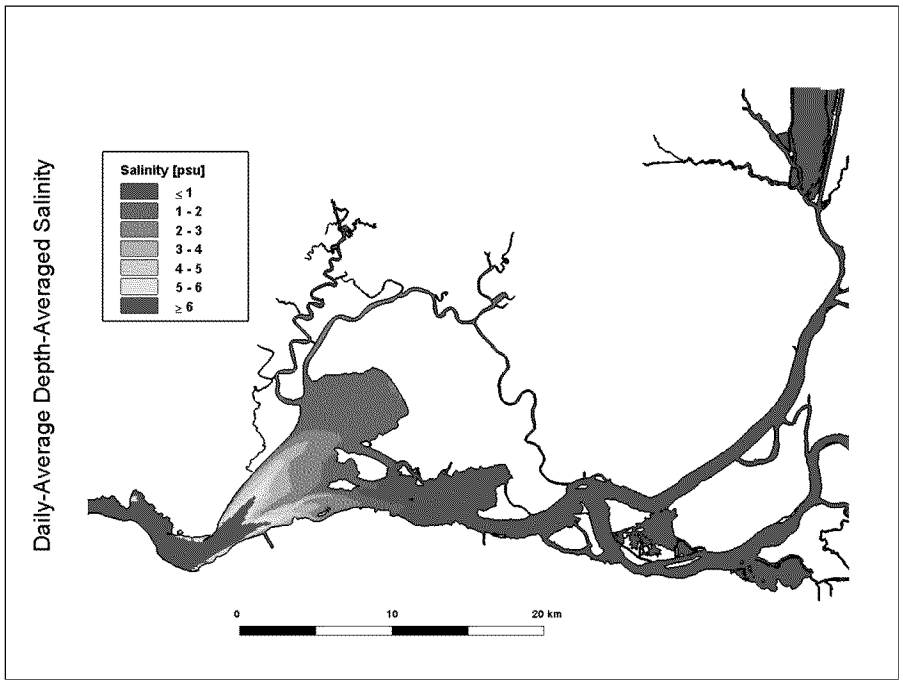
of estuarine habitat (in hectares) corresponding to the regulatory compliance points established for X2 under the 1995 Water Quality Control Plan; and (ii) the percentage of time per day the LSZ resides in a given location of the Bay Delta[16]. Presenting the data in this way unifies the 1D approach employed by the State Board since 1995 to manage the location of X2, and the 3D approach (depth, width, and river kilometer) now available to characterize the position and volume of the LSZ.



[16] The ability of the UnTRIM model to account for time means it can be used to model a 4th dimension of estuarine hydrodynamics.

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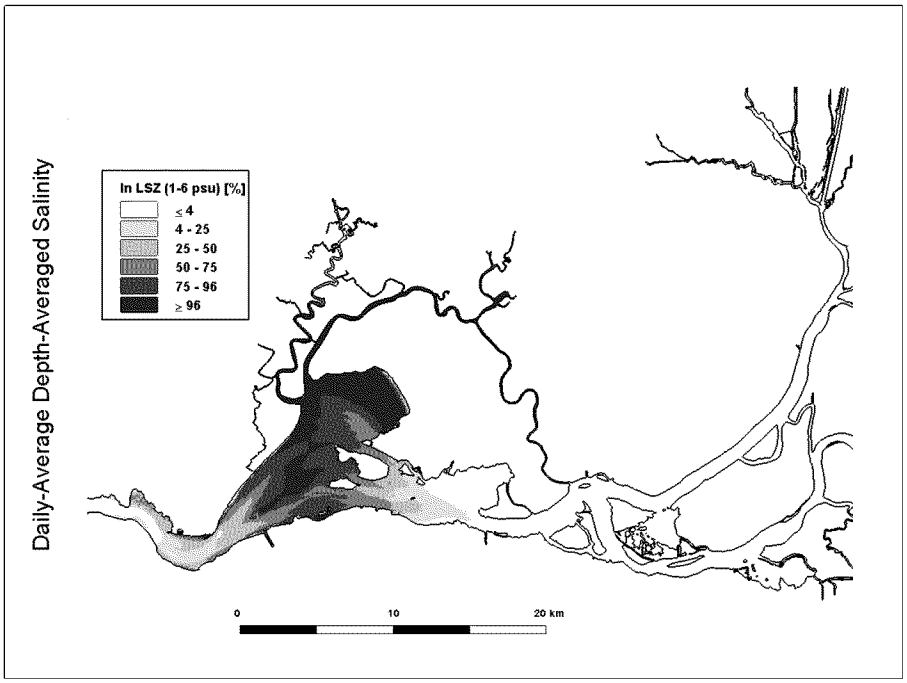

