Exxon Valdez Oil Spill
Long-Term Monitoring Program (Gulf Watch Alaska) Final Report

Extending the Timeline for Lingering Oil in Prince William Sound

Exxon Valdez Oil Spill Trustee Council Project 21200114-P
Final Report

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Study History: This project is part of the *Exxon Valdez* Oil Spill Trustee Council's Long-Term Monitoring Program known as Gulf Watch Alaska (Project 21120114). This subproject is designed to monitor locations where oil spilled from the *Exxon Valdez* has been known to linger. It adds to a series of studies (projects 02543, 040585, 050620, 070801, and 12120117) that have documented the presence of oil, and its distribution, volume, area, and weathering rate. This previous Trustee Council-funded work demonstrated that, on some beaches, subsurface oil persisted in a relatively unweathered state and this persistence occurred over a longer than expected time period. Current estimated rates of decrease do not differ from zero. Chemical analyses conducted during the first three years of this project (see final report for project 16120114-S) on archived samples and then on acquired samples from 2015 field work revealed the absence of weathering since the oil made landfall. The intent of the current study (21200114-P) was to determine if oil still remains in these locations. Samples were collected and archived, but no chemical analysis has been planned. Fieldwork for this study was delayed by the coronavirus pandemic and finally completed in 2021; this is the final report for that work.

Abstract: Small patches of *Exxon Valdez* oil have persisted on beaches contaminated in 1989. In 2021 we assessed five of these beaches (EL056B, EL056C, GR103B, KN114A, and SM006B) to update the Trustee Council on persistence of this oil. Surveys followed a random stratified design aimed at measuring the probability of encountering oil, from which we calculated the oiled area and the retention rate since 2015. We found oil on each of the beaches, but only one may have less oil than previously observed. There has been a decreasing trend in encounter probability on EL05C, and the estimated oiled area is significantly reduced. However, the decreasing trend was not different from zero. Oiled areas were reduced on all beaches, but no other evidence suggested that oil contamination had decreased. Reductions in oiled area are likely an artifact of sampling design. We conclude that subsurface oiling conditions are still much like they were when the oil made landfall. Previous work has shown that the oil has not weathered since making landfall. We conclude that after 32 years this oil is sequestered and therefore has limited bioavailability.

Key words: *Exxon Valdez*, Gulf of Alaska, lingering oil, long-term monitoring, Prince William Sound, weathering.

Project Data:

Data description -Data include the beach segment identifiers, descriptions of the sampling grid, the number of pits dug, number of pits with oil, and sediment descriptions for the survey conducted in 2021. Data are provided on Excel spreadsheets and are located online in the publicly available AOOS data portal (http://portal.aoos.org/gulf-of-alaska.php#metadata/91b73240-b68d-43d8-bd64- aea4ea14e976/project/files).

The data custodian is Carol Janzen, Director of Operations and Development, Alaska Ocean Observing System, 1007 W. 3rd Ave. #100, Anchorage, AK 99501, 907-644-6703. janzen@aoos.org. Data are archived by Axiom Data Science, a Tetra Tech Company, 1016 W. 6th Ave., Anchorage, AK 99501.

Data access limitations - These data are archived by the Gulf Watch Alaska's *Exxon Valdez* Oil Spill Trustee Council and the National Marine Fisheries Service. There are no limitations on the use of the data, however, it is requested that the authors be cited for any subsequent publications that reference this dataset. It is strongly recommended that careful attention be paid to the contents of the metadata file associated with these data to evaluate data set limitations or intended use.

Citation:

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EXECUTIVE SUMMARY

In March of 1989, the *Exxon Valdez* oil tanker ran aground on Bligh Reef spilling an estimated 11 million gallons of crude oil into Prince William Sound (PWS) (Rice et al. 2007) and the Gulf of Alaska, one of the most productive marine ecosystems in the world (Spies et al. 2007). The spill impacted coastal marine habitats from PWS to Kodiak and Katmai National Park and Preserve. Following the *Exxon Valdez* oil spill, numerous studies have been conducted to understand its effects on the region and restore injured resources through work funded by the *Exxon Valdez* Oil Spill Trustee Council (EVOSTC) (Mundy 2005, Harwell et al. 2010, Esler et al. 2018).

