United Heckathorn Superfund Site: Tier 1 Sediment Transport Study

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Introduction

The United Heckathorn Superfund Site is located in Richmond Harbor on the east side of San Francisco Bay in Contra Costa County, California (Figure 1). From the mid-1940s to the mid-1960s, the site was used for processing, packaging and shipping pesticides. Although many types of pesticides were processed on the site, DDT[1] and Dieldrin are the primary contaminants of concern. The remedy selected for the marine portion of the site in the 1994 Record of Decision (USEPA, 1994) consisted of dredging sediment from the Lauritzen Channel and Parr Canal, followed by at least five years of post-remediation monitoring. The remedy for the upland part of the site included capping and institutional controls. The remedies for the marine and upland portions of the site were completed in 1997 and 1999, respectively. Post-remediation monitoring data indicate that sediments in the Lauritzen Channel have been recontaminated by DDT and Dieldrin (Antrim and Kohn, 2000; Anderson et al., 2000). A focused feasibility study (FFS) is planned to address residual contamination in the channel sediments.

A study of sediment dynamics in the Lauritzen Channel is being performed because (1) sediment has accumulated in the channel since the remedy was completed; (2) surface and subsurface sediment DDT concentrations are above the remediation goal; (3) the source(s) of the sediment and sediment-associated contamination have not been definitively identified; and (4) additional cleanup cannot occur until any active, ongoing source(s) are controlled.

It is not clear whether the sediments that have accumulated in the channel since 1997 were already contaminated (i.e., sediments from undredged areas that have been resupended and redistributed throughout the channel), or whether they were transported into and deposited in the channel and subsequently contaminated by an ongoing local or far-field source, or whether both processes have occurred. Additionally, the amounts of sediment and sediment-associated DDT that are being transported into and out of the Lauritzen Channel and redistributed within the Lauritzen Channel are not known. A sediment transport analysis is necessary to understand the present distribution of contaminants in the channel.

The sediment transport analysis is being performed using a phased (tiered) approach as described in the U.S. Navy's *User's Guide for Assessing Sediment Transport at Navy Facilities* (Blake et al., 2007). In a Tier 1 study, sediment transport is assessed using basic site characterization data (e.g. bathymetric surveys, tidal ranges, sediment contaminant data) and analyses to address sediment management questions. A Tier 1 evaluation has relatively fewer data needs, a shorter time frame, and a higher level of uncertainty than a Tier 2 evaluation. A Tier 2 study focuses on collection of site-specific data and more refined data analyses, which may include use of analytical and numerical methods. Both Tier 1 and Tier 2 studies are being performed for the United Heckathorn site.

This document presents the results of the Tier 1 sediment transport study and the recommended scope and approach for the Tier 2 study. The results of the Tier 1 and Tier 2 studies will be evaluated in conjunction with the results of the source identification study and DDT fate and transport evaluation, long-term monitoring data, and data from previous investigations to refine the conceptual site model (CSM) for the site and support the development of remedial alternatives in the FFS.

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[1] (dichlorodiphenyltrichloroethane; for the purposes of this report, "DDT" refers to the sum of all 4,4'- and 2,4'- isomers of DDT, DDD, and DDE. Dieldrin is present at lower concentrations but co-occurs with DDT; therefore, the report focuses on DDT.

The primary goals of the sediment transport study are to address the following sediment management questions:

- What is the source(s) of the sediment accumulating in the Lauritzen Channel?
- How does sediment transport lead to the redistribution of contamination within the Lauritzen Channel, or movement of contamination out of the channel?
- If part of the Lauritzen Channel is actively remediated, could sediment transport lead to the recontamination of the remediated area?

Due to the complexity of the processes affecting the sediment and contaminant transport in the Lauritzen Channel, multiple lines of evidence will be evaluated to fully address the management questions. The Tier 1 sediment transport study will characterize the sediment erosion/resuspension and transport processes in Lauritzen Channel as follows:

- Estimate the residence time of water within the Lauritzen Channel
- Determine tidal transport and tidal velocities
- Document the types of vessels that cause scour and determine the approximate area(s) affected by scour
- Determine whether outfall discharges are sufficient to scour sediments at the north end of the Lauritzen Channel
- Determine the relative significance of physical transport processes at the site (vessel activity, tidal currents, dredging, waves, stormwater discharge)
- Develop a conceptual sediment budget for the Lauritzen Channel.

The Tier 1 evaluation uses data from previous investigations at the United Heckathorn site and other publicly-available sources. Additionally, high resolution multibeam bathymetric and side scan sonar surveys were performed in accordance with the *Tier 1 Sediment Transport Sampling and Analysis Plan for the United Heckathorn Superfund Site* (CH2M HILL and Sea Engineering Inc., 2013). This report is organized as follows:

- Tier 1 evaluation
- Sediment transport CSM, including the relative significance of physical transport processes and a conceptual sediment budget
- Sediment management questions
- Conclusions and recommendations for the Tier 2 evaluation.

Tier 1 Evaluation

Site Description

The Lauritzen Channel is a tidal waterway inside the Richmond Harbor on the eastern shoreline of central San Francisco Bay. The Lauritzen Channel is a single spur inside the Richmond Harbor off of the Santa Fe Channel (Figure 2 and Figure 3). The harbor was originally intertidal marsh that was dredged and filled in the 1920s to provide a deepwater berthing area for commercial and private vessels (White et al., 1994). An extensive offshore breakwater provides protection from waves generated in the central San Francisco Bay and beyond. The tidal range in the harbor is approximately -0.6 to 2.1 m Mean Lower Low Water (MLLW). The shorelines of the harbor are generally armored with rip-rap, sandy gravel fill, or pile-supported structures (White et al., 1994). The upland regions surrounding the harbor are generally level and at heights of 2.1 to 3.3 m MLLW. The Lauritzen Channel is approximately 0.5 km long and 40 m wide at the head widening to over 100 m at the mouth. The depths in the channel range from 3 to 12 m MLLW (Figure 2). Presently Manson Construction Company occupies the western shoreline and the Levin Richmond Terminal occupies the eastern shoreline.

The most recent maintenance dredging of the Lauritzen Channel occurred in 1985. Between August 1996 and 1997, approximately 107,945 cubic yards of total sediment were removed from the Lauritzen Channel and the Parr Canal during remediation activities. Of the total amount, 105,325 cubic yards were removed from the Lauritzen Channel. The sediment was disposed of offsite at designated disposal facilities. Clean sand was placed to a nominal thickness of 6 inches over dredged portions of the Lauritzen Channel to facilitate colonization by benthic organisms (Chemical Waste Management Inc., 1997). A thicker layer of sand (approximately 18 inches) was reportedly placed in inaccessible areas that were impractical to dredge (i.e., areas with pilings). No sand was placed underneath the Levin pier because the slope was too steep to hold sand. The sand was hydraulically pumped from a barge into the channel. A bathymetric survey was performed after sand placement was completed; however, the distribution and thickness of the sand layer do not appear to have been verified. No other dredging activities have been conducted in the Lauritzen Channel since 1997 (EPA, 2012).

A recent site survey documented a number of small outfall pipes on the banks of the Lauritzen Channel (Figure 3). One 1.5 m diameter concrete culvert at the northern end of the channel is a City of Richmond municipal outfall that provides the primary storm drainage from the surrounding area into the channel (Figure 3) (CH2M HILL, 2012). Stormwater runoff from the upland remediated area of the United Heckathorn site is monitored and discharged to City of Richmond publicly-owned treatment works (POTW). In October 2012, EPA installed a flap gate on the municipal outfall at the head of the channel to prevent DDT-contaminated sediment from moving into the storm drain system during high tide.

Bathymetry and Bottom Features

In 2012, Sea Engineering, Inc. conducted high resolution multibeam bathymetric surveys and sidescan sonar surveys to characterize the present state of the bottom sediment in the Lauritzen Channel. Figure 2 shows the results of the bathymetric survey. The survey clearly shows the extents of the dredged channel adjacent to the Levin terminal (Berths B and C), the shallower regions at the head of the channel, and the deeper dredged channels in the Santa Fe Channel with the deepest area on the south side of the Levin terminal (Berth A) to accommodate the largest ships in this portion of the Santa

Fe Channel. The side scan sonar survey map (Figure 4) shows acoustic imagery of the bottom, which shows hard structures, sediment characteristics, and other features.

The bathymetric and side scan sonar surveys reveal features that form in response to processes occurring at the channel bottom. For example, generally smooth, featureless sediment beds are indicative of a depositional environment where sediments are steadily accumulating in a pattern where sediment essentially "snows" down, creating a smooth surface. Alternatively, a rippled pattern at the bottom can be indicative of an active sediment transport environment.

The major features evident in the Lauritzen and Santa Fe Channels are the dredged channels and square regions reflecting different depths of dredging. Starting at the head of the Lauritzen Channel, the bottom appears generally smooth punctuated near the shorelines by some abnormal "hard" features that are likely due to shoreline debris, piers, and other structures. Of particular note in the upper channel is a single linear feature from north to south that resembles a furrow. This type of feature is typically the result of scour by a vessel propeller (i.e. prop scour) or the keel of a vessel dragging along the bottom. Further south in the channel, these linear furrow features become more evident, particularly in the deeper dredged channel. In the region of higher ship and associated tug activity near the Manson Construction and Levin facilities, there are more scour features. Of additional note are the "crater" features near the Manson facility. When Manson brings large crane barges into this area, the large vertical spuds are dropped into the sediment to anchor the barges in place. The craters are the bottom expression due to these spuds. Figure 5 provides delineation of these features by type. The effects of these processes on sediment fate and transport are discussed later in the report.

Sediment Properties

In general, sedimentologists define two types of native sediments in the San Francisco Bay: Younger Bay Mud (YBM) and Older Bay Mud (OBM). YBM is more recent sediment that has been deposited since the onset of the industrial age and hydraulic mining in the 19th century that was responsible for a large influx of sediment to the entire San Francisco Bay. The YBM has a high water content (low consolidation) and a high clay and silt content. The OBM is older sediment often underlying the YBM. The OBM is highly consolidated, has a low water content, and is comprised of primarily silt, silty sand, and clay with some gravel. Generally, the OBM is not contaminated (White et al., 1994). Table 1 summarizes the physical properties of the YBM and OBM in the Richmond Harbor region as measured in the remedial investigation (RI) (White et al., 1994). Figure 6 shows the distribution of mud (combination of silt and clay size fractions) and sand in surface samples taken in 1999 and 2003, after the remedy was completed (Kohn and Gilmore, 2001; Kohn and Evans, 2004). The samples show that the surface sediment is mud-dominated with six samples containing over 50% sand. These data show that the overall composition of sediment in the Lauritzen Channel is similar to the pre-remedial conditions.

When assessing sediment properties in regions comprised primarily of fine sediment it is important to consider fluid mud. When a region has low density fine sediment, such as the YBM in the Lauritzen Channel, it is possible for fluid mud to exist. Fluid mud is unconsolidated material that can move with any movement of the overlying water, potentially leading to frequent high-volume sediment transport. Although fluid muds are not common in environments such as Richmond Harbor, the U.S. Army Corps of Engineers (USACE) conducted an investigation to verify that fluid mud was not present (Welp, 2005). This assessment indicated “soft” bottom conditions in several areas; however, no typical fluid mud characteristics were found. The USACE concluded that it is highly unlikely that fluid mud existed in the Lauritzen Channel during the study.

Table 1. Sediment property summary (data from White et al., 1994).

