Refugio Beach Oil Spill Shoreline Oil Exposure Quantification Technical Report

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Prepared By:

Zachary Nixon

Research Planning, Inc.

Prepared For:

California Department of Fish and Wildlife

Office of Spill Prevention and Response

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Introduction

On 19 May, 2015, a 24-inch pipeline owned and operated by Plains All America Pipeline ruptured near Refugio State Beach in Santa Barbara County, California. The section of pipeline where the release occurred runs approximately 18 kilometers (km) between Gaviota, CA and the Exxon Mobil facility at Las Flores Canyon and was carrying crude oil. The spilled oil ran down a storm drain and into a culvert under the freeway, entering the Pacific Ocean where it was primarily transported east and southeast along the Pacific coast of California. While some of the spilled oil that reached the ocean was recovered or dispersed at sea, some portion of this oil was stranded on the shorelines of Santa Barbara, Ventura, and Los Angeles Counties. Shoreline surveys, cleanup, and response took place over the following weeks and months as part of the Unified Command (UC) with most of the active cleanup concluding by August 28, although active response and cleanup activities continued into January 2016.

As part of the effort by the Natural Resource Trustees to quantify injury to shoreline habitats and other intertidal resources from the Refugio Beach Oil Spill (RBOS) for the purpose of Natural Resource Damage Assessment (NRDA), it was necessary to estimate the total shoreline exposure to spilled oil within various habitat, oiling, and other categories relevant to injury assessment. As such, the Natural Resource Trustees compiled and integrated available observational shoreline oiling data, and other relevant data, into a consistent database suitable to quantify this shoreline exposure using multiple metrics. This document describes the data sources and methods used to assemble this database, and briefly summarizes subsequent estimates of shoreline exposure. Appendix A provides detailed descriptions of individual shoreline oiling exposure summary data products, including formats and data dictionaries, for the individual components of the database.

Shoreline Oiling Data Sources

The primary sources of surface shoreline oiling information used for this analysis are the Shoreline Cleanup Assessment Technique (SCAT) data and additional survey data collected by California Department of Fish and Wildlife, Office of Spill Prevention and Response (OSPR) and United States Coast Guard (USCG) personnel in Los Angeles County (referred to hereafter as LACO surveys). SCAT data (NOAA OR&R, 2014) are collected by teams consisting of Federal, State, local, and responsible party representatives, conducting field surveys to document the location, degree, and character of shoreline oiling using standard methods and terminology. These data extend from Gaviota State Park, approximately 13 km west of the spill site, to the inlet to Mugu Lagoon at Naval Air Station (NAS) Point Mugu, approximately 100 km east of the spill site. Some gaps in SCAT survey coverage exist in the vicinity of Carpinteria and Ventura, the interiors of Ventura and Port Hueneme harbors, as well as restricted areas within NAS Point Mugu. The LACO survey data (Gibson, 2016) were collected by joint OSPR/USCG teams and were intended to survey additional oiling in Los Angeles County which had unclear provenance at the time of the incident. These data extend from the Ventura-Los Angeles County border in the northwest to the southern extent of Torrance Beach in Malaga Cove in the southeast. Some small gaps in LACO survey data coverage exist along Malibu Beach. There is also an approximately 15 km gap between the southeastern extent of the SCAT data at NAS Point Mugu and the northwestern extent of LACO survey data at the Ventura-Los Angeles County border.

In both data collection efforts, surface oiling conditions are documented via linear “zones” with consistent surface substrate oiling and other characteristics, including no oil observed, and defined along specific alongshore extents of the shoreline. These surface oiling zones are defined only for a specific date, and, for SCAT data, may overlap in in space and time. These oiling zones are distinguished from SCAT *segments*, which are fixed non-overlapping portions of the shoreline used for operational progress tracking. Multiple distinct bands of oiling with different characteristics present at the same shoreline location at different tidal elevations were mapped as zones overlapping alongshore for response purposes. For SCAT surface oiling data, detailed characteristics (Figure 1) describing the dimensions and nature of oiling within each zone were recorded, and the start and stop locations of each zone were recorded with a consumer-grade GPS unit. Most critically, these metrics include distribution or percent cover of oil or oiled material within a zone, the across-shore width of the zone, the thickness of oil within a zone, the character of oil within a zone, and the tidal elevation of the zone, per NOAA SCAT protocol (NOAA OR&R, 2014). For the LACO survey-derived surface oiling data, a simpler set of characteristics describing the dimensions and nature of oiling within each zone were recorded within predefined start and stop locations for each zone. For the LACO survey data, these metrics included the distribution or percent cover of oil or oiled material within a zone, and the tidal elevation of the zone.

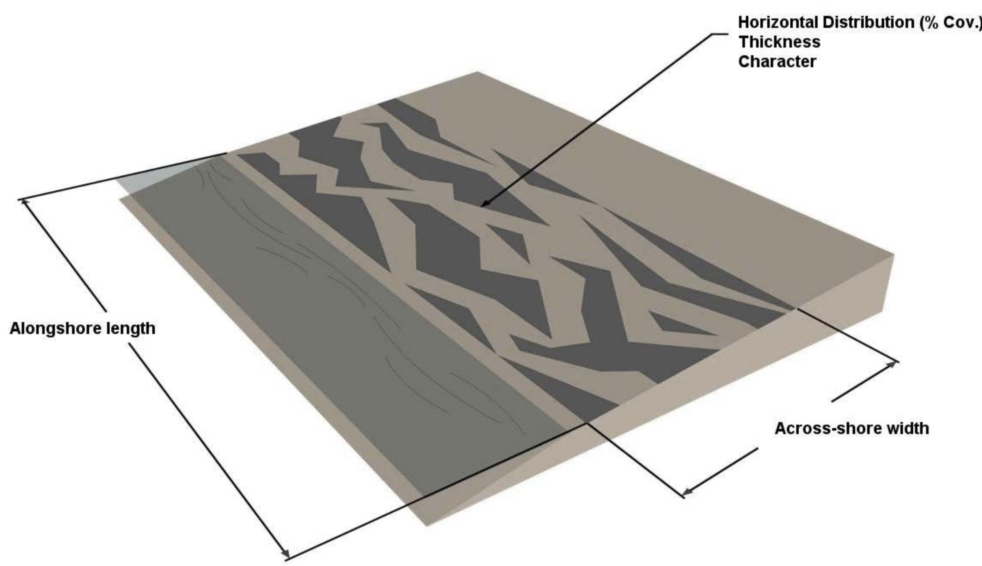

Figure 1. Schematic of observational metrics used to describe surface oiling along linear portions of a shoreline.

To enable simple comparisons of surface shoreline oiling with a wide variety of possible values of the various observational oiling metrics at different locations and times, surface oiling zones collected as part of SCAT during RBOS were assigned a categorical descriptor. For RBOS, as in other spills, this assignment was performed using a set of lookup matrices, and was done separately for continuous oiling and for tarball oiling where discrete counts of tarballs are recorded. Table 1 below describes the set of matrices used for non-tarball oiling according to the SCAT protocol used for the RBOS incident. The three metrics required to assign a given surface oiling observation to a categorical descriptor using this matrix are areal distribution or percent cover, oil thickness, and the width of the zone across-shore. Table 2 below describes the matrix used for tarball oiling according to the SCAT protocol used for the RBOS incident. The two metrics required to assign a given surface tarball oiling observation to a categorical descriptor using this matrix are tarball density and average size. The LACO survey-derived data did not include metrics sufficient to assign oiling category for either continuous or tarball oiling.

Table 1. Two-stage matrix used to assign categorical oiling descriptors to continuous (non-tarball) surface oiling zones based upon distribution, thickness in centimeters (cm), and across-shore width.

	Across-shore Band Width			
Oil Dist.	**Wide >6 m**	**Medium 3 - 6 m**	**Narrow 0.5 - 3m**	**Very Narrow < 0.5 m**
Continuous > 90%	Heavy	Heavy	Moderate	Light
Broken 51-90%	Heavy	Heavy	Moderate	Light
Patchy 11-50%	Moderate	Moderate	Light	Very Light
Sporadic 1-10%	Light	Light	Very Light	Very Light
Trace < 1%	Trace	Trace	Trace	Trace

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	Initial Categorization			
Average Oil Thickness	**Heavy**	**Moderate**	**Light**	**Very Light**
Thick/Pooled >1 cm	Heavy	Heavy	Moderate	Light
Cover 0.1-1.0 cm	Heavy	Heavy	Light	Light
Coat 0.01-0.1 cm	Moderate	Moderate	Light	Very Light
Stain/Film <0.01 cm	Light	Light	Very Light	Very Light

Table 2. Single-stage matrix used to assign categorical oiling descriptors to tarball surface oiling zones with discrete counts based upon tarball density and size.