Long-term persistence of subsurface oil on certain beaches was one of the principal findings of the effects of the *Exxon Valdez* oil spill. Initial assumptions were that beaches would be cleaned by winter storms reworking beach sediments and mobilizing lingering oil residues over one or two seasons. By the late 1990s it was evident that significant amounts of oil remained buried on certain beaches and this oil could exert toxic effects. This motivated a series of surveys in the early 2000s aimed at assessing the extent of lingering oil and evaluating its weathering state. Examination of the weathering state provided information on how quickly it was degrading and its potential toxicity. These surveys indicated that oil persisted on beaches in and outside of Prince William Sound and that the oil had not weathered since making landfall. Consequently, the lingering oil retained toxic potential. In the early 2010s efforts were made to model the distribution of the lingering oil patches by examining the geomorphology of affected beaches. In 2015, EVOSTC supported another survey of a small subset of beaches to validate model predictions and determine if oil was still present. That survey, *Extending the tracking of oil levels and weathering (PAH Composition) in PWS through time* (project 16120014-S), was incorporated into the Gulf Watch Alaska Long-Term Monitoring Program. The survey was conducted in 2015 and indicated that there was no evidence that the oil had dissipated nor was there evidence that the residues had weathered. Further, the authors suggested that the primary way sequestered oil was being mobilized on these beaches was through disturbance associated with digging sampling pits in the sediments. In 2019 another smaller survey was funded to extend the time series without support for chemical analysis. This latest survey is the subject of this report.

The overall goal of this lingering oil project was to extend previous efforts to track *Exxon Valdez* oil levels and weathering in PWS since the onset of the spill. The main objectives were to: (1) determine the probability of encountering oil on five beach segments previously known to harbor lingering oil and compare these probabilities to previous surveys, (2) use the observed encounter probabilities to estimate the oiled area on each beach and compare these areas to previous reports, (3) calculate the retention rate of oil on the beaches relative to the encounter probabilities observed in 2015, and (4) assess frequency of the residue oiling intensities relative to previous reports, and (5) compare the vertical distribution of oil residues to previous reports.

To accomplish Objective 1, a lingering oil survey, using established techniques, revisited a small set of the worst-case sites in PWS where sequestered oil was known to persist. Sampling incorporated a stratified random design that allowed for estimating the probability of encountering oil in different sections of each beach segment. On each site we stratified the beach into a series of blocks representative of the shoreline and vertical sections between high and low tide levels. In each of the blocks we dug two pits in randomly selected locations. Encounter probabilities were estimated by dividing the number of oiled pits by the total number of pits dug on the beach. Measurements of the horizontal and vertical extent of each block were combined with the number of contaminated pits found in the block to estimate the area covered by oil (Objective 2). The observed encounter probabilities were divided by the probabilities reported from the 2015 survey to estimate the retention rate (Objective 3). Ratios ≥ 1.0 indicated no loss of oil was detected. For Objectives 4 and 5 we estimated the frequency of oil residue intensities using a previously used ordinal scale and compared those frequencies to previous reports. We used a similar approach to the percentage of the oiled pits found in each of the vertical beach sections.

We found little evidence of change in the oiling status on the beaches we examined. Encounter probabilities have not changed for the beaches as indicated by slopes over time that did not differ from 0.0 and overlapping 95% confidence intervals. The area covered with oil was lower than that reported in 2015 on each of the beaches, but this may be an artifact of sample sizes. Oil retention rates relative to the 2015 survey had 95% confidence intervals that overlapped 1.0 for each of the beaches indicating that retention rate estimates include 100%. Oil residues are still found primarily in the lower portions of these beaches and the frequency of residue intensities did not indicate any oil is being lost on these beaches. The percentage of light oil residue, moderate oil residue, and heavy oil residue remained similar over time.

The 2021 survey indicates that there has been little change in the amount and distribution of oil sequestered on armored beaches in PWS. Surveys conducted over 20 years by both EVOSTC and ExxonMobil Corporation have revealed the long-term persistence of relatively unweathered oil on these beaches. This indicates that the oil is protected from winter storms and other processes that were expected to remove it. Protection from mobilization and degradation is further supported by the efforts by both the EVOSTC and ExxonMobil Corporation to characterize the weathering state of the oil. We conclude that anthropogenic disturbance occurring during lingering oil sampling is the primary action that results in oil mobilization and degradation on these beaches.