Figure 5a & 5b. X2 = 65 km (downstream of Roe Island). The upper figure shows parts of the LSZ in shades of blue from 1-6 psu stretching across 7,704 hectares and the broadest regions of Suisun Bay adjacent to Suisun Marsh. The lower figure shows the percentage of day that the LSZ occupies different areas of the Suisun Bay and Marsh.

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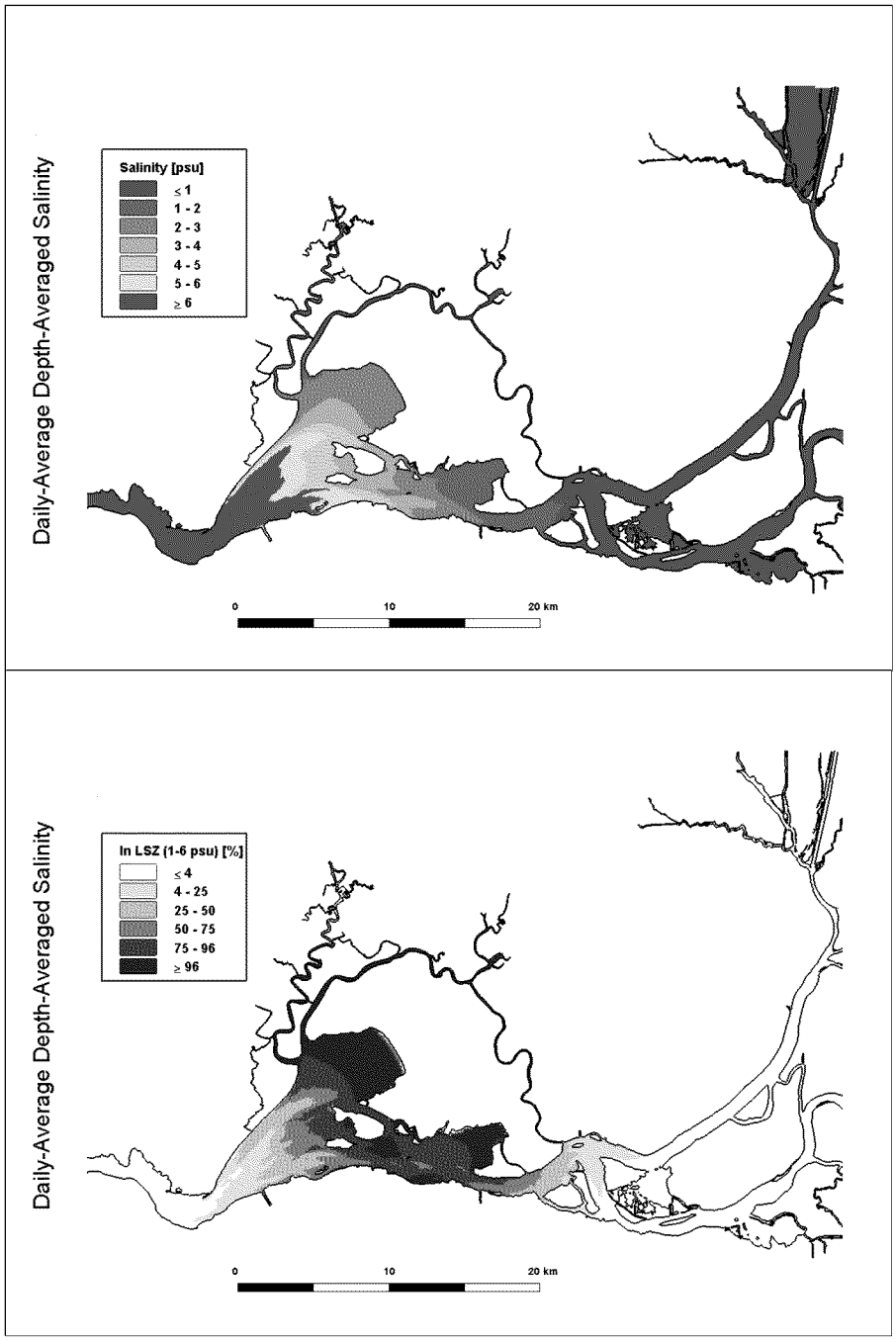