Location	Mean %TOC	Mean %Solids	Mean %Gravel	Mean %Sand	Mean %Silt	Mean %Clay
Lauritzen Channel (YBM)	1.91	49	6	26	25	42
Santa Fe Channel (YBM)	1.14	47	2	11	28	59
Inner Harbor (YBM)	1.14	45	0	5	32	62
Parr Canal (YBM)	5.19	45	4	24	27	34
Lauritzen Channel (OBM)	0.12	80	8	42	31	20
Santa Fe Channel (OBM)	0.23	77	1	30	37	32
Inner Harbor (OBM)	0.21	76	5	16	41	38

Sediment Accumulation

The USACE conducted an extensive dual-frequency hydrographic survey in the Lauritzen Channel to map sediment density distributions (Welp, 2005). By means of this survey, maps of YBM thickness were developed (Figure 7). The thickness of the YBM varied from less than 0.3 m to 2.5 m, with an average of 1.5 m. The thickest YBM was in the deep dredged channel adjacent to the Levin terminal while the shallower regions of the channel had relatively thin YBM layers. As the YBM layer represents more recent deposits of sediment, the map of thicknesses suggests that the dredged channel adjacent to the Levin terminal is the region of highest sediment accumulation in the channel, followed by the head of the channel as the second highest area of accumulation, and the areas adjacent to Manson Construction as the areas of lowest sediment accumulation.

The sand layer that was placed in the channel after remedial dredging was completed in 1997 potentially could serve as a marker layer to determine the amount of sediment that has accumulated since 1997. However, the sand layer was evident in only 3 of 25 cores collected in 1999 and 12 of 21 cores collected in 2007 (Kohn and Gilmore, 2001; CH2M HILL, 2008). Figure 8 shows the thickness of YBM at the 2007 coring locations; a yellow bar indicates locations where sand was found in the sediment core profile. The patchy distribution of the sand layer suggests some combination of heterogeneous placement of the sand and other sediment bed processes that could be responsible for mixing the sediment bed both vertically and laterally. It should also be noted that the sand identified at some locations in the 2007 sampling was associated with shell hash and may not be a result of the remedial activities.

The most recent bathymetric survey conducted in the Lauritzen Channel prior to the 2012 survey was in 2007. These surveys were conducted using a lower resolution single beam surveying system, and supporting detailed information regarding the survey procedures (e.g. survey equipment, benchmarks) is not available. However, a gross comparison of bathymetric change was conducted to ascertain large changes in sediment bed elevation. Although the same vertical datum (MLLW) is referenced in both surveys, there is uncertainty regarding the benchmarks and accuracy of the 2007 survey compared to the 2012 survey. Therefore, there is unquantified uncertainty in the bathymetric comparison. Figure 9 shows the changes in the channel bed elevation. Overall sediment accumulation is seen in the deep dredged channel near the Levin terminal. The shallower regions adjacent to the Manson facility show apparent sediment erosion. The head of the channel generally exhibits sediment accumulation with

some regions of erosion. Given the lack of quantifiable uncertainty, this comparison should be considered qualitative only.

Tidal Hydrodynamics

The Lauritzen and Santa Fe Channels are manmade features designed to provide low energy environments for vessel berthing. The region is further protected from San Francisco Bay by an extensive offshore breakwater designed to block any waves into the area. In low energy protected harbors such as this, regional sediments tend to accumulate in the dredged channels. The deeper dredged channels in Richmond Harbor overall have historically required periodic dredging due to the generally depositional environment.

The Lauritzen Channel is dominated by the tidal hydrodynamics of San Francisco Bay. The region experiences a semi-diurnal tide from the Pacific Ocean. The tide generally results in two high and two low tides per day with a dominant tidal period of 12.42 hours. Figure 10 shows an example of the local semi-diurnal tides. The average yearly tidal range in the harbor is approximately -0.6 to 2.1 m MLLW. Wave activity in the channel is negligible due to the offshore protection. Additionally, the narrow nature of the channels and relatively deep water negate the effects of any wave generation within the channels on hydrodynamics or sediment transport. The characteristics of the channels support the tidal dominance on circulation in the Channel.

Residence Time

Determining the movement of water particles and their residence times in a tidal system can be calculated using a few characteristic values. The residence time is the most basic calculation. The residence time (τ) is the length of time that a water parcel in the system will remain in the system. This can be calculated as:

$$\tau = \frac{P + V}{P} * T$$

Where V is the total system volume, P is the tidal prism, and T is the tidal period. The total volume of water in the Lauritzen Channel at MLLW is 277,406 m^3. The tidal prism between MLLW and mean higher high water (MHHW) is 74,138 m^3. Given a tidal period of 12.42 hrs, the residence time in the Channel is 59 hrs. This indicates that a parcel of water could remain in the Channel for approximately 2.5 days before being exchanged. For a small channel such as the Lauritzen, this is a fairly long residence time and the Channel could be considered to have low circulation.

Tidal Transport and Tidal Velocities

Given the cross sectional area at the mouth of the channel and the tidal prism, the maximum tidal velocity in the Lauritzen Channel can be calculated. Figure 11 shows the tidal flow rate at the Lauritzen Channel mouth required to transport the tidal prism during one tidal exchange. By dividing the maximum flow rate by the channel area, an average maximum velocity of approximately 1 cm/s can be calculated. Locally higher velocities can be driven by currents in the Santa Fe Channel and/or by abrupt changes in bathymetry; however, the basic analysis suggests that velocities are very low in the Lauritzen Channel.

The potential for sediment erosion and deposition can be evaluated using the velocities calculated above. To describe these processes, we use the shear stress in units of Pascals (Pa). The shear stress generated by water flowing over the sediment surface can be determined from the maximum water velocity. The critical shear stresses for erosion and deposition are the common parameters used to determine when the sediment particles are capable of eroding from or depositing to the sediment bed. When the critical shear stress for erosion is exceeded, particles erode and when the shear stress is lower than the critical shear stress for deposition, particles deposit.

For fine silt and clay such as the sediment in the Lauritzen Channel, a common screening value of 0.1 Pa is used for both the critical shear stress for erosion and deposition (Blake et al., 2007). A velocity of 1 cm/s generates a negligible shear stress; therefore, erosion due to the average tidal current is not expected. However, there is uncertainty on the potential for increased velocities in localized areas that can be investigated further in Tier 2 studies. Furthermore, the low tidal shear stresses would allow sediment particles transported into the region to settle out. The deposition rates would be particularly high in the deepest, lowest velocity areas. Combined with the long residence time (2.5 days) it is likely that particles transported into the Lauritzen Channel due to tides would have the opportunity to deposit in the channel. The low energy depositional environment is consistent with the need to periodically dredge other channelized regions in the Richmond Harbor.

Anthropogenic Processes

The Lauritzen and Santa Fe Channels are active waterways with ship and barge berthing activities and therefore experience ongoing anthropogenic activities that have the potential to affect sediment transport patterns. Additionally, anecdotal information from local vessel operators suggests that tugs pushing on barges and ships in the Lauritzen Channel provide ample scouring to prevent sediment accumulation beyond navigable depths. The key processes that will be considered here are vessel operations and outfalls. These processes are evaluated qualitatively in this Tier 1 analysis, which will be used for the basis of the design for the Tier 2 study.

Propeller Scour

The present description of vessel activity is based upon conversations with vessel and terminal operators in the area and anecdotal observations. The most common large bulk carrier vessels into the Lauritzen Channel are of the Handysize design between 40,000 and 55,000 Deadweight Tons (dwt) going to the Levin facility. The typical vessel docks and departs with two tugs. The tugs are characterized as tractor tugs. On average there are less than 12 ships per year into Levin Berth B in the Lauritzen Channel. The Levin Berth A, located in the Santa Fe Channel, is used for Panamax vessels of approximately 70,000 dwt. Approximately three of these vessels are in Berth A per year. Manson Construction Company has its main San Francisco Bay berthing and staging facility on the west side of the Lauritzen Channel. Manson generally has on the order of 6 to 10 unpowered crane and construction barges anchored with spuds in the channel. These barges are moved with tugs in the 1000 hp class. The values presented herein will be further investigated.

The high resolution survey of the navigable regions of the channel clearly shows that the vessel activities in the channels disturb the sediment in the system. Figure 12 is a satellite photo of tug and barge activity in the mouth of the channel showing a large suspended solids plume due to sediment resuspension. Figure 13 shows the regions of sediment disturbance due to both vessel scour and anchoring spuds. While these activities take place over a large region of the Lauritzen Channel and

extend throughout the Santa Fe Channel, it is important to note that the effects of both the scouring and anchoring spuds are discrete and localized. Figure 13 shows a number of profiles across some of the key features to provide some information about their dimensions. It is likely that the wide linear features are either direct scour from the large ship propellers or keel drags. A keel drag is possible for the largest scour features as the typical design draft of the Handysize ships (~ 11 m) is essentially equivalent to the scour depths. These features are on the order of 3 to 4.5 m in width and 30 cm or more in depth. There are only three to four distinct scour features, which is consistent with the relatively low ship traffic to the Levin Berth B. The smaller linear scar features often come in pairs consistent with two propellers on the typical tug used for these operations. These features are commonly less than a 1 m in width and on the order of 3 cm in depth. These observations are consistent with prop scour studies at other sites (Blake et al., 2007). The anchor spuds have a localized effect near the Manson facilities. The profiles through this area show that the zones of influence can be up to 2 m in diameter with a depth up to 0.5 m.

No evidence of scour features was seen in low tide shoreline visual surveys performed in December 2012 (CH2M HILL, 2012) or in the acoustic imagery. It is possible that the small amount of sediment present under the piers along the east shoreline and in the western shoreline areas could be resuspended by propeller scour; however, it is anticipated these volumes would be low in comparison to the sediment resuspended directly below the vessel activity.

It is evident that vessel scour and anchoring activities have a widespread and significant effect on the sediment in the Lauritzen Channel. The depths of the anthropogenically-induced mixing seen in the multibeam survey extend up to 1.4 m in depth and 5 m in width for individual events. With each individual event, the resuspended sediment over that depth has the potential to be transported before depositing. The low tidal circulation in the channel suggests that most of the sediment resuspended would disperse locally and likely settle within the channel; however, some dispersion and transport out of the Lauritzen Channel to the Santa Fe Channel is possible, particularly from the southern end of the Lauritzen Channel. The net effect of these activities is a high degree of vertical mixing of the sediment, high local dispersion, and low far-field dispersion of sediment resuspended during vessel activities.

This assessment of sediment disturbance does not take into account anecdotal accounts of intentional vessel operation to inhibit sediment accumulation through scouring which would necessarily be comprised of widespread scour and erosion. The qualitative bathymetric changes presented in Figure 9 would suggest that while the deeper east side of the channel and head of the channel is showing normal sediment accumulation, the west side of the channel could be undergoing a continuing scour due to the net effect of vessel activities.

Outfall Discharges

Outfall discharges are another anthropogenic process that could potentially affect sediment transport. The outfalls located around the perimeter of the Lauritzen Channel are generally inactive and are anticipated to have low flow rates during wet weather (CH2M HILL, 2012). The City of Richmond municipal outfall at the head of the channel, which has the largest wet weather flow rate, is a potential source of localized scour. However, examination of the geophysical survey data showed no change in morphology that typically indicates scoured sediment near the outfall. Additionally, the side scan reveals no change in sediment texture that would be associated with ongoing, episodic scour.