INTRODUCTION

Long-term persistence of stranded oil is one of the most unanticipated observations made following the 1989 *Exxon Valdez* oil spill (EVOS). The supertanker *Exxon Valdez* ran aground on Bligh reef in Prince William Sound (PWS) on Friday March 24, 1989, and spilled at least 11 million gallons of Alaska North Slope crude oil (ANSCO). The crude oil contaminated approximately 2,100 km of shoreline. Initial Shoreline Cleanup Assessment Teams (SCAT) in PWS estimated that 40% of the spilled oil made landfall on beaches in PWS (Galt et al. 1991). By 1992, it was estimated that 5-8% of the initial spilled oil had been recovered from beaches resulting from an unprecedented clean-up effort (Wolfe et al. 1994). Follow-up SCAT surveys showed there was a decrease of oiled shoreline in PWS from 783 km in 1989 to 10 km by 1992 (Neff et al. 1995). Given the considerable loss rate observed for surface oil by 1992, it was assumed that remaining oil would continue to weather and dissipate on a short time scale (Page et al. 1995). However, during the first decade after EVOS, some site-specific observations of oiled shoreline in PWS began to cast doubt on the expected loss rate and *Exxon Valdez* oil (EVO) was observed persisting in a fairly unweathered state at some sites (Brodersen et al. 1998). Entrenched subsurface oil was no longer being removed by natural processes in some places, which suggested loss rates had slowed down.

During the 2000s a new series of comprehensive surveys to update estimates of lingering oil in PWS were initiated by the *Exxon Valdez* Oil Spill Trustee Council (EVOSTC). National Marine Fisheries Service's (NMFS's) Auke Bay Laboratories (ABL) conducted a lingering oil survey in 2001 to provide a quantitative, probability-based estimate of the amount of oil remaining 12 years after the spill (Short et al. 2004, Pella and Maselko 2007). Estimates from this survey revealed a cumulative area of EVO of 11.3 ha and a mass of 55,600 kg of subsurface oil in PWS. The majority of the subsurface oil was located in the mid intertidal zone, although some occurred surprisingly low in the intertidal zone. The significance of this oil became apparent when locations of lingering oil from the comprehensive surveys was compared to the areas where sea otter recovery was slower than the rest of the PWS (Bodkin et al. 2014) and supporting evidence of chronic oil exposure and wildlife effects was detected (Iverson and Esler 2010).

Additional surveys conducted in 2003, 2005, and 2015 focused on determining the distribution of subsurface oil with respect to tidal elevation and the probability of encountering oil in a heavily oiled region of PWS (Short et al. 2006, 2007, Lindeberg et al. 2018). A comparison of survey results between 2001 and 2005 showed the likely rate of decline of oiled beach area within PWS was 3-4 % yr^{-1} and the oil was moderately weathered. Given the quantitative consistency of the surveys conducted in the 2000s, a geomorphic spatial model was developed to predict where subsurface oil was likely to occur in addition to known locations (Michel et al. 2010, Nixon and Michel 2015). Model estimates based on data collected between 2001 and 2015, revealed lingering subsurface oil represented 0.6% of the total spill volume (Michel et al. 2016). A comparison of the 2015 survey data with data aggregated from the Trustee surveys and Exxon-sponsored surveys indicated that between 2003 and 2015 the oil on these particular beaches was not mobile, nor had it undergone any substantive weathering.

The long-term persistence of this oil has led to some concern on the part of the public and motivated a need for the Trustees to continue monitoring these sites. Detailed surveys conducted by both the Trustee Council and the Exxon-Mobil Corporation have demonstrated that the composition of the oil is changing very slowly. Consequently, the Trustee Council developed a survey approach aimed at verifying the continued presence of this oil, while minimizing survey cost. This presence/absence approach included assessing a small subset of the most contaminated beaches for presence of oil and contrasting the probability of encountering oil with the probability observed by previous surveys. Changes in the vertical distribution of the oil, the apparent area of oiling, and the probability of encountering oil relative to previous surveys would be interpreted as evidence that the beaches are becoming less contaminated.