	Tarballs per square meter			
Average Tarball Size	**High > 100**	**Medium 10 - 100**	**Low 1-10**	**Very Low < 1**
Large > 10 cm	Heavy TB Oiling	Heavy TB Oiling	Heavy TB Oiling	Light TB Oiling
Medium 1-10 cm	Heavy TB Oiling	Heavy TB Oiling	Moderate TB Oiling	Light TB Oiling
Small < 1 cm	Heavy TB Oiling	Moderate TB Oiling	Light TB Oiling	Negligible TB Oiling

The tabular attributes for SCAT data were stored in a Microsoft Access database and spatial data describing the location of shoreline, segments, zones, and pits were stored in an ESRI File Geodatabase. The LACO survey data were stored as an ESRI shapefile with all tabular attribute data contained as part of the shapefile.

Quality Assurance/Quality Control

All SCAT and LACO survey data collected during the response were subjected to manual and automated Quality Assurance/Quality Control (QA/QC) processes before use in shoreline exposure estimation. For the SCAT data, linear features representing surface oiling zones stored as line features in the accompanying ESRI File Geodatabase intended for use in GIS were inspected for topological integrity. Topological issues with these linear features from surveys dated from 1 August 2015 or after were corrected by re-digitizing these linear features to match the existing shoreline segments. Lengths were then recalculated for these zones and corrected in the SCAT database.

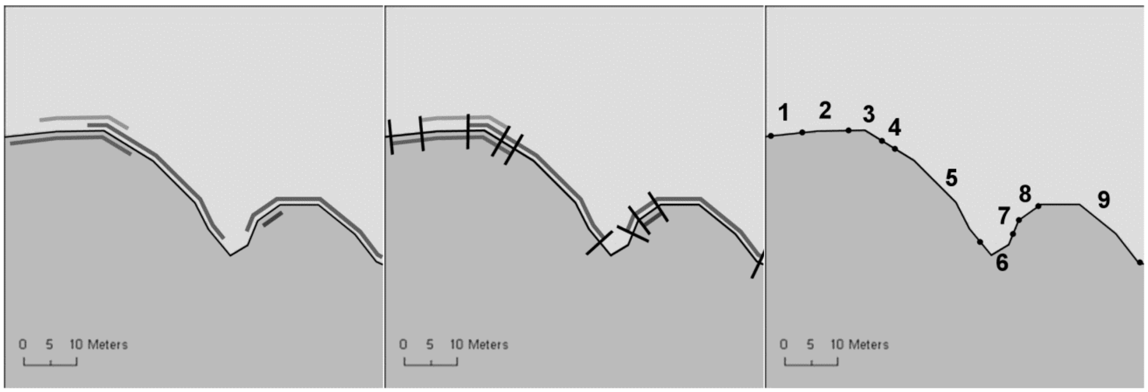
Transcription verification was conducted for all scanned raw data forms where shoreline oiling was observed, and all data entry transcription errors associated with either zone dimensions or oiling characteristics for these zones were corrected in the SCAT database. Trustees conducted additional automated QA/QC by verifying that the numbers of oil zones in the spatial data matched the number of oil zones in the SCAT database and correcting errors. Trustees corrected errors such as zones being duplicated spatially or incorrect dates recorded in either the database or associated with the spatial data.

The database assigned zones a categorical oiling descriptor based on the tarball count and size information, but tarball counts were not universally recorded for the RBOS surveys. There were a few zones in the database where the oiling category as described above could not be determined, generally due to lack of information from the survey forms regarding tarball counts for zones consisting of <1% distribution of tarballs. All zones with insufficient tarball data to assign a tarball-specific categorical oiling descriptor were assigned the category of “Trace”. There were a limited number of zones in the database that indicated no oil observed but contained tarball or other oiling information indicating some type of oil in the zone. Trustees confirmed that these zones, in fact, represented no oil observed and removed the additional tarball or other oiling information from the zone record in the database. There were a limited number of zones in the database where the tidal zone was not recorded. Trustees added the missing tidal zone information for zones where oiling was updated based on inspection of raw data forms.

The linear features representing LACO survey data were also re-digitized to match the existing shoreline segments. Because access to the raw data forms was not available, the attributes for the LACO survey data were verified against the reported survey results contained in the summary report by Gibson (2016).

Shoreline Exposure Oiling Summary

After ensuring that all surface oiling data were referenced to a common shoreline segment, described as part of the QA/QC process above, all linear survey features representing surface oiling were intersected such that each resulting line segment represented a unique combination of all possible attributes that could be assigned to a given shoreline location (Figure 2). These unique segments were the primary unit of analysis for generating a linear shoreline oiling exposure summary product described below. These unique segments are not of a fixed length or size but instead are formed by the patterns of spatial overlap of all survey observations over time, as well as other pre-existing shoreline attribute data. These unique segments range in size from sub-meter where many small linear shoreline observations overlap one another over time, to very large where shoreline conditions are un-surveyed or were only surveyed once and found to be homogenous.



A. B. C.

Figure 2. Schematic of A.) multiple hypothetical overlapping coincident line segments, B.) those same line segments intersected with themselves and C.) resulting unique line segments formed by overlap of all linear survey observations over time.

After integrating and intersecting all data, a number of oiling, habitat, and other attributes and statistics were computed for all surface oiling observations at each unique linear segment of shoreline. These attributes and statistics included habitat, observation source, count of unique surveys, earliest and latest dates of survey, maximum categorical oiling descriptor, earliest and latest dates of observed oiling, maximum across-shore width of observed oiling, and many others. A full list of computed shoreline oil exposure summary attributes is included in the description of the linear shoreline exposure summary layer in Appendix A.

Because the LACO survey data recorded only a subset of oiling metrics as compared with the SCAT data, some assumptions were made about these observations for the purposes of computing summary statistics in locations where these surveys took place. Where oiling was recorded in multiple intertidal zones, oiling was generally assumed to have been primarily in the highest intertidal zone. All oiling in these locations were assumed to be tarball oiling in character, per descriptions in Gibson (2016). Because no across-shore width was recorded, all surface oiling zones in the LACO survey data were assigned a width of 4 meters (m) - the median across-shore width of all tarball oiling zones in the SCAT portion of the data. Because no oiling thickness was recorded, all surface oiling zones in the LACO survey data were assigned a thickness of “cover” or “CV” - the most frequently observed oiling thickness of all tarball oiling zones in the SCAT portion of the data. These zones were also assigned a categorical oiling descriptor of “Undifferentiated Oiling”. Figures 3 and 4 depict the maximum categorical oiling observed over the time span of shoreline surveys, and selected additional summary attributes, computed as part of linear shoreline oiling exposure summary product.

This database documents oiling along 214 km of shoreline out of 241 km of shoreline surveyed. Of this oiled shoreline, approximately 12 km (6%) was heavily oiled, 40 km (19%) was moderately oiled, 41 km

(19%) was lightly oiled, and the remaining 121 km (57%) was characterized as having very light, tarball, or undifferentiated oiling only.

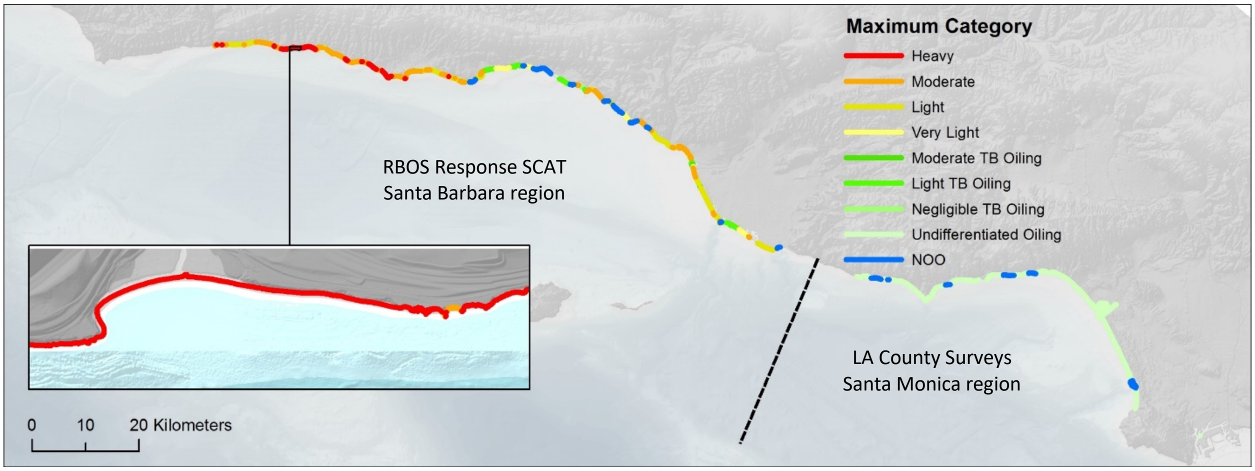


Figure 3. Maximum categorical oiling observed over time span of shoreline surveys computed as part of linear shoreline oiling exposure summary product. Inset of Refugio Beach State Park.