Figure 6a & 6b. X2 = 74 km (at Chipps Island). The upper figure shows the LSZ covering 9,140 hectares. While the total areal extent of estuarine habitat is greater than in Figure 5a, the benefits derived from this greater expanse of the LSZ might be offset by the occurrence of higher salinities across Grizzly Bay and the squeezing of lower salinities into Honker Bay. The lower figure shows the percentage of day that the LSZ occupies different areas.

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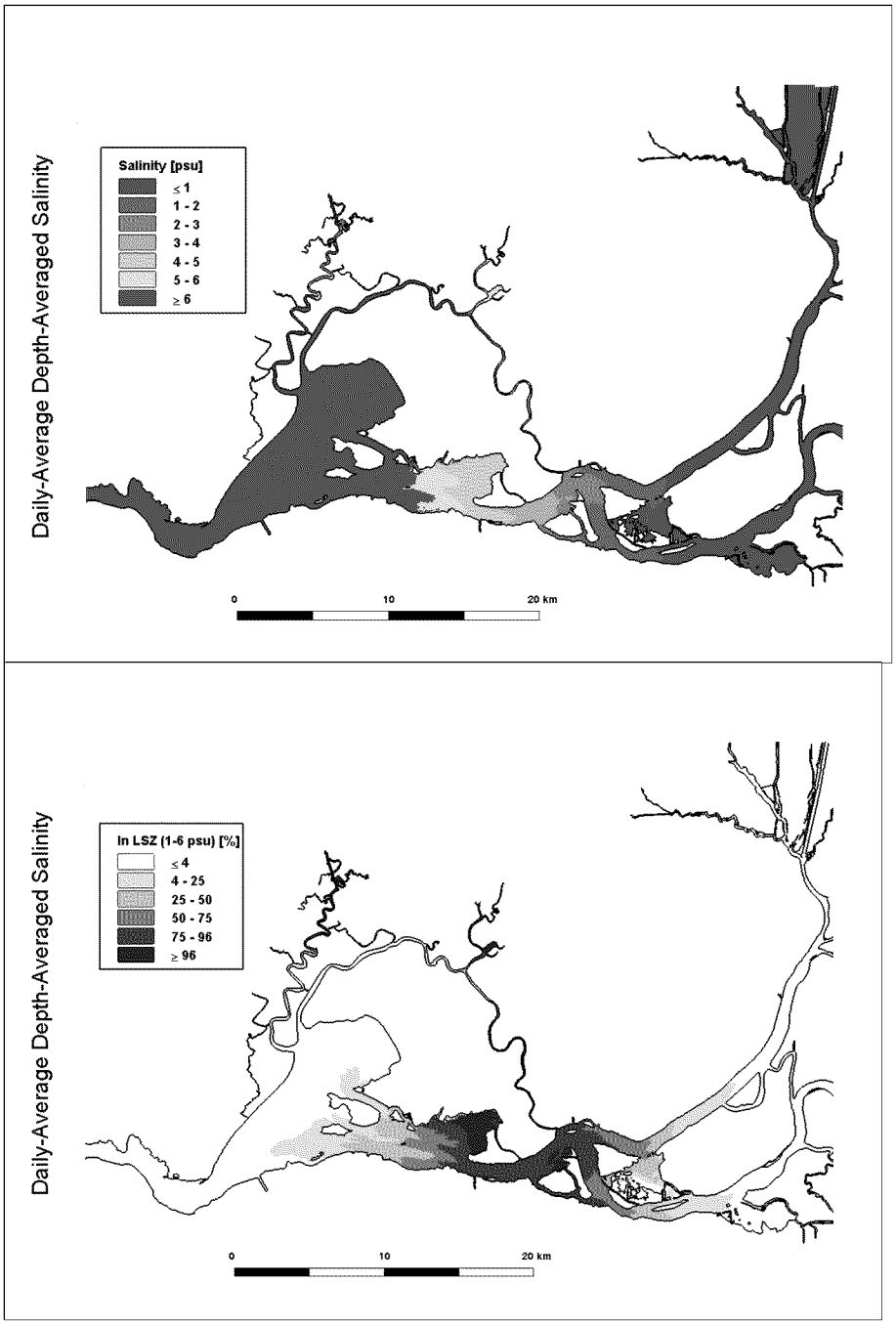