OBJECTIVES

The following lists each of the objectives for the 2021 survey conducted to assess the presence or absence of oil on contaminated beaches in PWS:

1. Determine probability of encountering oil on beaches previously described as harboring lingering oil and compare those probabilities with encounter rates from previous surveys.
2. Use survey data to estimate area occupied by oil on the beaches and compare with previous surveys.
3. Estimate the proportion of oil retained on the beaches since the last survey in 2015.
4. Determine the degree with which sediments are oiled using an ordinal scale of measurement and compare those results with previous surveys.
5. Determine the vertical distribution with which sediments are oiled and compare that distribution with results from previous surveys.

METHODS

We adopted methods for surveying beach segments used in previous surveys (Short et al. 2006, Short et al. 2007, Boehm et al. 2008, Lindeberg et al. 2018) to ensure comparability in oil encounter rates and classification. Our goal was to use a sampling protocol designed to be simple and relatively inexpensive, facilitating ease of this and future assessments. In general, our strategy was to revisit and survey five beaches that had the highest probability of encountering lingering oil in 2021. Surveys were intended to estimate the probability of encountering oil using a stratified random sampling design.

Site selection

The five beaches known to have the highest probability of encountering oil were selected from those surveyed in 2015 (Table 1, Fig. 1). These beaches should be considered “worst case” and are not random samples of beach segments in PWS. The sites selected for long-term monitoring have a history of human disturbance and loss of subsurface oil (SSO) could be variable among these sites over time. Since the onset of the spill, oiled beaches have been surveyed and treated by using a variety of mechanical removal and remediation techniques.

Table 1. List of beach segments selected for re-surveying during summer 2021 in Prince William Sound (PWS), Alaska.

Location Name	Shore Segment	Initial Oiling	Oil Surveys Excavation History[a]	Most Recent Oil Class[b]	Shore type prone to persistent oil
Northwest Bay, Eleanor Island	EL058B	Heavy oil 1989	2001[3], 2005[3]	MOR	breakwater
Northwest Bay, Eleanor Island	EL056C	Medium oil 1990-1993	2001[3], 2007[4]	MOR	rubble accumulations
Green Island	GR103B	Heavy oil 1990-1993	2001[3], 2005[3], 2007[4]	HOR	armored, slope
Herring Bay, Knight Island	KN0114A	Heavy oil 1990-1993	2003[3]	HOR	breakwater
Smith Island	SM006B	Heavy oil 1990-1993	1989-92[1,2], 2001[3], 2008[4]	HOR	armored

[a]Excavation history - [1]National Oceanic and Atmospheric Administration (NOAA) Hazmat (now Office of Response & Restoration), [2]*Exxon Valdez* Oil Spill Trustee Council Gibeaut and Piper 1998, [3]NOAA Auke Bay Laboratories, [4]Nixon and Michel 2015.

[b]Oil classes are defined as moderate oil residue (MOR) and heavy oil residue (HOR).

Figure 1. Map of sites for monitoring lingering oil in western Prince William Sound for 2021.

Beach surveys

Lingering oil monitoring surveys were conducted from a chartered vessel during a single five-day cruise, from June 24, 2021, to June 28, 2021, that coincided with a summer low tide window (zero tide height or lower). On each beach the survey crew (five members) established the survey grid, randomly selected pit locations, excavated the pits, assessed the pits for presence and intensity of oil, and collected samples.

Establishing a site survey grid

Survey grids were established during a falling tide to enable the random stratified sampling scheme. Grids divided the beach into a series of 20 m wide columns and then divided each column into rows arrayed along elevation drops between high and low tide. This created a series of sampling blocks. All sites were sampled on the early morning tide, the larger of the two daily low tides in a diurnal cycle. The crew arrived at the site on a falling tide around 30-45 minutes before zero tide and used a Topcon 360-degree self-leveling laser with receiver to measure and mark the grid columns (A-E) and the meter vertical drops (MVDs; 1-5/column). Each beach segment was 60 m to100 m wide and divided into 20 m wide columns. Two pits were randomly selected for excavation in each block. Figure 2 illustrates the sampling design.