Sediment Transport Conceptual Site Model

A site characterization describes the physical, biological, and chemical processes at a site. The processes associated with the contaminant fate and transport are integrated and synthesized into a CSM. Development of a CSM is a fundamental step in developing a comprehensive understanding of contaminant fate and transport. At the Lauritzen Channel, where sediment-bound contaminants are the key risk factor, a sediment transport CSM is critical to addressing sediment management questions. The sediment transport CSM synthesizes all available data, describes a mass balance (i.e., a simple representation of all inputs and outputs to a system), and describes inferred sediment transport patterns (areas of deposition and erosion) based on grain size distribution, contaminant distribution, and geomorphology. The sediment transport CSM for the Lauritzen Channel presented below represents the Tier 1 CSM based on available data and provides a qualitative description that will be further quantified in the Tier 2 studies.

Sediment Transport Process Summary

The information presented in the previous sections provides individual lines of evidence regarding the behavior of the sediment in the Lauritzen Channel. This section summarizes the key points and develops a description of the general patterns of sediment transport based on the multiple lines of evidence presented.

In the absence of anthropogenic activity, the Lauritzen Channel is a low energy, constructed channel that is dominated by tidal circulation. The low tidal velocities in the channel limit any potential for sediment resuspension due to tidal currents. Generally, with the continuation of the San Francisco Bay as a primary sediment source, the channel on the whole is a sediment sink with the highest sediment accumulation occurring in the deep channel along the east side of the waterway. In the absence of anthropogenic activity, the channel would continue to fill until a dynamic equilibrium between the tides and sediment sources is achieved (Bearman et al., 2010).

The geophysical surveys show that vessel scour and spud anchoring activities have a widespread effect on mixing sediments up to 0.5 m in depth over wide swaths. It is also possible that the small amount of sediment available in under-pier and shoreline areas could be resuspended; however, these volumes would be low in comparison to the sediment resuspended directly below vessel activity. The low tidal circulation in the channel indicates that most of the sediment resuspended would disperse locally and likely settle within the channel; however, some dispersion and transport out of the Lauritzen Channel to the Santa Fe Channel is possible. It is surmised that the net effect of these activities is a high vertical mixing of the sediment, high local dispersion, and low far-field dispersion of sediment resuspended during vessel activities. The contaminant distribution pattern seen in the RI, which was characterized by over an order of magnitude decline in sediment DDT concentration with increasing distance from the Lauritzen Channel, is consistent with low net contaminant transport out of the channel (White et al., 1994).

The net effect of the vessel activity in the low energy depositional channel can be examined through two lines of evidence describing the sediment bed. Both the maps of YBM thickness (Figure 7) and bathymetric change (Figure 9) show the general accumulation behavior of sediment in the Lauritzen Channel. Both lines of evidence reveal that the largest amount of sediment accumulation is in the deepest area on the east side of the channel. The accumulation is occurring in the region where currents are likely the lowest, causing the dredged channel to behave locally as a sediment trap. Conversely, the

west side of the channel, which experiences high vessel activity in shallow regions, exhibits low to no sediment accumulation of YBM and potential erosion in the bathymetric change (Figure 9). Finally, the head of the channel with low energy shallow water and moderate barge activity shows a moderate YBM accumulation and a mix of potential erosion and deposition. Although each line of evidence has uncertainty associated with it, they are completely independent of each other and all express similar trends, thereby increasing the confidence in the overall pattern.

Since the remedial dredging and sand placement in 1996 and 1997, no dredging activities have been conducted in the Lauritzen Channel. Follow-on sampling in the channel revealed that the sand layer was not present in the majority of cores, including those where the YBM and OBM interface was present. The sampling additionally revealed that the sand distribution was heterogeneous throughout the channel. The fact that the sand, where present, is often buried to a depth of 0.5 m or more shows that there has been either deposition or downward mixing of the sand at locations throughout the channel (or both) (Figure 14). The patchy distribution of the sand could be due to some combination of inconsistent sand placement and sediment disturbance.

Contaminants, particularly DDT, can also act as an indicator of sediment movement. Contaminant patterns in the Lauritzen Channel show heterogeneity similar to the sand distribution. Figure 14 illustrates the scatter in surface sediment DDT concentrations and the distribution of contamination between the surface layer and the bottom of the YBM layer. The highest DDT concentrations are in regions of sediment accumulation in the head of the channel and the deep area on the east side of the channel. Lower concentrations are present along the west side of the channel, consistent with the thin YBM layer and potential sediment erosion in this region.

It is important to note that bioturbation can mix sediments over an interval of a few mm to about 10 cm depending upon the resident species. However, given the large-scale mixing and heterogeneity in both the vertical and lateral distribution of sediment and DDT in the channel, it can generally be considered a secondary process with respect to sediment transport.

In summary, the Lauritzen Channel is a low-energy protected region with tidal velocities that are not likely to result in resuspension. The low energy coupled with sediment input from San Francisco Bay result in a net sediment accumulation in the channel. Ongoing vessel operations in the channel are responsible for localized mixing of the sediment bed, resuspension, and redistribution of sediment within the channel. A portion of the resuspended material may also be tidally dispersed into the Santa Fe Channel. Figure 15 graphically summarizes the key sediment transport processes. The net effect of these processes on sediment and contaminants in the channel are a heterogeneous distribution of contaminants with generally higher concentrations in areas of higher sediment accumulation.

Conceptual Sediment Budget

A sediment budget is developed to account for the external inputs, outputs, and storage of sediment in a region due to the net effects of all of the sediment transport processes. The budget provides a useful tool for accounting for sediments and evaluating the effects of any changes to the system. Essentially the sediment budget is described by:

$$Sediment\ Input - Sediment\ Output = \Delta Sediment\ Storage$$

At a contaminated site in particular, the sediment budget provides the basis for accounting for contaminated sediment movement into and out of the system and storage within the system. The goal of the conceptual sediment budget here is to identify the external inputs and outputs of sediment to the system and identify potential methods for quantifying these processes. It is important to note that processes such as propeller scour can significantly alter deposition and erosion patterns within the system while the external exchange of sediment between the channel and the estuary remains unchanged.

The key external sediment inputs to the Lauritzen Channel are the tidal delivery of sediment from San Francisco Bay and upland runoff during wet weather (this will be verified as part of the Tier 2 study). The bay provides a constant delivery of silt and clay to the margins, including harbors. The sediment source is generally lowest in the summer and highest in the winter (Schoellhamer, 1996). Determining tidal fluxes of sediment into any water body is generally accomplished through some combination of field measurements of sediment flux, empirical modeling, and numerical modeling. The delivery of sediment from upland sources is primarily due to the municipal stormwater outfall at the head of the channel. Data are not readily available on the yearly flow and associated sediment load associated with the outfall; however, efforts will be made in Tier 2 to further assess the need for these data in the sediment budget and determine if the magnitude is significant. Figure 16 summarizes the key sources to be quantified as part of the Tier 2 sediment transport study. Qualitative indicators suggest the tidal delivery of sediment is the largest order of magnitude external sediment source to the region. Data from the Richmond Harbor suggest this external sediment source is below levels of concern for all contaminants of concern.

Indicators evaluated in this study show that the head of the Lauritzen Channel is a region of consistent sediment deposition; however, sediments in this region still have elevated levels of DDT and Dieldrin. While the San Francisco Bay does represent the largest external source of sediment, the persistence of high contamination in the channel is most likely due to a combination of incomplete removal during remedial activities, anthropogenic resuspension, and secondary sources (e.g. nearshore regions, outfalls). Ongoing sampling activities are being conducted to better characterize these processes.

The sediment outputs are the net result of suspended sediment in the channel that can be transported out by the tide. The key resuspension processes that have been identified are the vessel operations. As discussed, the props, keels, and anchor spuds of vessels may cause localized resuspension. Another source of suspended sediment in the system is suspended solids from outfalls during storm events. Although much of this material is likely to accumulate locally in the Lauritzen Channel, DDT contamination in the Santa Fe Channel suggests that tidal dispersion and transport of sediment resuspended in the channel occurs.

By summing the inputs and outputs of sediment over any given time, a change in sediment storage can be determined. A common method for accounting for the change in sediment volume in a harbor is through the dredging records. Often the average amount of sediment removed periodically for maintenance dredging can provide a direct measure of these volumes. Bathymetric change is another method of estimating the net volumetric change in sediment storage in a harbor. Although only sparse datasets are available at present for these types of analyses, these data sources are being thoroughly evaluated for quantitative analysis in the Tier 2 sediment transport analysis.

Sediment Management Questions

This document developed a Tier 1 sediment transport CSM for the United Heckathorn Superfund Site. The Tier 1 CSM has been used address the following sediment management questions:

- What is the source(s) of the sediment accumulating in the Lauritzen Channel?

The tidal transport of San Francisco Bay sediment into the low energy Lauritzen Channel provides an ideal environment for deposition of bay sediment. The supply of sediment from the bay and the controlled nature of any other outfalls into the Lauritzen Channel indicate that the bay is the primary source of accumulating sediment.

- How does sediment transport lead to the redistribution of contamination within the Lauritzen Channel, or movement of contamination out of the channel?

Vessel activity is the primary source of resuspension in the Lauritzen Channel. The low energy environment of the channel allows this material to disperse and settle locally which can lead to redistribution of contamination within the channel. Some portion of the material resuspended, particularly during an ebb tide, can be transported out to the Santa Fe Channel and deposited.

- If part of the Lauritzen Channel is actively remediated, could sediment transport lead to the recontamination of the remediated area?

If high contaminant concentrations remain in locations that could be disturbed by anthropogenic activities, they could be redistributed to actively remediated areas.

Conclusions and Recommendations for Tier 2 Evaluation

The Tier 1 sediment transport CSM for the United Heckathorn Superfund Site revealed several areas where improved data and analysis will provide more comprehensive answers to the sediment management questions. The goal of a Tier 2 evaluation is to address the management questions with a higher degree of certainty using targeted, site-specific data and more sophisticated data analysis methods guided by Tier 1 investigation. The following analyses are recommended to further describe the sediment transport processes identified in this report.

The magnitude and frequency of sediment resuspension and transport due to anthropogenic processes should be quantified to accurately determine the potential for sediment accumulation, contaminant redistribution, and potential for recontamination; and to support the development of effective remedial alternatives in the FFS.

The following field activities are recommended to provide the necessary data for the transport quantification:

- Deploy current meters with optical backscatter sensors to measure profiles of velocity and proxies for total suspended solids (TSS) at two locations.
    - Location one - central location in the mouth of the Lauritzen Channel to address net sediment transport into and out of the channel

    - Location two - the northern end of the channel in areas of no vessel activity to evaluate currents and suspended solids to determine sediment accumulation
- Collect channel velocity and TSS measurements during instrument deployment to determine sediment flux throughout the channel throughout the tidal cycle.
- Collect erosion rate measurements and develop a spatial picture of sediment erosion properties to better understand the potential for future sediment mixing, erosion, and transport. A series of sediment cores will be collected in areas of high, moderate, and low sediment accumulation for sediment erosion (Sedflume) analysis to characterize erosion potential of sediments as follows:
    - In areas of typical tug and barge movements
    - In the relatively undisturbed northern end of the channel
    - Under typical and storm conditions
- Deploy and monitor sediment tracers in an area of high vessel activity to assist in quantifying sediment transport due to the activity. The Tier 1 analysis hypothesized transport of sediment from high vessel activity areas to high accumulation areas within the Lauritzen Channel and potentially out of the channel.
- Collect sediment cores in the regions of high, moderate, and low sediment accumulation identified in the Tier 1 analysis and analyze samples for DDT to validate sediment contaminant distribution patterns and establish temporal trends in contaminant transport.
- A marker bed composed of feldspar or a similar material could be deployed in areas isolated from vessel activity (e.g. at the head of the Lauritzen Channel) to determine the magnitude of sediment accumulation and the quality of the sediment after the municipal storm drain system has been cleaned of residual sediment. A marker bed is not planned as part of the Tier 2 investigation because it could not be deployed until after the municipal storm drain system is cleaned, and it would need to be deployed for at least one year to capture seasonal variations.