Figure 7a & 7b. X2 = 81 km (at the confluence of the Sacramento and San Joaquin rivers). The upper figure shows the LSZ being compressed into 4,914 hectares within the relatively deep channels of the western Delta. The lower figure shows percentage of day that the LSZ occupies different areas.

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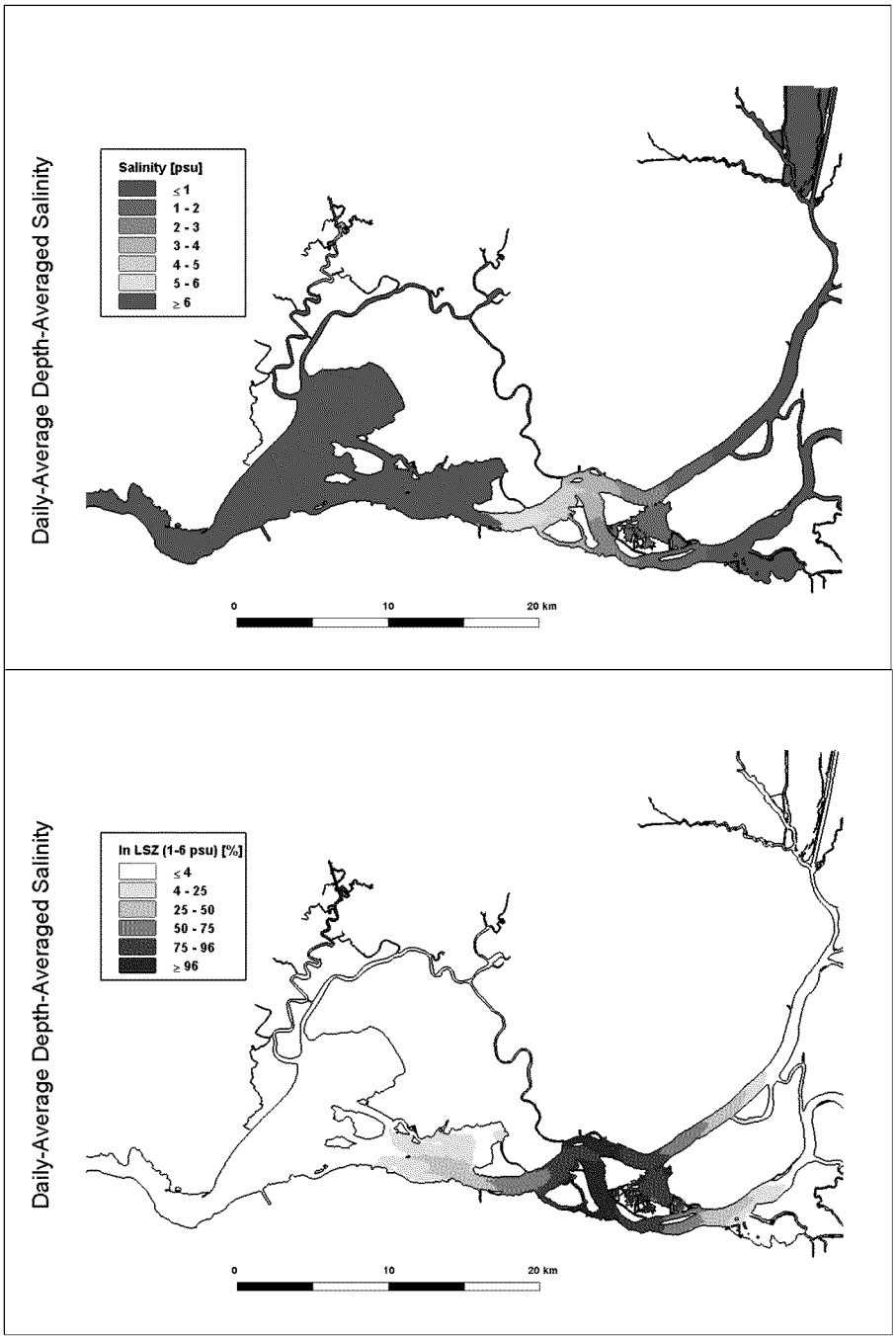