When establishing the survey grid, the start point was the left end of the beach segment when looking at the beach from the water, and all columns were to the right of the start point. At the start point, a vertical meter tape was laid from the top of the beach down to the water's edge (e.g., 0 m at top of beach and X m to bottom), perpendicular to the top of the beach. On the vertical tape, a horizontal meter tape was laid across the whole site (0 to X m) near the upper third of the intertidal zone. At each of the 20 m marks, vertical meter tapes (A-E; five survey tapes) were laid perpendicular to the top of the beach. The Mean High Water Level (MHWL) was estimated and then the survey crew adjusted each tape as they established the grid.

Once the columns were arrayed the locations of the vertical drops were established. Beginning with the top of column A, the MHWL was first determined, set at 5 m for Prince William Sound. The laser level on a tripod was set up near the upper third of the intertidal zone close to the beginning of site. A stadia rod was walked with the receiver down to the water's edge and extended until the receiver was in line (pinged) with the Topcon. The stadia rod receiver was adjusted up or down ("+ X cm" or "– X cm" from 5-meter MHWL to 0 tide line) based on time at tide correction from the tide tables listed in 5 min increments. This was the vertical height for MHWL. The laser level and tripod were moved up or down the beach until it pinged the stadia receiver. The laser level was now leveled to MHWL.

The MHWL was identified at the top of beach by moving the stadia rod/receiver to the start point of the site, turning it upside down so the receiver was near ground and finding the location where it pinged the laser level. This was the start of Column A, MHWL. The vertical survey tape was adjusted so 0 meters was on the MHWL mark. This location was marked with a tent stake.

Next, the location of vertical drops from MHWL at 1 m, 2 m, 3 m, 4 m, and 5 m were identified on the tape measure anchored at 0 m. These drops are referred to as MVD 1, MVD 2, MVD 3, MVD 4 and MVD 5, respectively. To find MVD 1, the stadia rod and receiver were set to 1 m height. A crew member then walked down the survey tape with the stadia rod until MVD 1 was found with the receiver pinging. The horizontal tape distance (rounded to the nearest 0.5 m) was recorded, with a tent stake placed at the base of the pinged stadia rod. The process was repeated to find MVD 2, 3, 4, and 5 by increasing the height of the receiver on the stadia rod to reflect the vertical drop. That is for MVD 2, 2 meters, MVD 3, 3 meters, and so on until the bottom of the grid at 5 meters (bottom of MVD 5).

The MVDs 1-5 were similarly established for the remaining columns. The next column was the vertical meter tape 20 m to our right (note - our right or left was always referenced as we were facing the beach, looking toward the top of the beach). We found the top of the columns again by moving the stadia rod/receiver to the starting point of the site, turned upside down so the receiver was near the ground and found the location where it pinged the laser level. We adjusted the vertical survey tape so zero meters was on the MHWL mark for each column, marking these locations with a tent stake.

Selection of pit locations

Once a block and its dimensions were established, the random pit locations were calculated so diggers could begin. Using the survey data sheet, a crew member calculated the coordinates (horizontal and vertical tape distances) for the random pits within each block. The horizontal distance was calculated by multiplying the width of the block minus 0.5 meters to make sure all random pits are within the block by a uniformly generated random number between 0 and 1. The vertical distance was calculated by multiplying the height of the block minus 0.5 meters by a uniformly generated random number between 0 and 1. See Fig. 2 for a diagram of the survey grid showing columns A-E, MVDs (1-5), and random pits (R1, R2). If a subsequently chosen pit overlapped a previously selected pit, we regenerated the random number until there were no overlapping pit locations (i.e., the pits within a block were sampled without replacement).