In addition to the recommended field activities, further analytic activities are recommended as part of the Tier 2 analysis to support the quantification of the sediment and contaminant transport processes. The following analytic activities are recommended:

- Determine erosion potential using accepted models of propeller scour, and quantify sediment mixing depths and volumes during typical vessel operations using the bathymetric, sediment erosion, and suspended solids data for model calibration and validation.
- Develop a sediment flux analysis to determine offsite transport and potential recontamination within the Lauritzen Channel based on the field data. The flux analysis will provide a key input to a quantitative mass balance of sediment and contaminant transport (Wall et al., 2006).
- Modeling of resuspension, transport, and deposition in the area using the Environmental Fluid Dynamics Code (EFDC) will be performed determine spatial and temporal patterns of sediment and contaminant transport in the Lauritzen and Santa Fe Channels. The model will be used to:
    - Facilitate the extrapolation of long term tidal sediment fluxes to examine long term recovery impacts of various remedial scenarios
    - Examine natural deposition patterns to be expected from the estuary for future recovery

- Determine transport and deposition patterns of material resuspended during various anthropogenic events
- Conduct deeper examination of sediment and DDT mass balances
- Examination of spatial variation in residence time in channel in support of remedial evaluation

The quantitative model coupled with the analysis of the field data will be used to refine the CSM and answers to the sediment management questions. An updated quantitative sediment and contaminant fate and transport CSM will guide the remedial alternative development and analysis in the FFS.

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Figures

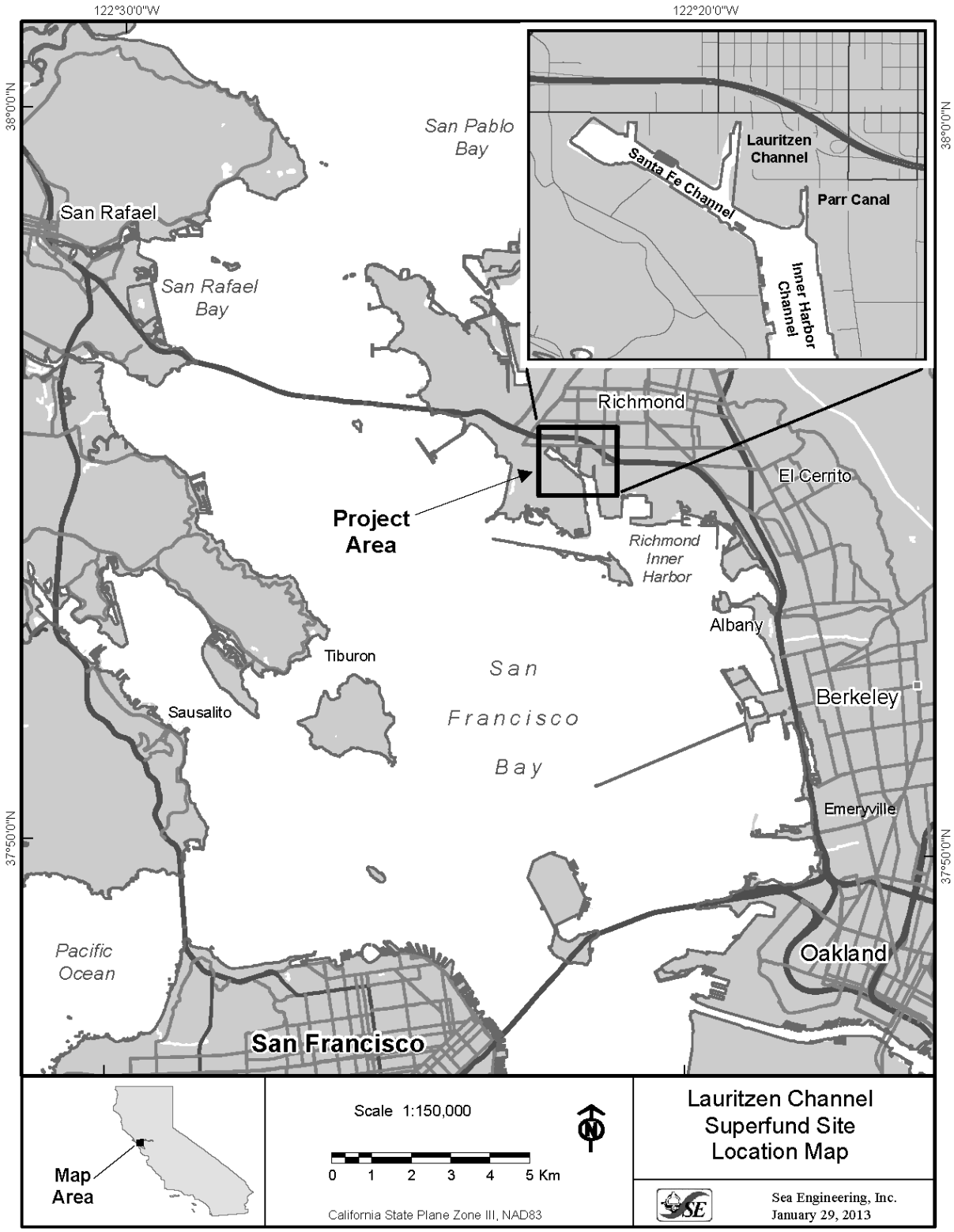

Figure 1. Location of Richmond Harbor.

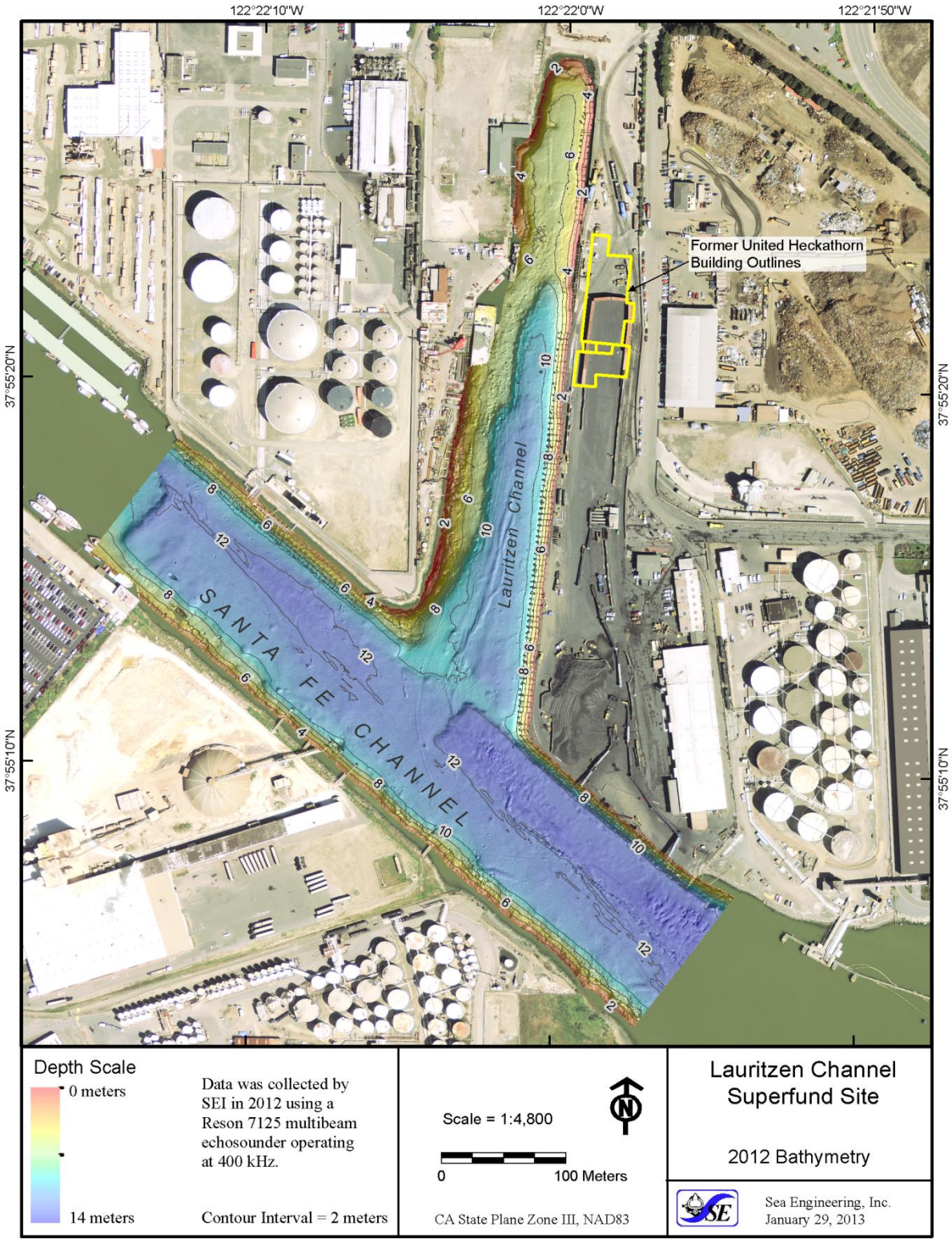

Figure 2. Bathymetry map of the Lauritzen Channel and portions of the Santa Fe Channel.