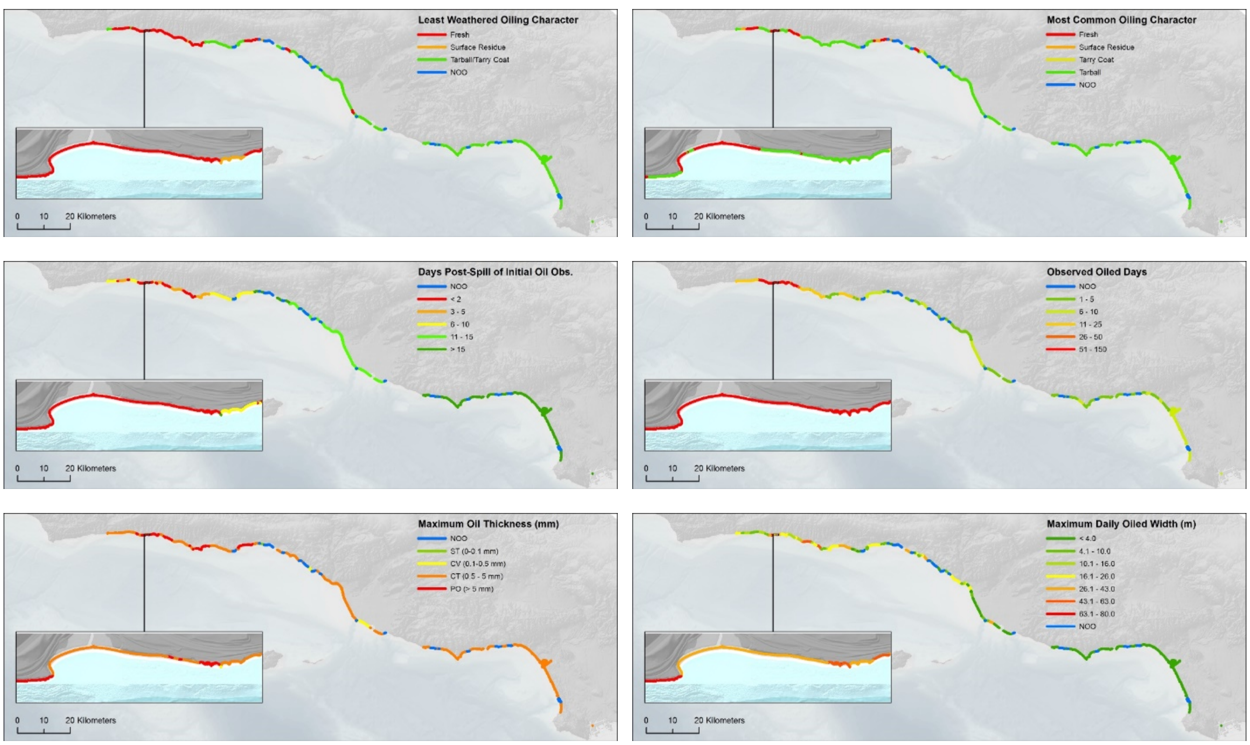


Figure 4. Additional visualization of summary oiling statistics generated as part of linear shoreline oiling exposure summary product. See Table 3 for complete list of computed statistics. Insets of Refugio Beach State Park.

Shoreline Exposure Areal Estimation

For some injury quantification applications, it is necessary to estimate the total potentially exposed *area* rather than length of shoreline exposed to oiling within various habitat, oiling, and other categories. For some spills in some physical settings, these areas may be explicitly computed using SCAT data which record the cross-shore width of observed oiling for linear shoreline segments. For the moderate-energy exposed sand beach and rocky intertidal habitats that were oiled during RBOS, however, there are often substantial changes in the volume and disposition of stranded oil over short time-frames during and immediately after initial stranding. Recent work (Wang and Roberts, 2013; Bernabeu et al., 2006, 2016; González et al., 2009) provides a good review of basic principles of the deposition and persistence of stranded oil on beaches in the context of beach morphologic features, swash-surf zone conditions, and beach morphodynamics. The landward limit of deposition of oil is controlled by the most energetic conditions during stranding periods, with maximum surface deposition occurring near maximum combined still water level and wave run-up, particularly during high energy events such as storms. Surface exposure time-scales are often greatest (~days-weeks) at the zones of maximum deposition as well, because the conditions that deposit or mobilize oil at these higher elevations recur more rarely by definition (Figure 5). Exposure of surface beach sediments lower on the intertidal foreshore, or beach face, by contrast, typically occurs over shorter time scales (~hours-days) as oil, mixed into the water column by wave breaking in the swash zone, is transported both landward over the beach face by breaking wave onrush and then seaward by wave bore retreat. During the RBOS, as in many spills, SCAT surveys typically took place several days after the time of initial stranding and rarely recorded conditions during or immediately after stranding, during the time of maximum cross-shore exposure extent. See Figure 6 for example oblique and vertical aerial and ground survey photographs of a location approximately 2 km east of Refugio Beach State Park over multiple dates and times during and after stranding. For this reason, the Trustees required alternative methods to estimate the intertidal area that was exposed to oil during and immediately following initial stranding.

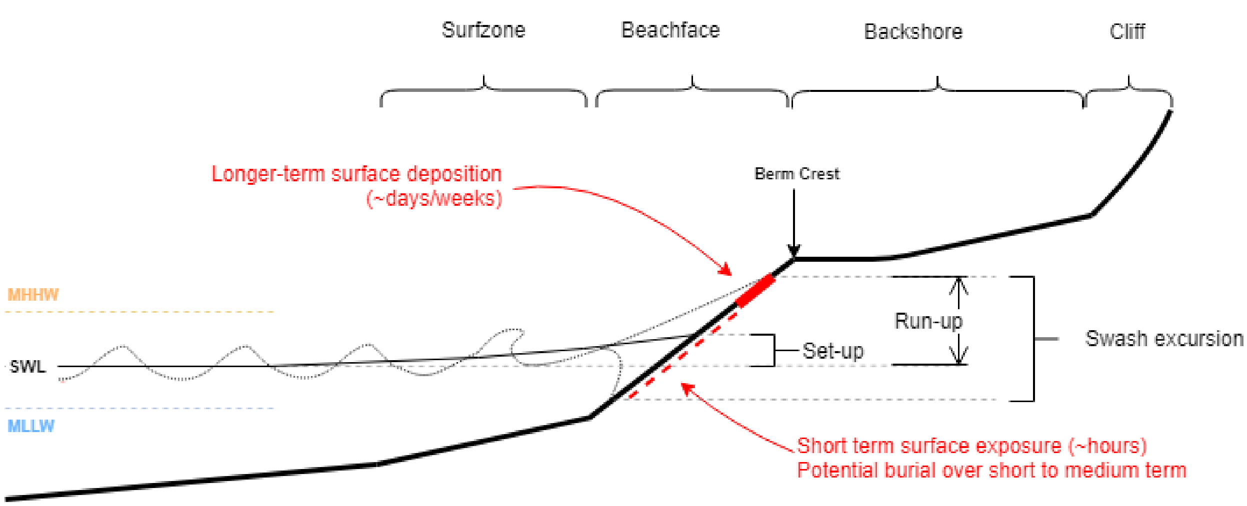


Figure 5. Schematic of conceptual model of extent and duration of oil exposure across the intertidal of an idealized profile of Southern California beaches and shorelines.

Figure 6. Example oblique and vertical aerial and ground survey photographs from multiple dates for location approximately 2 km east of Refugio Beach State Park. Overflights indicate oil initially stranded at this location on the evening of 19 May 2015. Note oil visibly mobile in swash zone in the first 24-36 hours after initial stranding.

To estimate this area, Trustees explicitly mapped the polygonal portion of the intertidal exposed to oil in the surf and swash during, and in the hours and days following initial stranding. This was accomplished by estimating the time window during which oil stranding likely occurred for various sections of the coast where oiling was observed, the still water levels and wave run-up vertical extents during each of these time windows, and the resulting vertical interval of the intertidal beach that was exposed to oil.

Then, the Trustees extracted the portions of LIDAR-derived Digital Elevation Models (DEMs) of the beach surface and nearshore subtidal within those vertical intervals. Detailed descriptions of each component of the methodology are described below.

Initially, polygons were generated summarizing the approximate timeline of oil stranding for all oiled locations along the shoreline where oiling was documented. Trustees began by digitizing large polygons and subdivided them using compiled information on both the earliest date/time of observed or predicted stranded oil, and the latest date/time of no observed or predicted stranded oil prior to initial oiling. These time estimates were compiled from SCAT ground survey, overflight observation describing oil onshore or in the surf zone, beached oil predictions from NOAA GNOME trajectory modeling, spill release reports from the California Governor's Office of Emergency Services (CALOES, 2018) and the time and dates of collection of tarballs with positive forensic match results to RBOS oil. Both field observation data and NOAA trajectory model output were obtained from NOAA's Environmental Response Management Application (ERMA, 2015). All oil was assumed to have made initial landfall by 30 May 2015. The final time intervals selected (initial release until 4:30 PM on 22 May 2015, 4:30 PM on 22 May 2015 until 4:30 PM on 26 May 2015, and 4:30 PM on 26 May 2015 until 4:30 PM on 30 May 2015) are depicted in Figure 7 below.