Figure 8a & 8b. X2 = 85 km. The upper figure shows the LSZ being positioned mostly between Antioch and Pittsburg where the areal extent of estuarine habitat drops to 4,262 hectares, and important connections to Suisun Bay and Marsh have nearly been lost. The lower figure shows the percentage of day that the LSZ occupies different areas.

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UnTRIM depictions of Depth, Area, and Volume of the LSZ in relation to X2

The diverse geometry of the upper San Francisco Estuary produces different physical characteristics of the LSZ at different locations. The predictability of the relationship between X2 and the physical characteristics of the LSZ is markedly different upstream and downstream of Carquinez Strait.

The area of the LSZ modeled by UnTRIM shows a strong relationship with X2, due to the distribution of shallow habitats along the axis of the estuary. However, this relationship is much more consistent east of Carquinez Strait (X2 > 50) than westward (Figure 9). The relationship of average LSZ depth with X2 is almost perfectly inverse to that of the LSZ area (Figure 10).

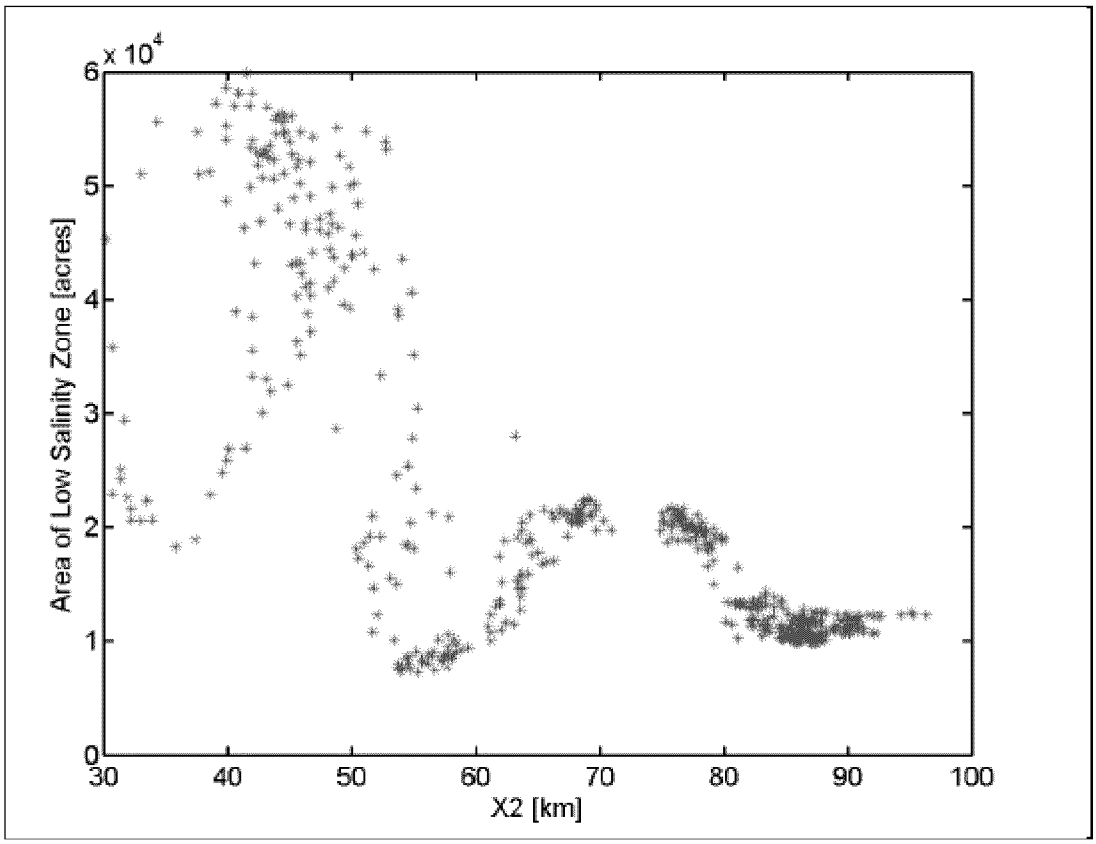

Figure 9. Average acreage of the Low Salinity Zone as a function of X2 using 549 days of data spanning 1 April 1994 to 1 October 1995.

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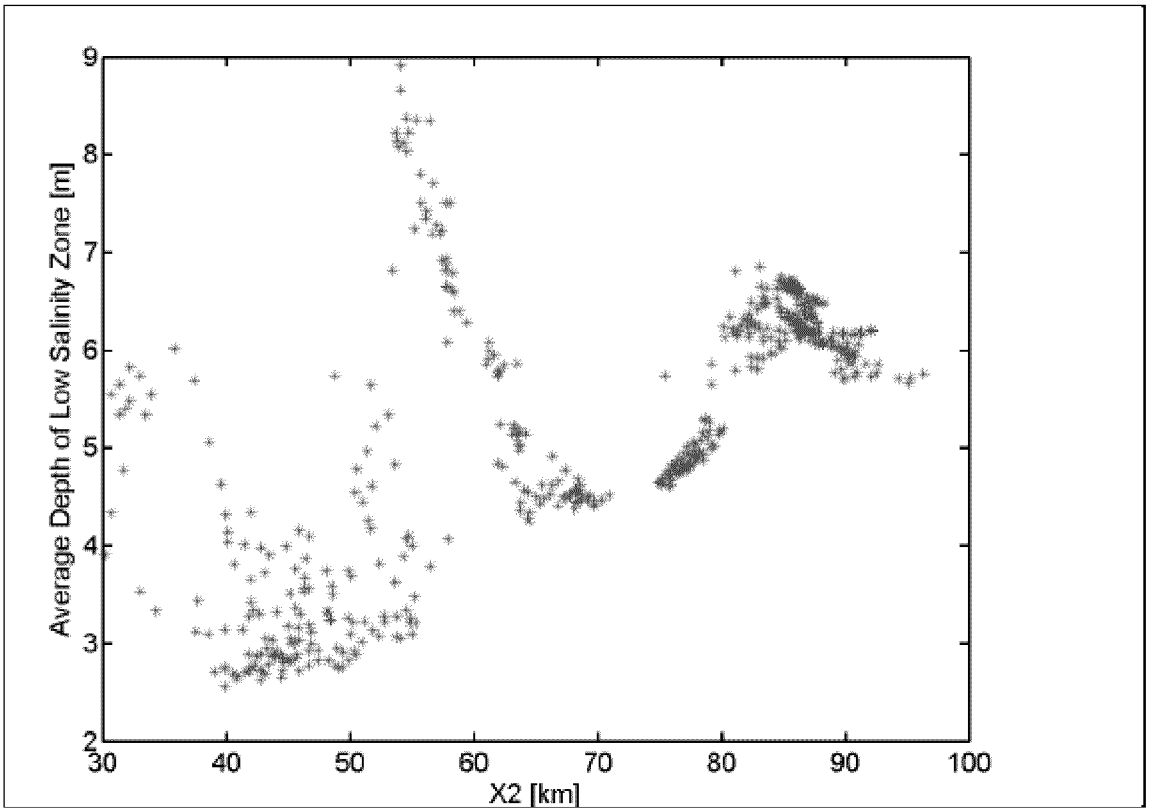

Figure 10. Average depth of the Low Salinity Zone as a function of X2 using 549 days of data spanning 1 April 1994 to 1 October 1995.

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The volume of the LSZ shows the least relationship with X2 due to the opposing nature of depth versus areal extent (Figures 11a, 11b, and 11c). Many ecological processes within estuarine habitat depend on the depth, area, and volume of the LSZ and its proximity to various habitats and stressors, which 3D models can fairly accurately and precisely predict. Deeper areas support gravitational circulation, shallow areas expose more of the water column to the photic zone, etc. Unlike the one-dimensional X2 approach, the 3D models lend themselves to the construction of predictive models of ecological processes.