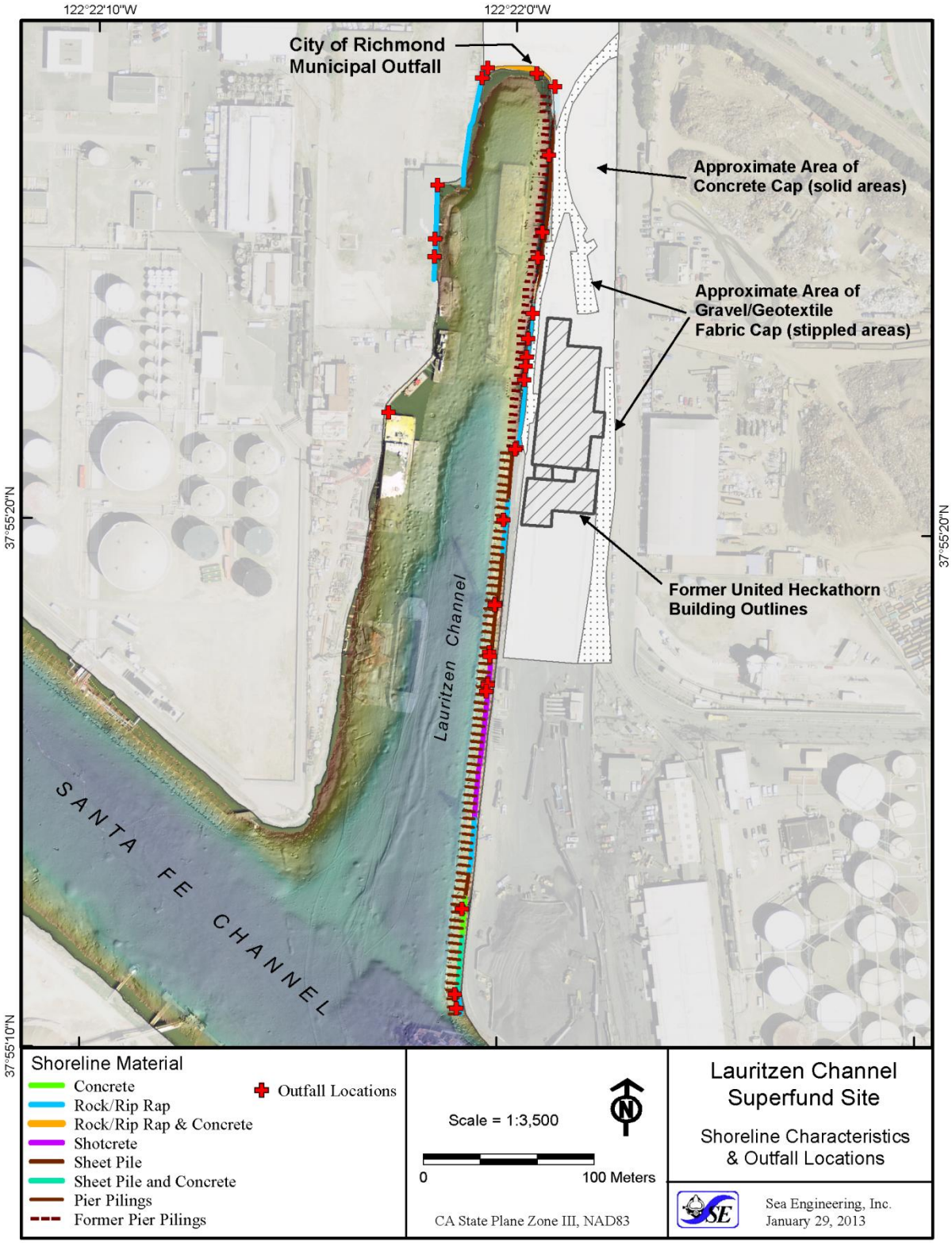

Figure 3. Shoreline characteristics and outfall locations.

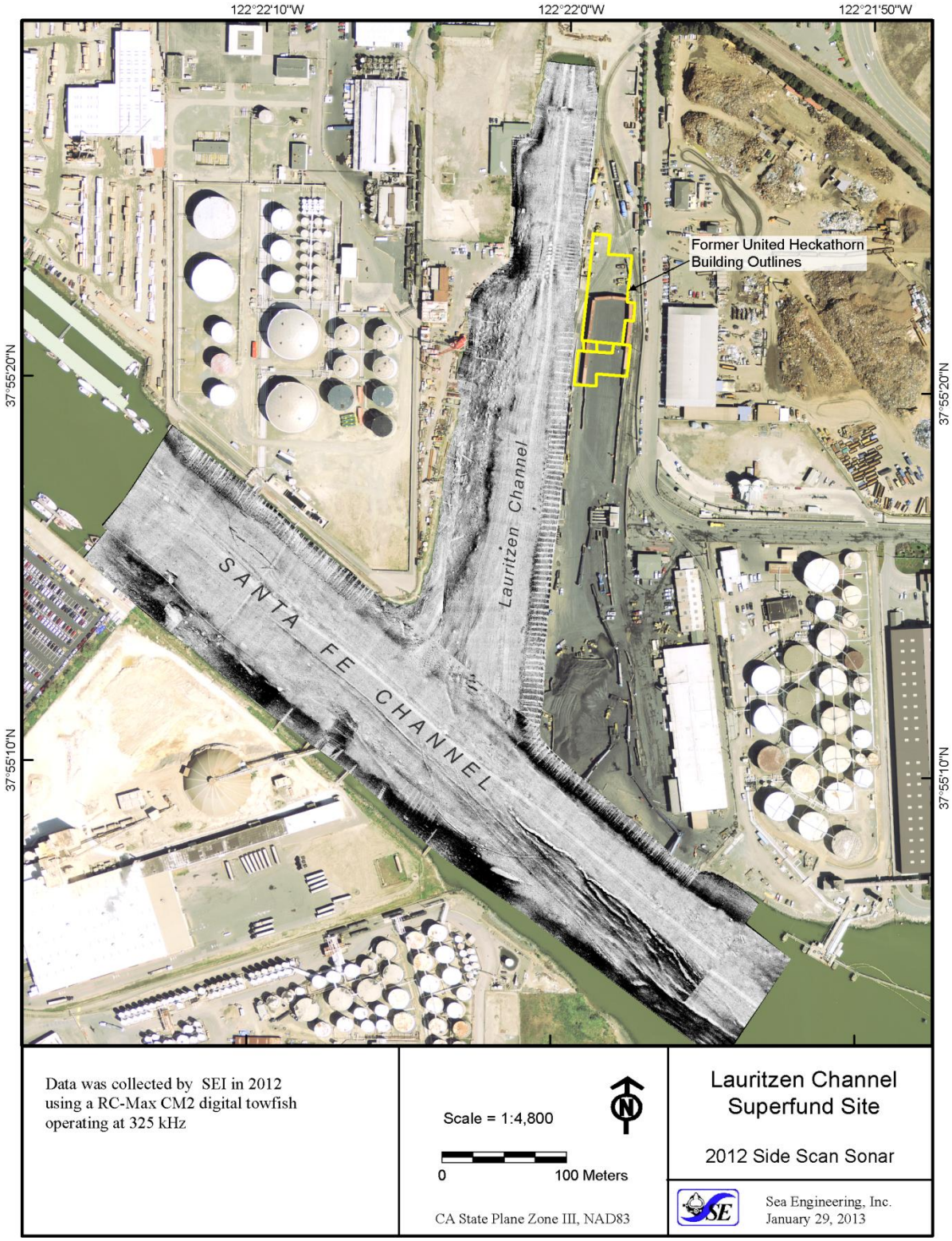

Figure 4. Sidescan survey map of the Lauritzen Channel.

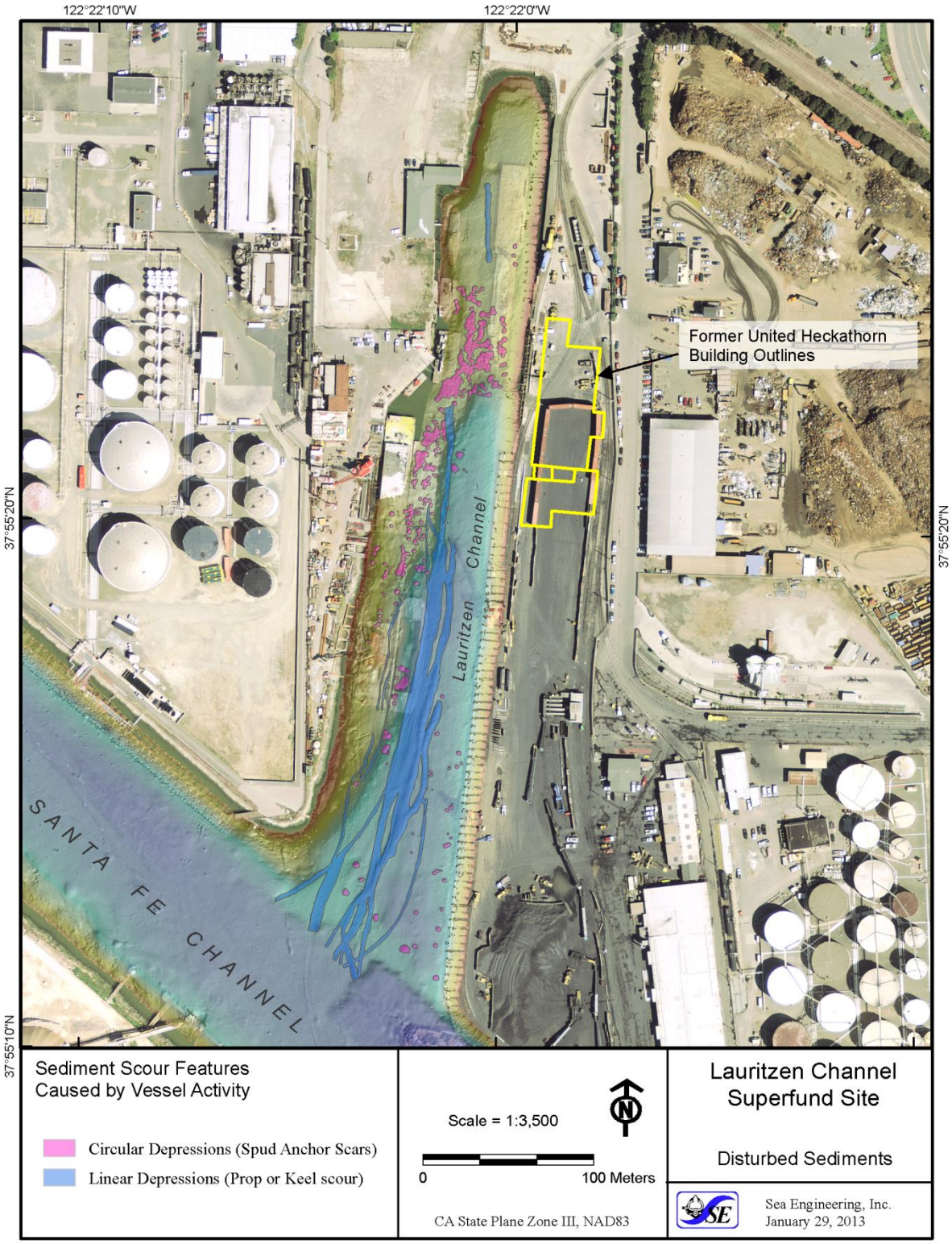

Figure 5. Map of areas of sediment disturbance.