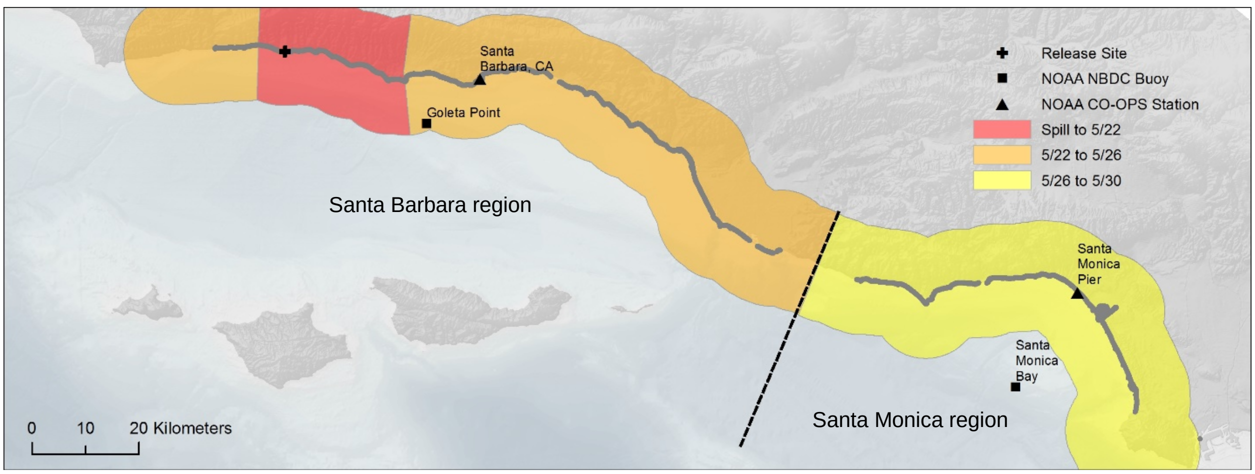


Figure 7. Estimated time intervals of oil stranding along impacted shorelines for three regions at increasing distance from spill. Also depicted are selected representative NOAA CO-OPS stations and NBDC buoys for the two principal regions in the response.

Trustees then obtained hourly still water level elevations for the period from 19 May 2015 to 30 May 2015 for two representative NOAA CO-OPS stations (NOAA CO-OPS, 2016a) across the area of interest: station 9411340 at Santa Barbara as representative of the Santa Barbara region, and station 9410840 at the Santa Monica Pier as representative of the Santa Monica region. Still water levels above the tidal datum were converted to North American Vertical Datum of 1988 (NAVD88). Trustees also obtained archived hourly significant wave height and average period for the period from 19 May 2015 to 30 May 2015 for two representative NOAA National Buoy Data Center stations (NOAA NBDC, 2016a) across the area of interest: buoy 46216 at Goleta Point as representative of the Santa Barbara region, and buoy 46221 in Santa Monica Bay as representative of the Santa Monica region. Supplemental data for the two NBDC buoys were obtained from the Coastal Data Information Program, Integrative Oceanography Division, operated by the Scripps Institution of Oceanography (CDIP) which summarized significant wave height and average period by both sea and swell components by partitioning the wave energy based on a cutoff period of 10 seconds (CDIP, 2016). The locations of the selected NOAA CO-OPS stations and NBDC buoys are depicted in Figure 7. Hourly still water levels at Santa Barbara and Santa Monica Pier NOAA CO-OPS stations (top), as well as significant deep water wave heights and average wave period for both wind waves and swell at Goleta Point and Santa Monica Bay NOAA NBDC buoys for 11 days following release during time period of oil stranding are depicted in Figure 8.

For each hourly time-step, Trustees then estimated swash excursion as the vertical interval between the 2% and 98% exceedance values of wave run-up after the empirical relationship derived by Stockdon et al. (2006). The authors provide a general empirical formula for estimating and combining both *setup*, the time-averaged super-elevation of the mean water level above still water level driven by wave breaking, and *swash*, the time-varying vertical fluctuations of water level above and below the temporal mean due to the advance and retreat of individual waves. These values may be combined to estimate the total 2% exceedance value (R_2) and 98% exceedance value (R_{98}) of swash elevation as:

$$R_2 = 1.1\left[<\eta> + \frac{S}{2}\right]$$

$$R_{98} = 1.1\left[<\eta> - \frac{S}{2}\right]$$

respectively, where $<\eta>$ is setup and S is swash. Setup may be estimated as:

$$<\eta> = 0.35\beta_f (H_0 L_0)^{1/2}$$

and swash is estimated as:

$$S = \left[H_0 L_0 \left(0.563\beta_f^2 + 0.004\right)\right]^{1/2}$$

where H_0 is deep-water equivalent wave height, L_0 is deep-water wave period, and β_f is beach slope. For the purpose of computing wave run-up, beach slope was estimated as 0.042 for the Santa Barbara region and 0.058 for the Santa Monica region based upon average widths of the intertidal between local Mean Lower Low Water (MLLW) and Mean Higher High Water (MHHW). This formulation is for a single value of H_0 and L_0, whereas for RBOS, Trustees evaluated both period and height separately for sea and swell. As such, Trustees estimated both setup and swash separately for sea and swell, and combined them by summing the setup estimates, and considering sea and swell-derived swash estimates as two independent Gaussian distributions, and combining them as such:

$$S = \sqrt{(S_{sea})^2 + (S_{swell})^2}$$

For each hourly time step, Trustees computed total swash excursion by adding still water level to computed setup value, and then estimated the R_2 and R_{98} values to obtain the maximum and minimum water level elevations for that time step. Figure 9 depicts a time series of final still water level, setup, and the swash excursion (interval between R_2 and R_{98} values) for impacted shorelines.

Figure 8. Observed still water levels (SWL, in m above NAVD88) at Santa Barbara and Santa Monica Pier NOAA CO-OPS stations (top), as well as significant deep water wave heights (Hs, in m) (middle) and average wave period (Ta, in s) for both wind waves and swell at Goleta (bottom).