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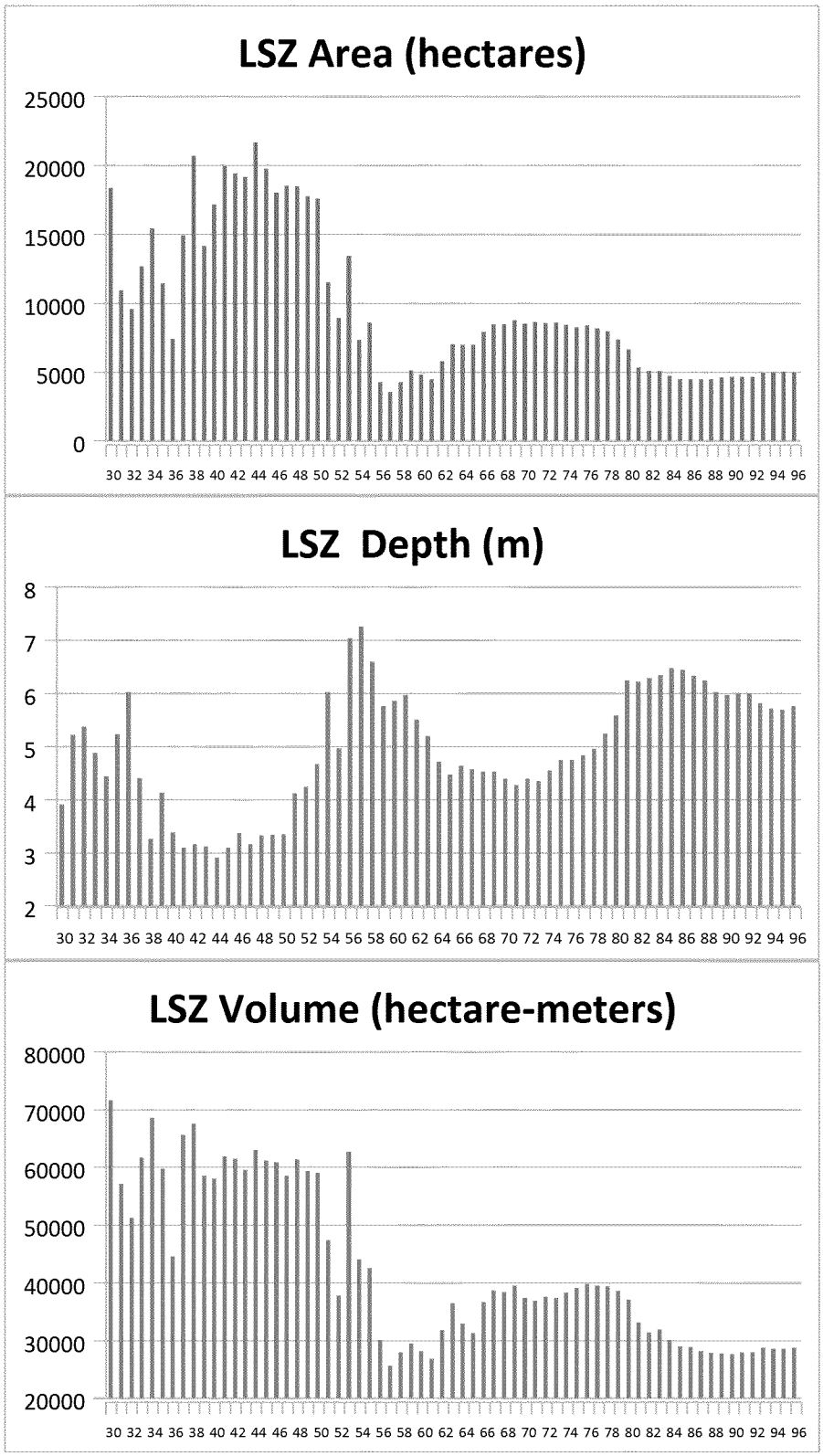

Figures 11a, 11b & 11c. Average area, depth, and volume of the LSZ at 1 km changes in X2.

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