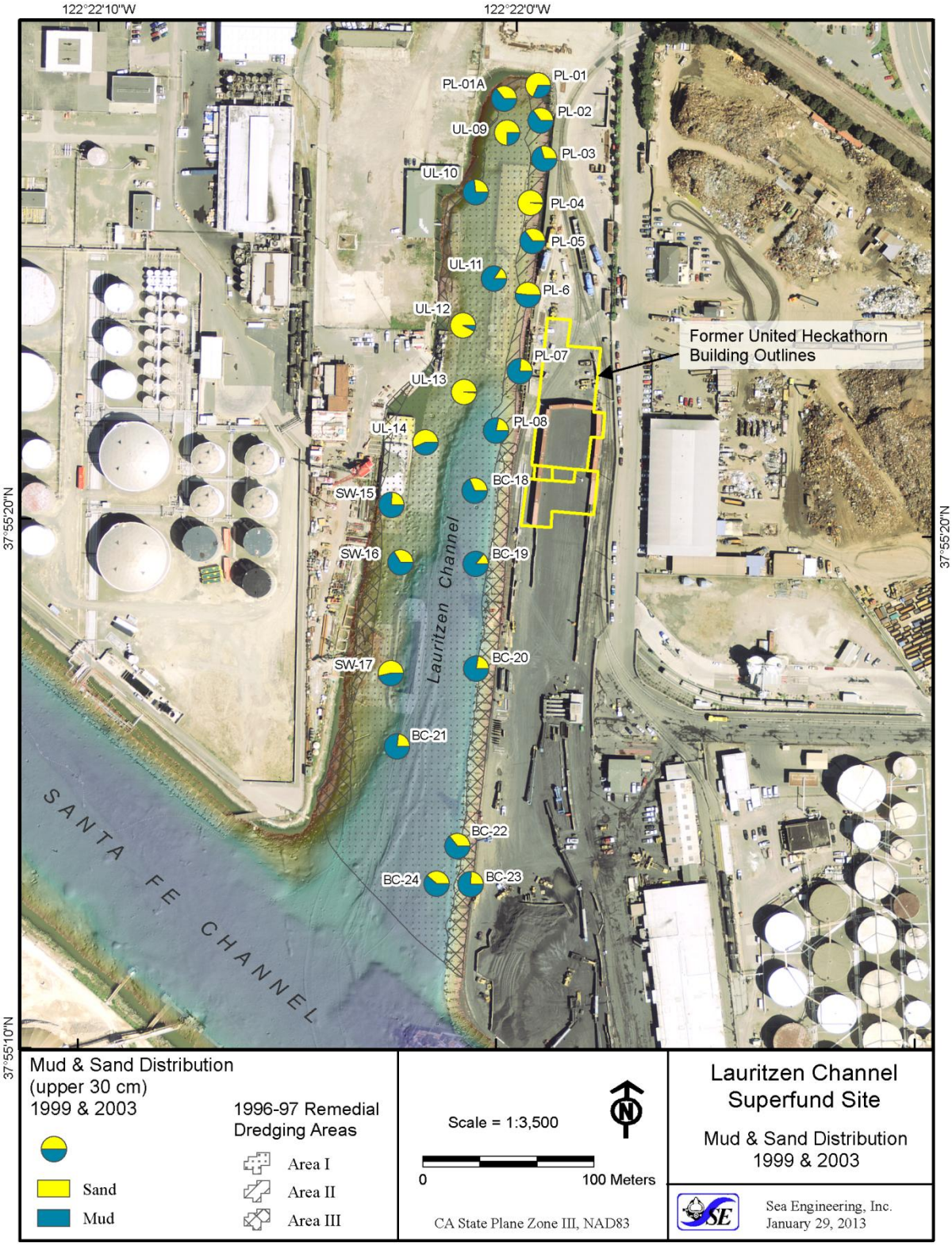

Figure 6. Mud and sand distributions in surface samples of the Lauritzen Channel.

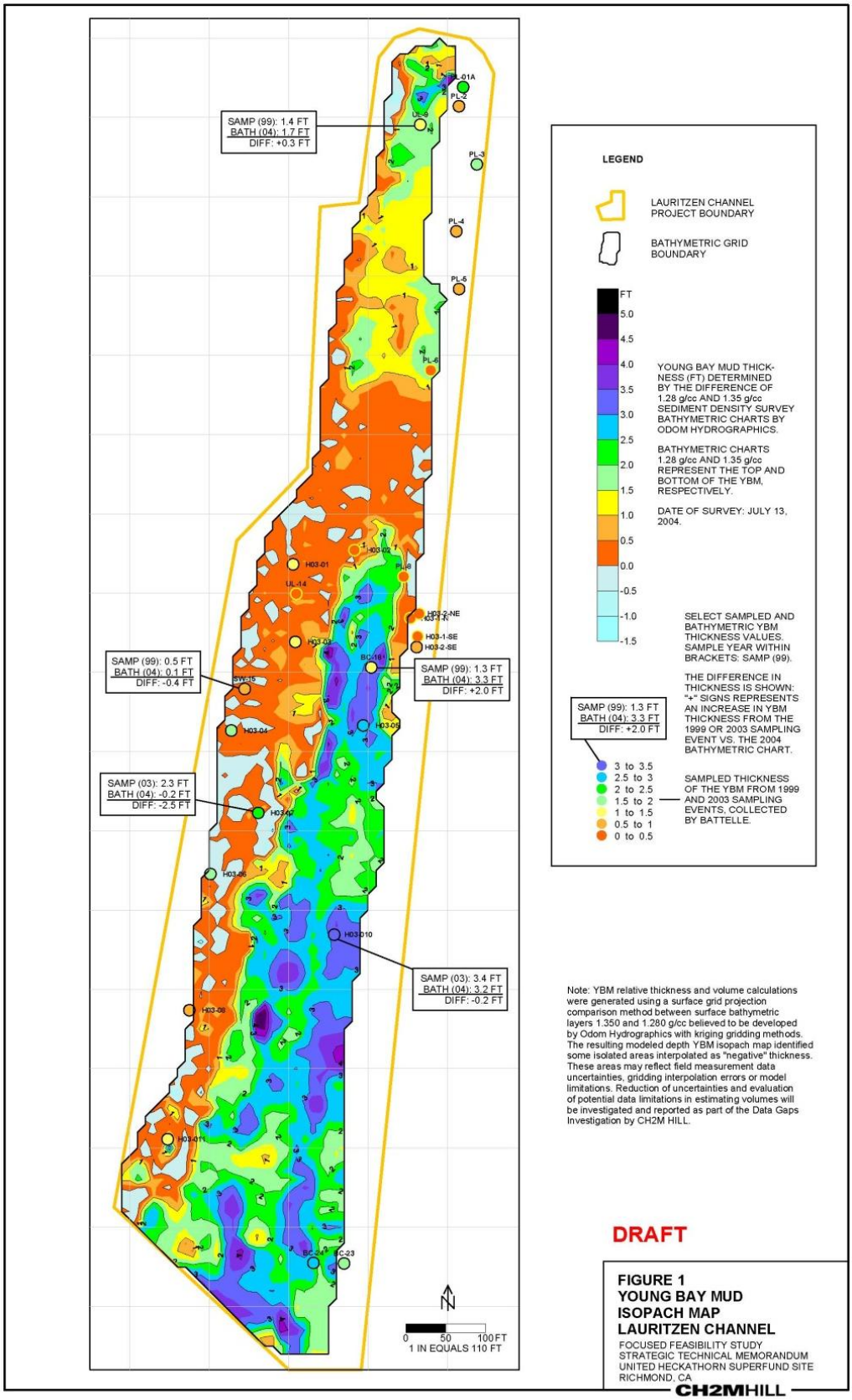

Figure 7. Map of young bay mud thickness in the Lauritzen Channel (Welp, 2005; CH2MHILL, 2006).

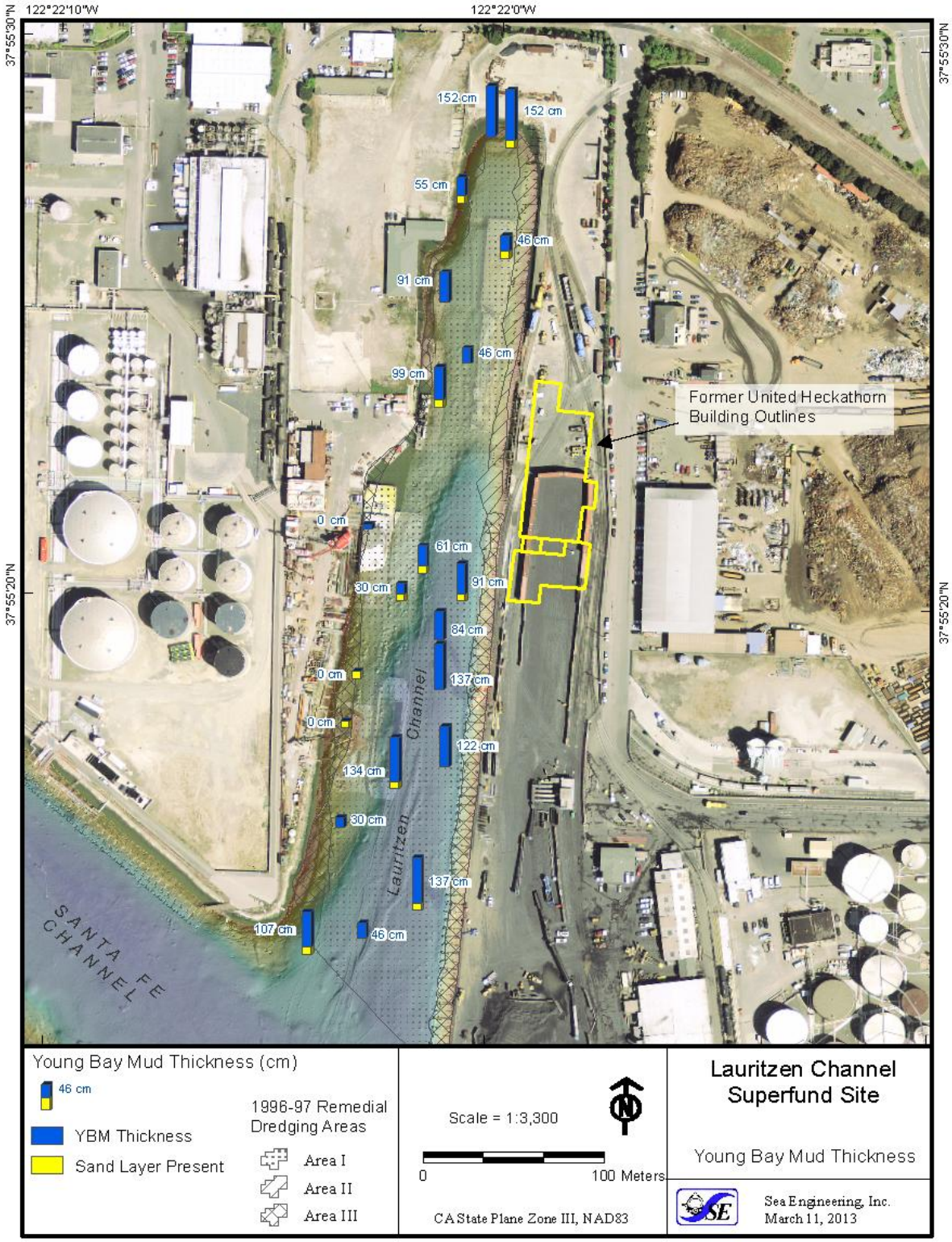

Figure 8. Map of young bay mud thickness and sand where present in 2007 coring.