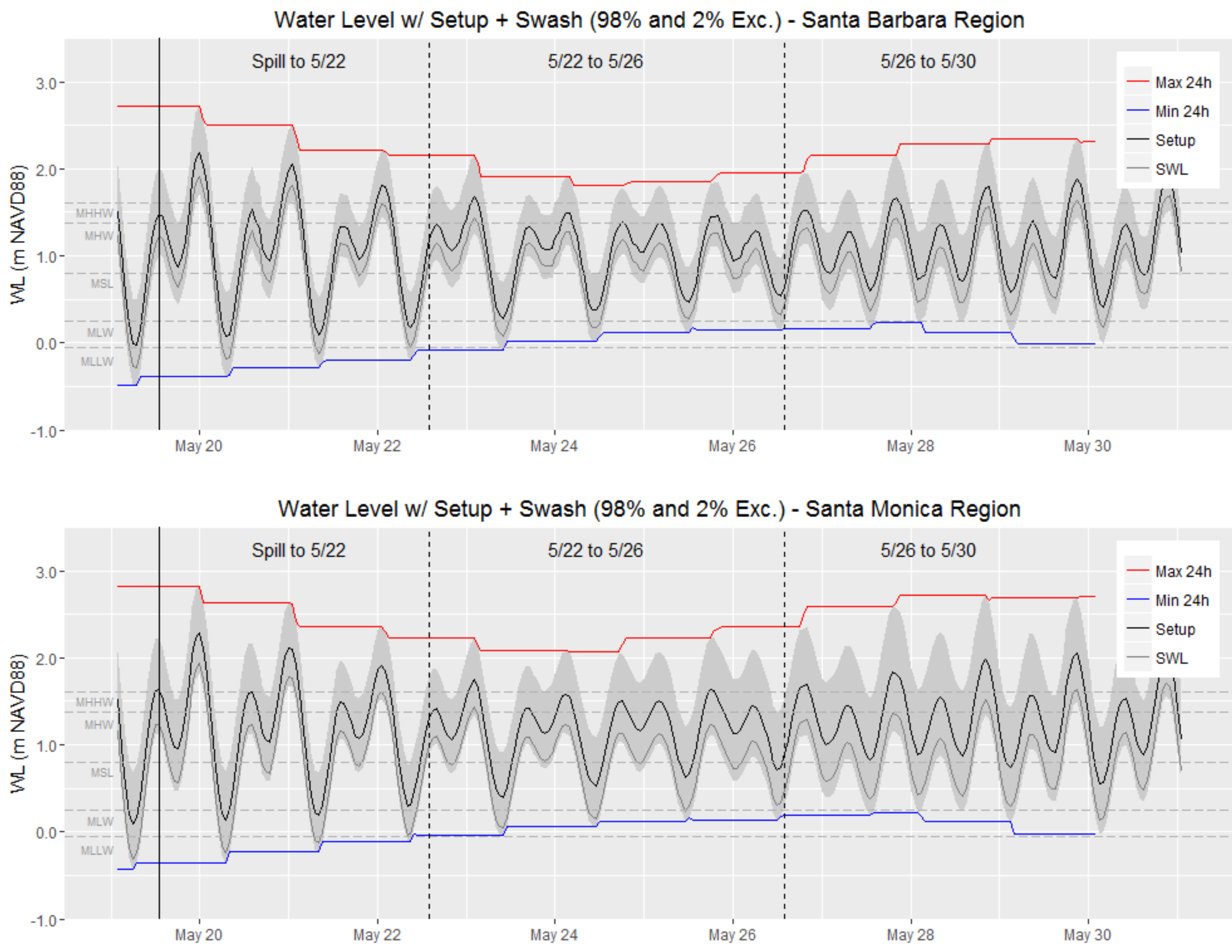


Figure 9. Time series of total estimated water level (m above NAVD88) including still water levels (SWL), wave setup, and swash excursion, as well as rolling 24-hour minimum and maximum values, for 11 days following release during time period of oil stranding for Santa Barbara region (top) and Santa Monica Region (bottom). The grey band represents swash excursion defined as the interval between the 2% and 98% swash elevation exceedance values. Solid vertical line indicates release, and dotted lines indicate breaks between date ranges of stranding across impacted shorelines.

Within each time interval of stranding from Table 3, Trustees also computed the rolling 24-hour minimum and maximum total estimated water level. For the first time period, Trustees selected the minimum and maximum reported total estimated water level as representative of the vertical interval exposed to oil because, in these locations and during this shorter initial period, oil was more concentrated along the shoreline, more mobile, less viscous, and was repeatedly stranded, re-floated, and re-stranded. For the other two stranding intervals, Trustees selected the average values within those intervals of the rolling minimum and maximum hourly total estimated water level as representative of the vertical interval exposed to oil. For these larger areas more distant from the release location, oil stranding was more likely to be a discrete event, and the precise timing of stranding is less well known. Table 3 describes the specific elevations in meters above NAVD88 that represent the final minimum and maximum total estimated water levels selected as presentative of the vertical interval exposed to oil for the three regions representing the three estimated stranding intervals.

Table 3. Estimated time intervals of oil stranding, and corresponding final minimum and maximum total estimated water levels during those intervals selected as presentative of the vertical interval exposed to oil.

Time Interval	Representative Statistic	Minimum Elev. (m NAVD88)	Maximum Elev. (m NAVD88)
4:30 PM on 19 May 2015 (release) to 4:30 PM on 22 May 2015	Minimum and maximum of hourly values	-0.39	2.71
4:30 PM on 22 May 2015 to 4:30 PM on 26 May 2015	Mean of rolling 24-hour minimum and maximum hourly values	0.05	1.93
4:30 PM on 26 May 2015 to 4:30 PM on 30 May 2015	Mean of rolling 24-hour minimum and maximum hourly values	0.06	2.70

Trustees obtained LIDAR-derived topographic-bathymetric (topo-bathy) DEMs of the Southern California coast based on data collected between 2009 and 2015 (NOAA OCM, 2013; USACE NCMP 2018a; USACE NCMP, 2018b). These data consist of raster grids derived from topographic and bathymetric LIDAR data for coastal areas in southern California representing orthometric heights in feet referenced to the North American Vertical Datum of 1988 (NAVD88). The 2015 USACE NCMP LIDAR derived DEMs, based on data collected between June and August 2015, include areas from the western extent of surveyed area to Santa Barbara. The 2014 USACE NCMP LIDAR derived DEMs, based on data collected between September and October 2014, extend from Santa Barbara to the eastern extent of the study area in Los Angeles. The 2013 merged topo-bathy DEM, based on data collected between October 2009 and August 2011, covers the entire study area. Initially, a best-available raster topo-bathy DEM was assembled from the 2015 data, where available, and the 2014 data for the remainder of the study area. This best-available raster DEM was processed to remove voids, or areas of no data, using the elevation void fill function in ArcGIS 10.5 (ESRI, 2018). This process uses a combination of plane-fitting and inverse-distance-weighting interpolation to infill small areas of no data using the values of surrounding pixels. In some locations within the extent of the 2014 USACE NCMP LIDAR derived DEM, these voids extended to the seaward limit of the DEM tile, preventing accurate infilling using the void filling algorithm. In these locations, the 2014 data were replaced with similarly void-filled elevation data extracted from the 2013 merged topo-bathy DEM. Prior to this step, certain limited areas in the 2013 topo-bathy DEM where irregularities in the shallow subtidal were apparent due to merging of multiple bathymetric and topographic datasets were manually removed and re-filled using the elevation void fill function as described above.

The portions of this best-available topo-bathy DEM contained within each polygon depicting an estimated date range of oil stranding (Figure 7) were reclassified as either subtidal, intertidal, or supratidal using the elevation intervals for that date range described in Table 3. The boundaries between these regions in the reclassified rasters were smoothed using the boundary clean function in ArcGIS with default settings, and then the intertidal regions were converted to vector polygons.

These vector polygons were further manually processed to remove areas that were disconnected from, and landward of, the continuous intertidal area along the coast. These areas were generally interior, ephemeral, and seasonal tidal inlets or lagoons that were not open to the ocean at the time of stranding and are assumed to have not been exposed to stranded oil. Similarly, intertidal areas were trimmed to only surveyed areas by removing portions of the polygon that were beyond a line generated orthogonally to the shoreline at the end of surveyed portion.

Because the Trustees intended to consider oil exposure and injury to surf-grass habitats in the lower intertidal separately from the shoreline resources, these areas (Ocean Imaging, 2014) were removed from the resulting intertidal polygons. Figure 10 depicts different steps of the process used to generate vector polygons representing exposed intertidal area from topo-bathy DEMs. This process yields an estimate over the entire investigated area of approximately 2,118 and 2,068 acres, before and after removal of surf-grass areas respectively. Trustees computed these areas for all locations seaward of surveyed shorelines, as well as seaward of approximately 2 km of shoreline between Long Beach marina and the mouth of the San Gabriel River.

Trustees subdivided the resulting polygon based upon the nearest linear segment in the linear shoreline oiling exposure summary product. This was accomplished using a Euclidean allocation operation carried out in ArcGIS (ESRI, 2016) on a raster with a 1-m grid cell size where each grid cell was assigned to the closest line segment. The resulting raster was converted to a vector polygon, and intersected with the simplified and edited intertidal polygon described above, both with and without surf-grass areas removed. There were 19 line segments of the total of 1,130 total unique line segments in the linear shoreline oiling exposure product that were less than 1 m long, and so were not assigned any area in the initial grid. Another 10 line segments were not assigned to any subdivision of the intertidal because they were situated outside the intertidal and in such a way that no portion of the intertidal was closer to those segments than to others. Using these subdivisions, Trustees estimate that oil was observed on along shorelines which correspond to an intertidal area of approximately 1,927 and 1,884 acres, before and after removal of surf-grass areas respectively.

The DEM source data have inherent vertical measurement error of approximately 10 centimeters (cm) Root Mean Square Error (RMSE), with additional unquantified uncertainty introduced by the gridding process (USACE NCMP, 2018a) and the additional processing described here. Stockdon et al. (2006) estimate the RMSE in measured vs modeled vertical swash excursion using the dataset used for empirical parameterizations at 46 cm. Further, the beaches along the Santa Barbara, Santa Monica, and San Pedro littoral cells undergo changes in width, position, shape, and elevation continuously, in response to multiple forcing factors on a variety of temporal periods and scales. These include tidal and wave climate changes on hourly and daily timescales, individual storm cycles, seasonal cycles, and on longer timescales in response to El Nino/Southern Oscillation (ENSO) and Pacific Decadal Oscillation forcing factors. See Orme et al. (2011) for a recent regional review. Trustees used best-available DEM data acquired between 10 months prior to the spill to 3 months after the spill for the vast majority of the area of interest, but changes in beach width and elevation between time of DEM data collection and the spill are unknown. Trustees did not carry out quantitative uncertainty assessments of these areal estimates. Indeed, this would be very challenging given the variety of data and processing steps required and lack of authoritative contemporaneous ground truthing. However, initial efforts conducted using the same methods, but entirely with the 2013 merged topo-bathy DEM (NOAA OCM, 2013) which is based on data collected between October 2009 and August 2011, resulted in areal estimates that were only 3-4% different from those presented here. As such, Trustees qualitatively estimate that the uncertainty in these areal estimates is likely less than 10% of actual values.