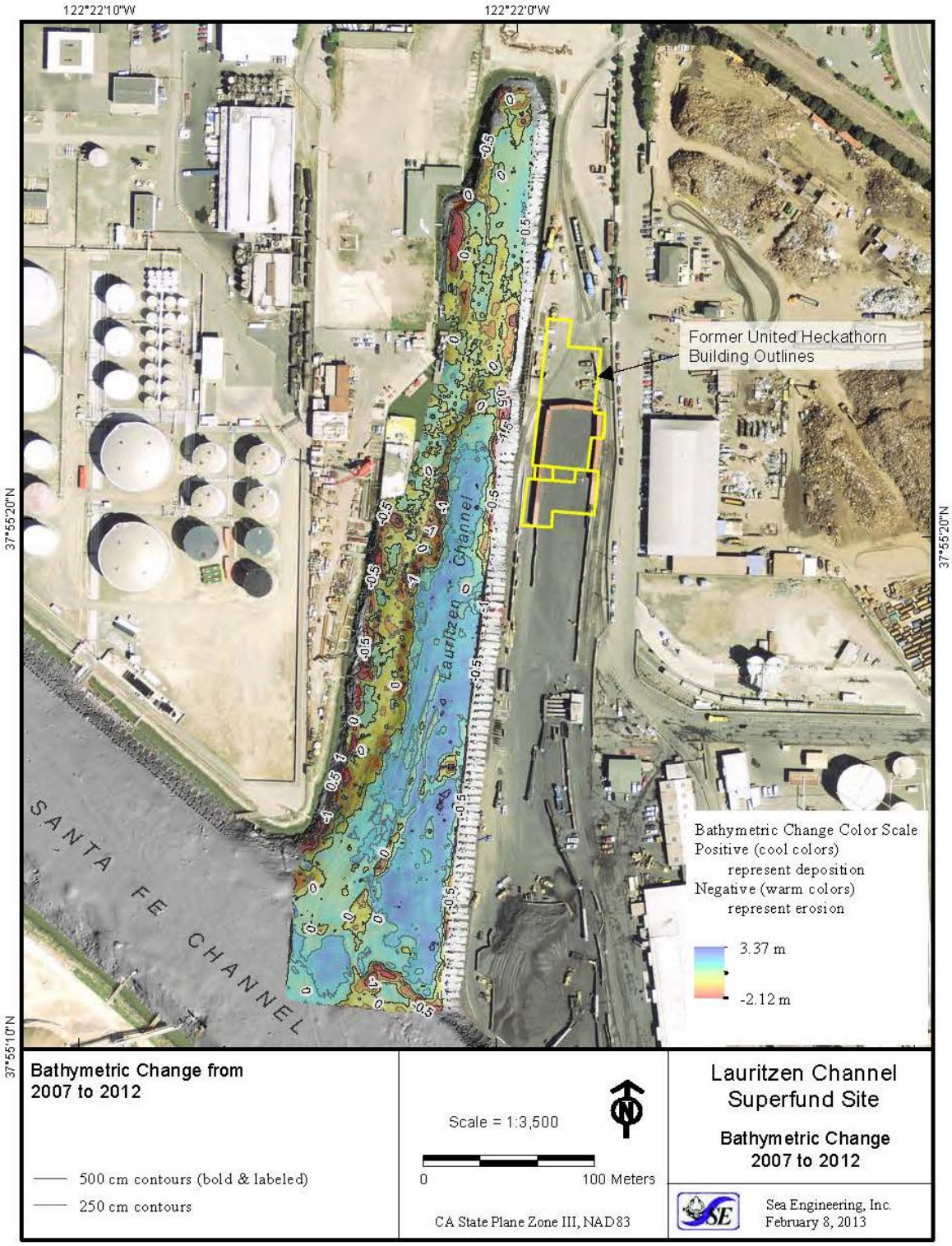

Figure 9. Bathymetric change between the 2007 and 2012 surveys.

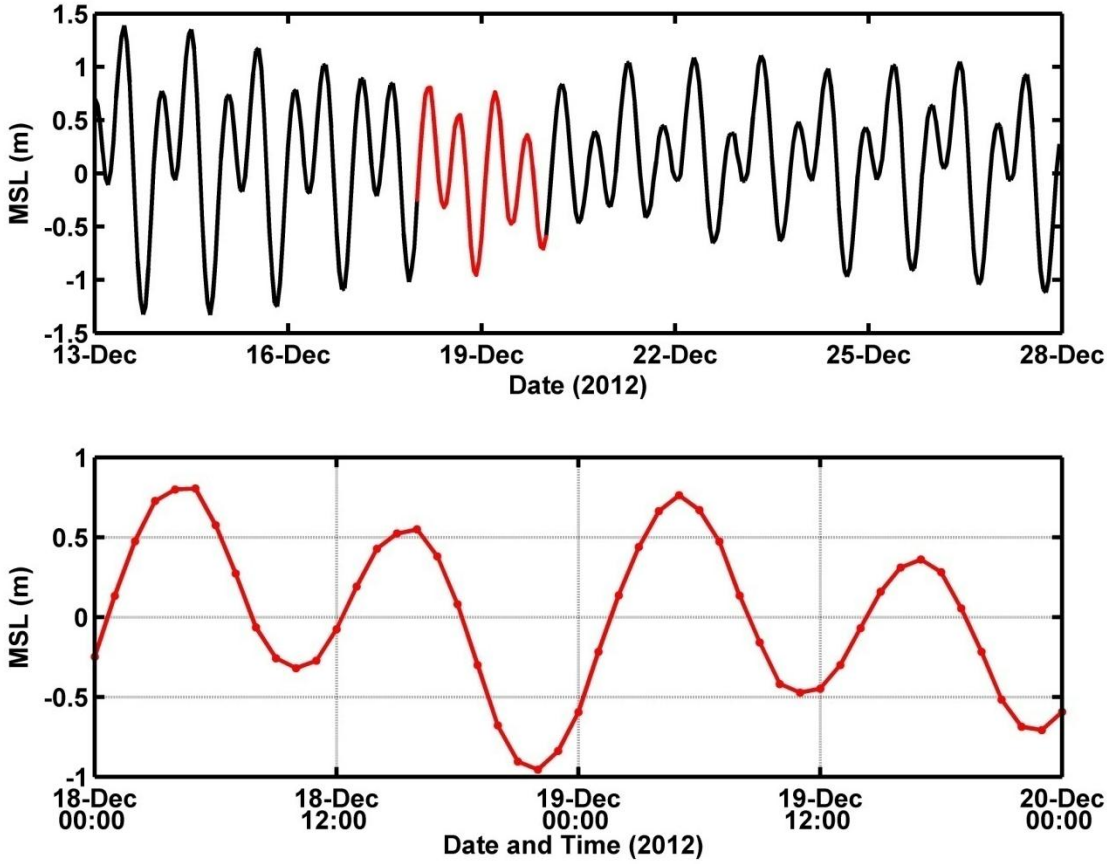

Figure 10. Example tide for the outer Richmond Harbor.

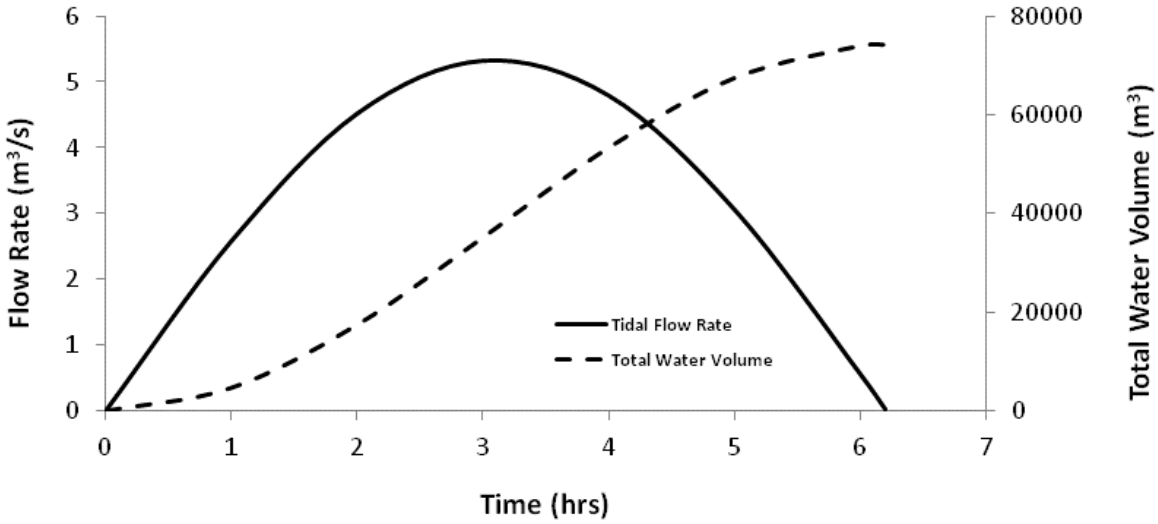

Figure 11. Tidal flow rate and cumulative water volume exchanged during a tide change.

Figure 12. Satellite photo showing sediment plume during tug and barge activity (October 2011, Google Earth).

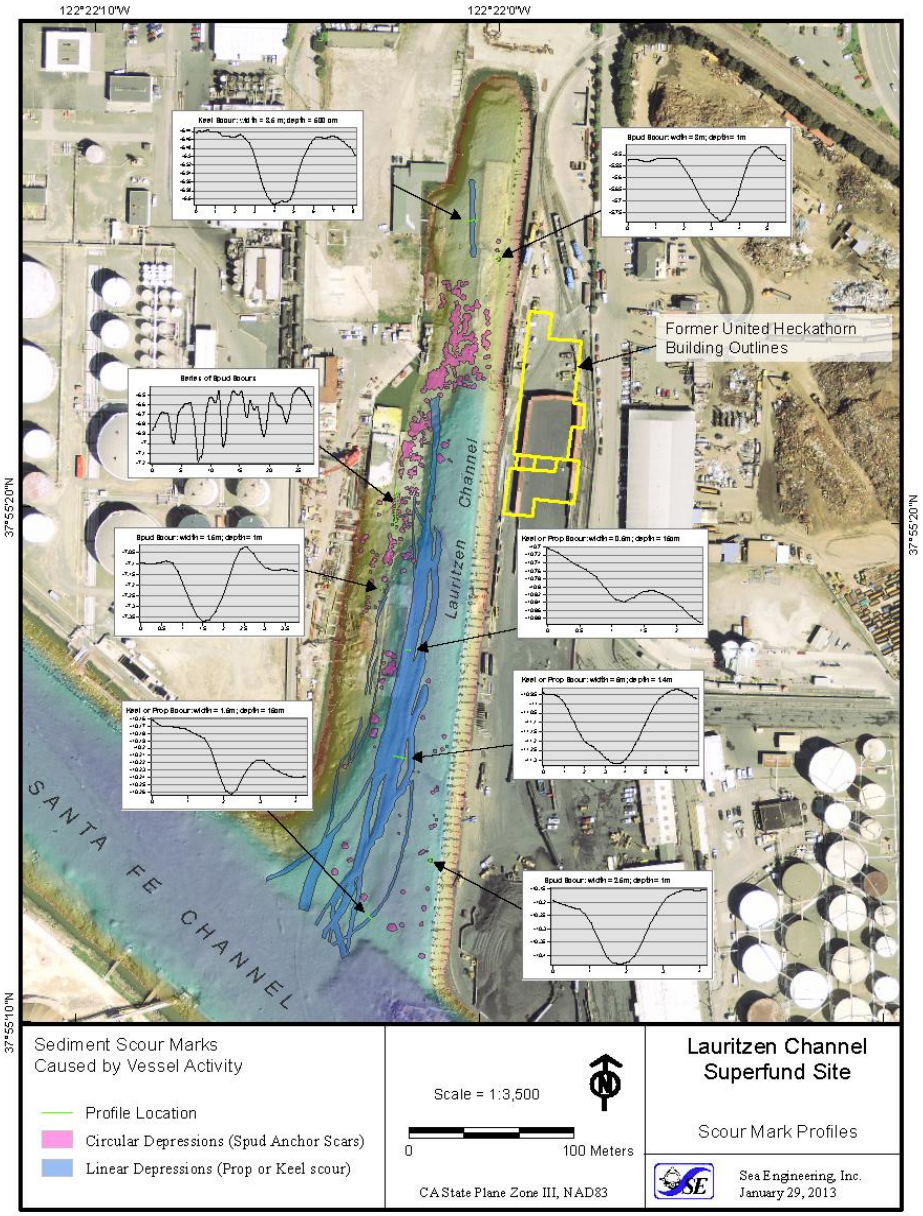

Figure 13. Profiles of vessel and spud disturbance at the sediment bed.

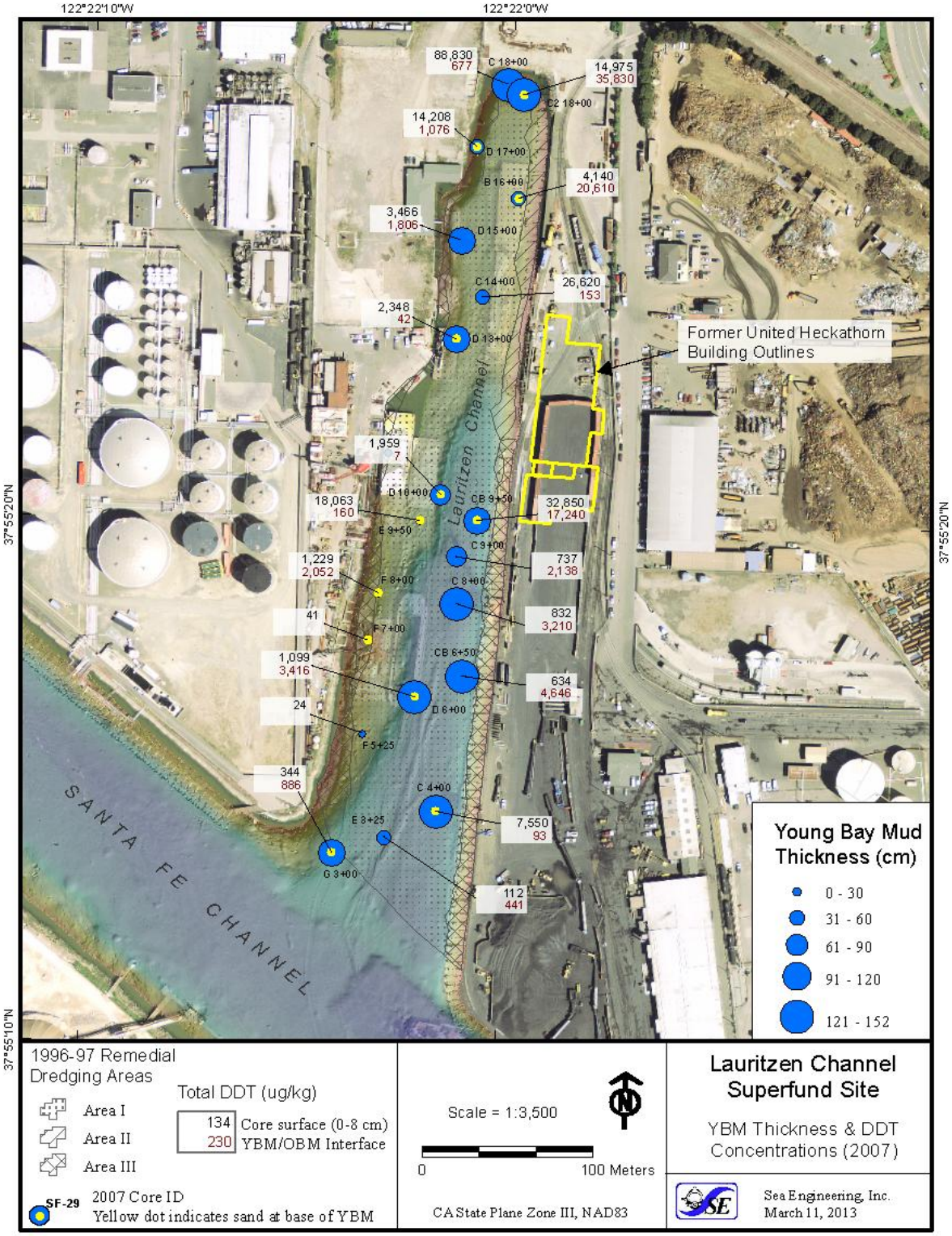

Figure 14. Map of YBM surface and interface DDT concentrations, thickness of YBM, and sand presence.

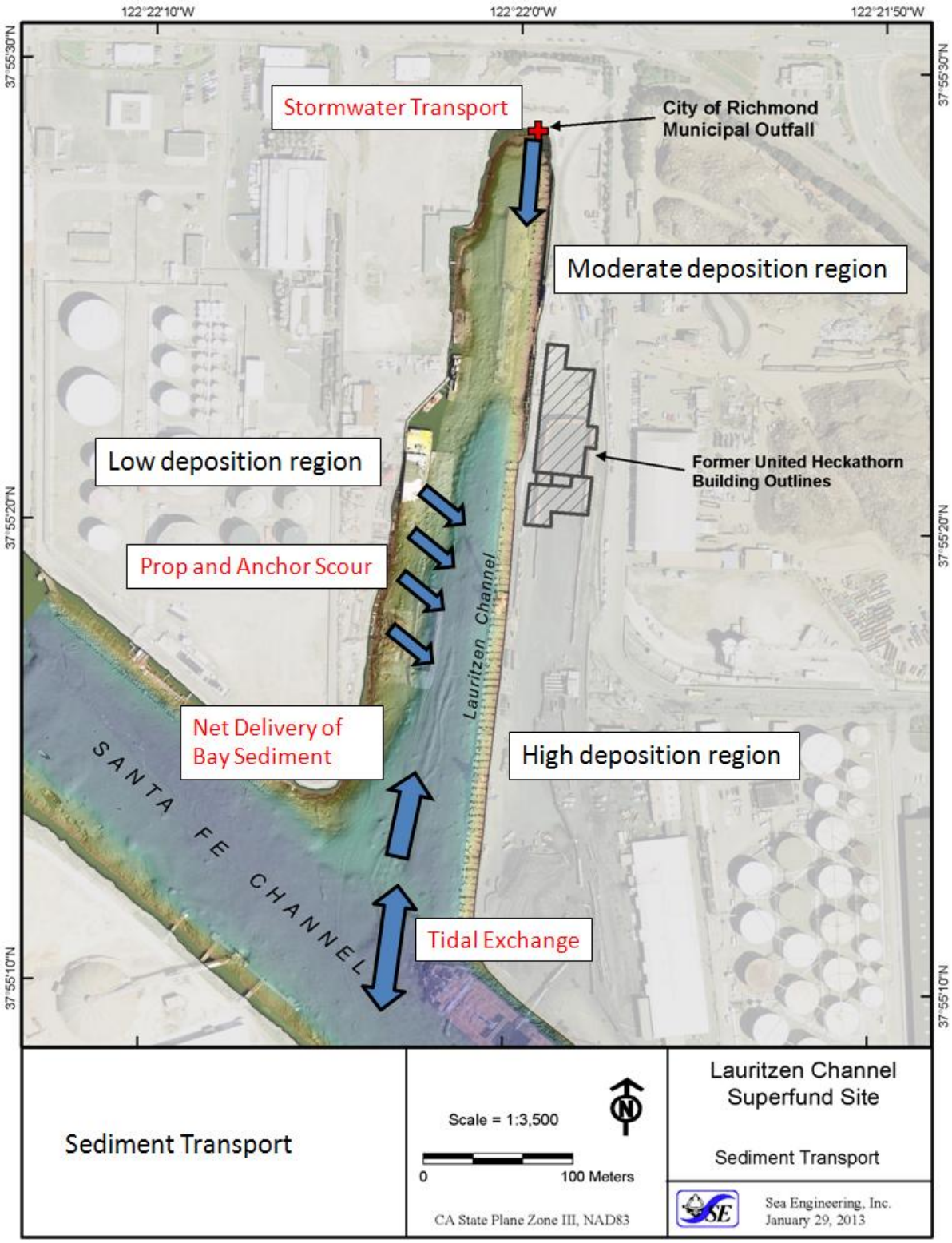

Figure 15. Sediment transport process summary.

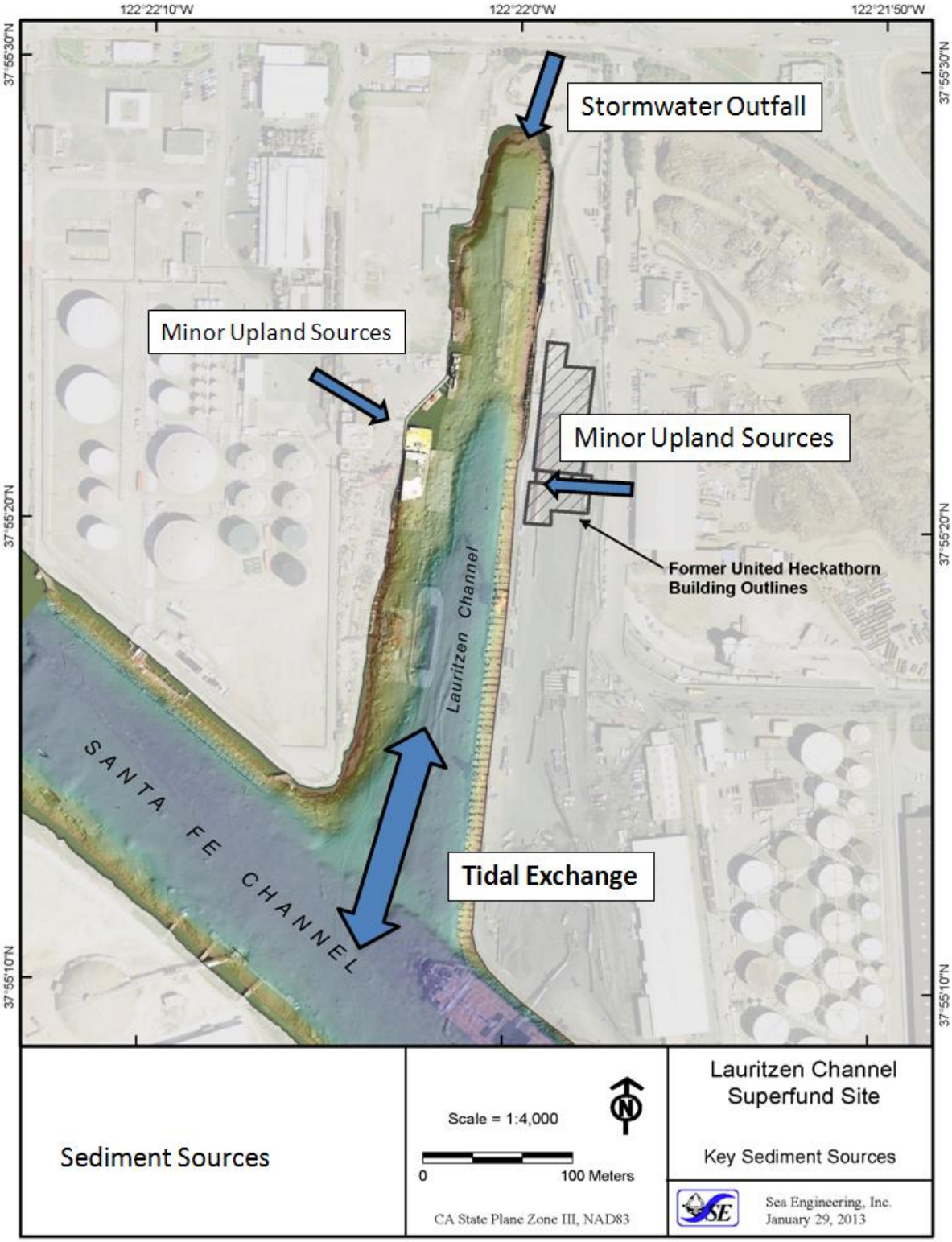

Figure 16. Key sediment sources to the Lauritzen Channel.