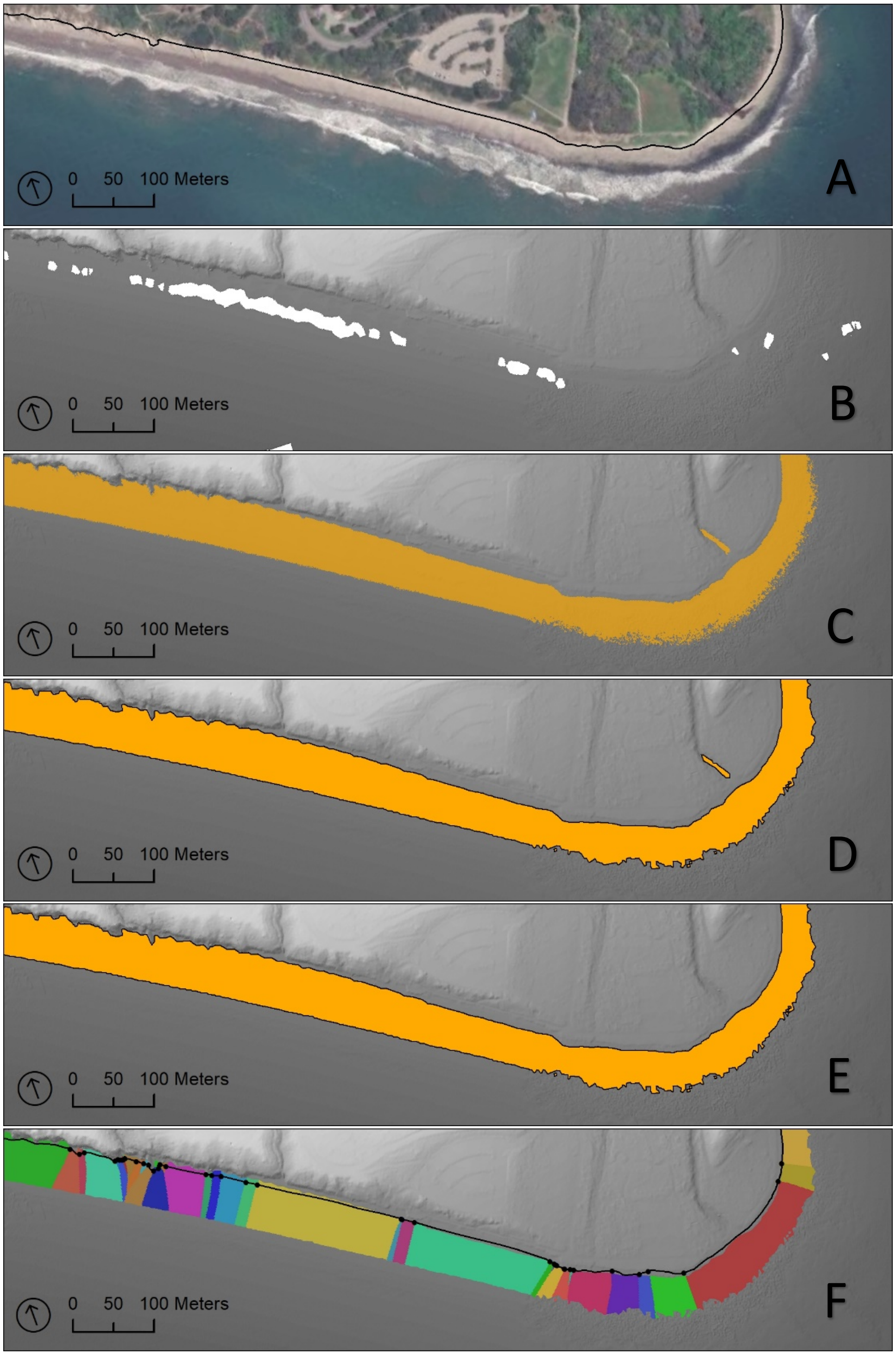


Figure 10. Illustration of intertidal area estimation: A.) example area located at El Capitan State Beach with linear shoreline; B.) 2015 USACE NCMP topo-bathy DEM; C.) void-filled DEM reclassified to extract time-specific intertidal elevations (in orange); D.) vector polygons representing intertidal from boundary cleaned reclassification; E.) vector polygons representing intertidal with disconnected interior polygons (e.g. tidal inlets) removed; and F.) vector polygons representing intertidal subdivided by proximity to closest linear shoreline segment (assigned random colors).

Shoreline Habitat Classification

A simplified habitat classification (Table 4) was originally assigned to all linear shoreline segments via ruleset based upon shoreline attributes derived from NOAA Environmental Sensitivity Index (ESI) data for Southern California (NOAA OR&R, 2010), habitats assigned via classification of multispectral aerial imagery collected in 2012 for MPA habitat mapping (Ocean Imaging, 2014), and multiple ESI classes assigned to individual shoreline surface oiling zones along the surveyed shoreline collected as part of the SCAT data process. See NOAA OR&R (2002) for a more detailed description of ESI codes and their meaning. ESI codes were converted to the simplified habitat classification in Table 5 using the cross-walk scheme described in Table 5.

Table 4. Simplified intertidal habitat classifications assigned to all linear shoreline segments.

Simplified Habitat Class	Definition
Rocky	Majority (>70%) of intertidal substrate composed of either bedrock or gravel or larger sized clasts
Beach	Majority (>70%) of intertidal substrate composed of sand or smaller sized sediment
Beach/Rocky	Intertidal substrate composed of significant components (each >30%) of both sand or smaller sized sediment, and bedrock or gravel or larger sized clasts
Riprap	Intertidal composed of permeable, manmade surfaces such as revetment, tetrapods, etc.
Manmade	Intertidal composed of solid impermeable manmade surfaces such as seawall, bulkhead, etc.
Beach/Riprap	Intertidal substrate composed of both sand or smaller sized sediment and permeable manmade surfaces (typically in the upper intertidal)
Beach/Manmade	Intertidal substrate composed of both sand or smaller sized sediment and solid, impermeable manmade surfaces (generally higher in the intertidal)

Table 5. Cross-walk table used to assign simplified habitat classes to linear observations in the SCAT data and ESI data based upon NOAA ESI codes.

ESI Code	ESI Code Description	Simplified Habitat Class
1A	Exposed rocky shores	Rocky
1B	Exposed, solid man-made structures	Manmade
2A	Exposed wave-cut platforms in bedrock	Rocky
3A	Fine- to medium-grained sand beaches	Beach
3B	Scarps and Steep Slopes in Sand	Beach
4	Coarse-grained sand beaches	Beach
5	Mixed sand and gravel beaches	Beach/Rocky
6A	Gravel beaches	Rocky
6B	Riprap	Riprap
6D	Boulder rubble	Rocky
8A	Sheltered Rocky Shores	Rocky

Upon further review of this classification and contemporaneous NOAA NGS-acquired oblique imagery (NOAA NGS, 2016), it became apparent that an improved approach was required. The variability in seasonal and inter-annual movement of sand on and offshore, alternately burying and exhuming wave-cut bedrock platforms and large talus and boulder accumulations at the cliff and bluff toes, as well as variability in the manner different SCAT teams assigned ESI codes during field survey, made it challenging to use these data to accurately map the extent of beaches, rocky intertidal, and mixed beach/rocky habitats in a way that reflected the specific beach conditions at the time of the spill and subsequent response. Figure 11 below depicts different intertidal habitat datasets for single location and the variability of intertidal habitat assignments at that location over time.

As such, Trustees subdivided the linear shoreline oiling exposure summary described above, and assigned each segment a new simplified intertidal habitat classification based upon manual photo-interpretation of the August 2015 NOAA NGS oblique imagery using heads-up digitization at a scale of 1:1,000. Trustees then generated a set of ground-truth points to evaluate the accuracy of mapping of “Rocky” or mixed “Beach/Rocky” simplified habitat specifically based upon this new mapping process. These ground-truth data were compiled by merging all Rocky Intertidal Assessment (RIA), rocky intertidal sampling sites, and hard substrate mussel sampling locations collected by NRDA teams during and after the spill, as well as the centroid of polygonal abalone habitat mapped as part of the NRDA (ERMA, 2015). Trustees merged all points at the same location, clustered all points in these datasets within 25 meters of one another into a single location, removed one obviously erroneous observation location, and then snapped the resulting 58 unique ground-truth point locations to the closest location along the shoreline. Finally, Trustees devised a new ruleset to classify shoreline habitats according to the scheme in Table 5 so as to maximize classification accuracy of rocky habitats according to this dataset. All shoreline locations were assigned a simplified intertidal habitat based upon the heads-up digitization described above. Any location thusly mapped as “Beach”, but where rocky intertidal habitat (ESI = 1A or 2A) was reported during ESI mapping (NOAA OR&R, 2010) or during SCAT surveys, or along the linear extent of mapped abalone habitat, was then reclassified as “Beach/Rocky”. This ruleset yielded an accuracy of 90% in mapping of “Rocky” or mixed “Beach/Rocky” habitats. The final simplified intertidal habitat classification is depicted in Figure 12.

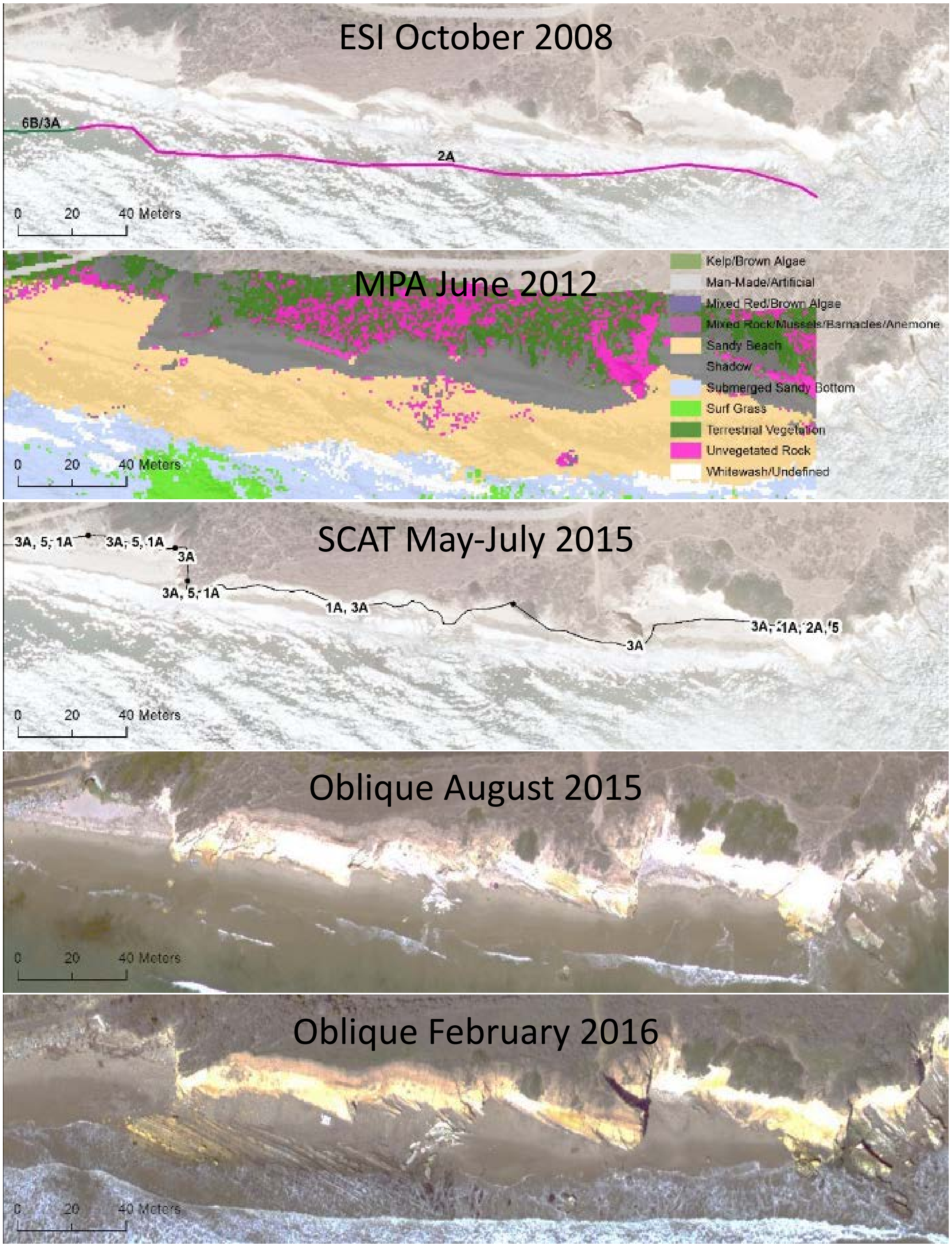


Figure 11. Examples of different intertidal habitat datasets for single location based upon mapping, field survey, and aerial imagery collection over multiple dates. Note the discrepancies in visible rocky substrate between August 2015 and February 2016, and variability in other classifications. Alphanumeric codes are ESI codes (NOAA OR&R, 2002) as described in Table 5.

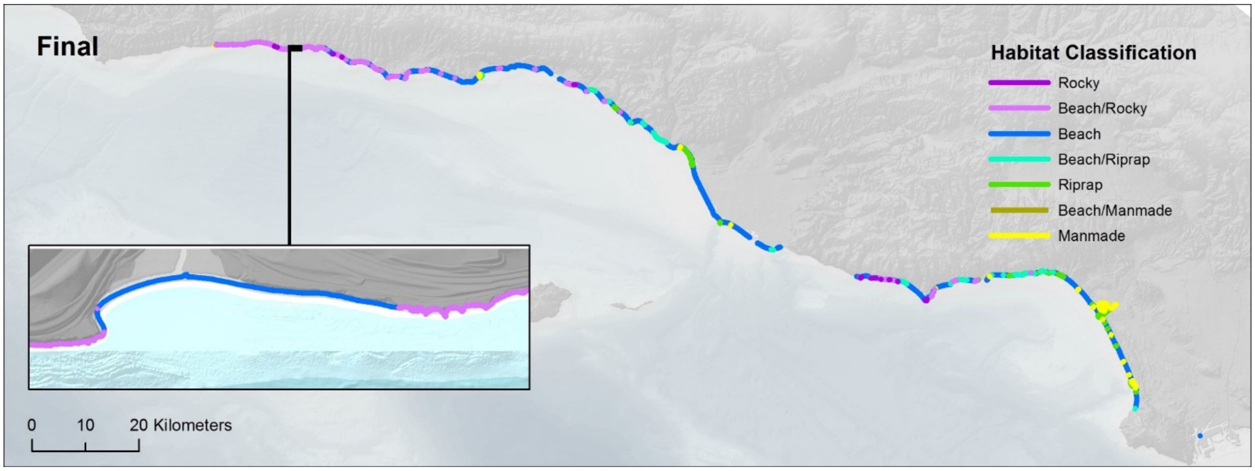


Figure 12. Final simplified habitat classification assigned to linear shoreline segments based upon integration of multiple digital data sources, and manual review of oblique aerial imagery. Inset of Refugio Beach State Park.

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Appendix A – Description of Shoreline Oiling Exposure Summary Data Products

The database described here is provided as a set of data layers intended for use in Geographic Information Systems (GIS) software, and are provided in both ESRI shapefile and ESRI File Geodatabase (FGDB) formats. Table A-1 lists individual shapefile file names or feature class layer names for that layer, and describes the contents of that layer.

Table A-1. Layers included as part of accompanying database

Layer	Contents
rbos_shoreline_exposure_linear	Vector line features with attributes describing compiled shoreline oil exposure metrics and statistics
rbos_shoreline_exposure_regions	Vector polygon features with attributes describing estimated date ranges of initial shoreline oiling for locations within each feature
rbos_intertidal_area	Vector polygon features describing the estimated extent of exposure to oil in the intertidal during and after the time of oil stranding
rbos_intertidal_ area_subdivided	As rbos_intertidal_area above, but subdivided by proximity to individual shorelines segments from the linear shoreline exposure summary product
rbos_intertidal_ area_nosurfgrass	As rbos_intertidal_area above, but with surf-grass areas removed
rbos_intertidal_ area_nosurfgrass_subdivided	As rbos_intertidal_area_nosurfgrass above, but subdivided by proximity to individual shorelines segments from the linear shoreline exposure summary product

Individual attributes of each layer are described in Tables A-2 through A-5. Note that the attributes of intertidal exposure area and subdivided area layers, with and without surf-grass extents included, are identical. Note that attribute names longer than 10 characters are truncated in ESRI shapefile versions.

Table A-2. Attributes of the linear shoreline exposure summary layer

Attribute	Definition
UNIQUE_ID	Unique line segment ID assigned to all overlapping intersected line segments
SEG_ID	SCAT segment ID
CAT_MAX	Maximum alongshore categorical SCAT surface oiling descriptor
SURV_MAX	Date of maximum alongshore categorical SCAT surface oiling descriptor
CAT_MR	Most recent alongshore categorical SCAT surface oiling descriptor
SURV_MR	Date of most recent alongshore categorical SCAT surface oiling descriptor
SURV_ALL	Comma-separated list of integer days post spill (5/19/2015 = 0) on which surveys took place
SURV_E	Integer day post spill of earliest survey

Table A-2. Attributes of the linear shoreline exposure summary layer

Attribute	Definition
SURV_L	Integer day post spill of latest survey
SURV_CNT	Count of total unique survey days
SO_OB_ALL	Comma-separated list of integer days post spill (5/19/2015 = 0) on which surface oil was observed
SO_OB_E	Integer day post spill of earliest surface oil observation
SO_OB_L	Integer day post spill of latest surface oil observation
SO_OB_CNT	Count of total unique survey days with surface oil observations
SO_OB_DAYS	Count of days between earliest and latest surface oil observation
C_ALL	Comma-separated list of integer codes representing categorical descriptors of all surface oiling observations at all tidal elevations for each survey day (0=No Oil Observed, 1=Undifferentiated/Unknown Oiling, 2=Negligible TB Oiling, 3=Light TB Oiling, 4=Moderate TB Oiling, 5=Heavy TB Oiling, 10=Trace/TB, 20=Very Light, 30=Light, , 40=Moderate, 50=Heavy)
C_ALL_DMAX	Comma-separated list of integer codes representing daily maximum of categorical descriptor of all surface oiling observations for each survey day (see codeset descriptions above)
C_ALL_MAX	Integer code representing maximum of categorical descriptor of all surface oiling observations over all tidal elevations and days (see codeset descriptions above)
C_LI_MAX	Integer code representing maximum of categorical descriptor of all surface oiling observations over all days in lower intertidal (see codeset descriptions above)
C_MI_MAX	Integer code representing maximum of categorical descriptor of all surface oiling observations over all days in middle intertidal (see codeset descriptions above)
C_UI_MAX	Integer code representing maximum of categorical descriptor of all surface oiling observations over all days in upper intertidal (see codeset descriptions above)
C_SU_MAX	Integer code representing maximum of categorical descriptor of all surface oiling observations over all days in supratidal (see codeset descriptions above)
W_ALL	Comma-separated list of daily sum across-shore widths in m of all surface oiling observations over all tidal elevations for each survey day
W_ALL_DMAX	Maximum daily sum across-shore width in m of all surface oiling observations over all tidal elevations and days
W_LI_MAX	Maximum across-shore width in m of all surface oiling observations in the lower intertidal over all survey days
W_MI_MAX	Maximum across-shore width in m of all surface oiling observations in the middle intertidal over all survey days
W_UI_MAX	Maximum across-shore width in m of all surface oiling observations in the upper intertidal over all survey days
W_SU_MAX	Maximum across-shore width in m of all surface oiling observations in the supratidal over all survey days
DIST_ALL	Comma-separated list of surface oil percent cover distribution values of all surface oiling observations over all tidal elevations for each survey day
DIST_MAX	Maximum surface oil percent cover distribution values of all surface oiling observations over all tidal elevations and days
DIST_AVG	Average surface oil percent cover distribution values of all surface oiling observations over all tidal elevations and days

Table A-2. Attributes of the linear shoreline exposure summary layer

Attribute	Definition
THICK_ALL	Comma-separated list of text codes representing oil thickness of all surface oiling observations at all tidal elevations for each survey day (TO=Thick oil, CV=Cover, CT=Coat, ST=Stain, ST=Film)
THICK_MAX	Maximum estimated oil thickness in cm (converted from text codes, TO=1.00, CV=0.50, CT=0.05, ST=0.01, ST=0.01) of all surface oiling observations over all tidal elevations and days
THICK_AVG	Average estimated oil thickness in cm (converted from text codes, see codeset descriptions and conversion above) of all surface oiling observations over all tidal elevations and days
CHAR_ALL	Comma-separated list of text codes representing oil characters of all surface oiling observations at all tidal elevations for each survey day (FR=Fresh, TB=Tarballs, TC=Tarry Coat, PT=Tar Patties, SR=Surface Residue, MS=Mousse, AP=Asphalt Pavement)
CHAR_UNQ	Comma-separated list of text codes representing unique oil characters of all surface oiling observations at all tidal elevations for each survey day (see codeset descriptions above)
CHAR_MAJ	Text code representing most commonly observed oil character of all surface oiling observations over all tidal elevations and days (see codeset descriptions above)
SUBSTR	Text code representing substrate of all surface oiling observations over all tidal elevations and days (S=Sediment, V=Vegetation, B=Both)
SURV_S	Text code representing survey source or sources of all surface oiling observations (SCAT=RBOS SCAT Program, LASCAT=LA County Oiling Surveys)
ESI_ALL	Comma-separated list of text codes representing ESI classes of all observations at all tidal elevations for each survey day (see NOAA ESI Guidelines)
ESI_UNQ	Comma-separated list of text codes representing unique ESI classes of all observations at all tidal elevations for each survey day (see NOAA ESI Guidelines)
ESI_MAJ	Text code representing most commonly observed ESI classes of all observations over all tidal elevations and days (see NOAA ESI Guidelines)
LI_M2_DMAX	Average daily across-shore areal loading index (m^2/m) computed from all surface oiling observations at all tidal elevations for each survey day
LI_M2_DAVG	Maximum daily across-shore areal loading index (m^2/m) computed from all surface oiling observations at all tidal elevations for each survey day
LI_M3_DMAX	Average daily across-shore volumetric loading index (decaliter/m) computed from all surface oiling observations at all tidal elevations for each survey day
LI_M3_DAVG	Maximum daily across-shore volumetric loading index (decaliter /m) computed from all surface oiling observations at all tidal elevations for each survey day
ESI	Text code representing ESI class of adjacent shoreline in NOAA Southern California ESI Atlas (see Atlas and NOAA ESI Guidelines)
LINE	Text code representing line class of adjacent shoreline in NOAA Southern California ESI Atlas (see Atlas and NOAA ESI Guidelines)
SOURCE_ID	Text code representing line source ID of adjacent shoreline in NOAA Southern California ESI Atlas (see Atlas and NOAA ESI Guidelines)
ENVIR	Text code representing environment class of adjacent shoreline in NOAA Southern California ESI Atlas (see Atlas and NOAA ESI Guidelines)
ESI_SOURCE	Text code representing ESI classification source ID of adjacent shoreline in NOAA Southern California ESI Atlas (see Atlas and NOAA ESI Guidelines)
MOSTSENSIT	Text code representing most sensitive ESI class of adjacent shoreline in NOAA Southern California ESI Atlas (see Atlas and NOAA ESI Guidelines)
HAB_SIMP	Text description of simplified habitat classification assigned to shoreline segment for RBOS NRDA

Table A-2. Attributes of the linear shoreline exposure summary layer

Attribute	Definition
DIST_MAX_CAT	Text description of simplified classification of maximum surface oil distribution value (DIST_MAX) for RBOS NRDA
THICK_MAX_CAT	Text description of simplified classification of maximum surface oil thickness value (THICK_MAX) for RBOS NRDA
SO_OB_DAYS_CAT	Text description of simplified classification of days between first and last surface oil observation (SO_OB_DAYS) for RBOS NRDA
SO_ESI_ALL	Comma-separated list of text codes representing ESI classes of all surface oiling observations at all tidal elevations for each survey day (see NOAA ESI Guidelines)
SO_ESI_UNQ	Comma-separated list of text codes representing unique ESI classes of all surface oiling observations at all tidal elevations for each survey day (see NOAA ESI Guidelines)
SO_ESI_MAJ	Text code representing most commonly observed ESI classes of all surface oiling observations over all tidal elevations and days (see NOAA ESI Guidelines)
REGION	Text description of simplified geographic region description for RBOS NRDA
AREA_INT_M2	Area in m^2 of portion of adjacent intertidal polygon proximal to line segment for RBOS NRDA
AREA_INTNS_M2	Area in m^2 of portion of adjacent intertidal polygon, with surf-grass areas removed, proximal to line segment for RBOS NRDA

Table A-3. Attributes of the shoreline exposure region layer describing estimated date ranges of initial shoreline oiling

Attribute	Definition
R_NUM	Integer code of region
R_START_DT	Date/time of estimated earliest shoreline oil initial stranding within region
R_END_DT	Date/time of estimated latest shoreline oil initial stranding within region
REGION	Text description of simplified geographic region description for RBOS NRDA

Table A-4. Attributes of the intertidal area summary layers

Attribute	Definition
R_NUM	Integer code of region
R_START_DT	Date/time of estimated earliest shoreline oil initial stranding within region
R_END_DT	Date/time of estimated latest shoreline oil initial stranding within region
REGION	Text description of simplified geographic region description for RBOS NRDA
DEM_SOURCE	Text code representing simplified geographic region description for RBOS NRDA
AREA_AC	Area of polygon in acres
AREA_M2	Area of polygon in m^2

Table A-5. Attributes of the subdivided intertidal area summary layers

Attribute	Definition
R_NUM	Integer code of region
R_START_DT	Date/time of estimated earliest shoreline oil initial stranding within region
R_END_DT	Date/time of estimated latest shoreline oil initial stranding within region
REGION	Text description of simplified geographic region description for RBOS NRDA
DEM_SOURCE	Text code representing simplified geographic region description for RBOS NRDA
UNIQUE_ID	Unique line segment ID of closest line segment in the linear shoreline exposure summary product (rbos_shoreline_exposure_linear). See Table A-2 above.
AREA_AC	Area of polygon in acres
AREA_M2	Area of polygon in m^2