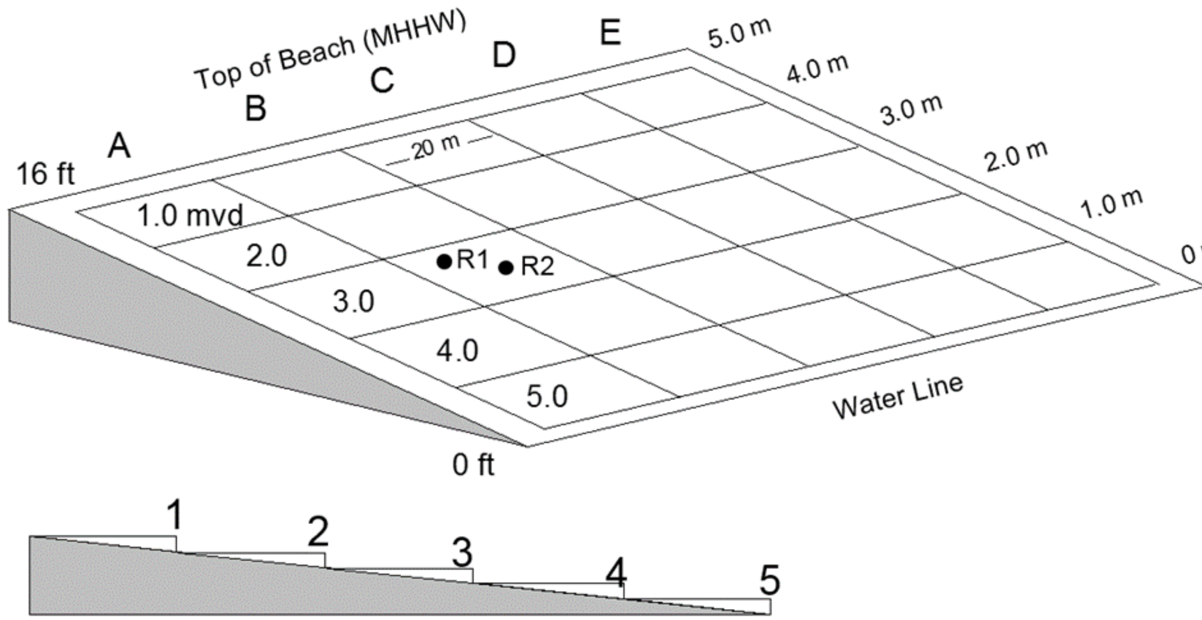

Figure 2. Diagram of survey grid for a 100 m beach segment showing: 10 m columns (A-E), meter vertical drops (MVDs; 1- 5), and random pits (R1, R2) within column B, MVD 3.

Pit excavation

The presence or absence of subsurface oil was determined by excavating randomly selected pits. To excavate a pit, a 0.5 m x 0.5 m perimeter of the pit quadrat was established and the overburden was removed and piled carefully to one side of the pit. The content of the pit was dug out to a depth of 0.5 m, while looking for evidence of oil seeping along the edge of the hole, on the undersides of cobble or boulders, sheening on the water, or the smell of oil. Once encountered, digging ceased and a designated oil sampler evaluated the pit and collected a sediment sample. The evaluator donned a fresh pair of nitrile gloves and conducted the evaluation. After evaluation, the pit was backfilled with the excavated material. If the pit was oiled, we attempted to top off the pit with surrounding clean material. Shovels and other tools were thoroughly cleaned using soap and a brush if in contact with an oiled pit and the evaluator discarded their gloves.

Evaluation of oiled pits

The Chief Scientist of the survey team was designated the oiled pit evaluator. They were responsible for thoroughly filling out the oiled pit data sheet. Before the pit was backfilled, the evaluator classified the residue in the pit following descriptions given in Table 2.

Table 2. Subsurface oil types used for classification.

Code	Type	Definition
OP	Oil Pore	Pore spaces are completely filled with oil resulting in oil oozing out of sediments - water can't penetrate OP zone
HOR	Heavy Oil Residue	Pore spaces partially filled with oil residue but not generally flowing out of sediments
MOR	Moderate Oil Residue	Heavily coated sediments; pore spaces are not filled with oil; pore spaces may be filled with water
LOR	Light Oil Residue	Sediments lightly coated with oil
OF	Oil Film	Continuous layer of sheen or film on sediments; water may bead on sediments
TR	Trace	Discontinuous film; spots of oil on sediments; an odor or tackiness with no visible evidence of oil

The depth of the pit and the depth where the oil started and ended were recorded. The top of the pit was considered 0 cm and the bottom of the pit 50 cm. We noted the different substrates and any single or multiple bands of oil in the pit, oil layers near the surface, or oil at the bottom of the pit going deeper than our sampling effort. If there was water in the pit, we recorded the presence and how much (e.g., 10 cm in bottom of pit), along with the color of the oil sheen floating on the surface (brown, rainbow, silver, none). We then classified and recorded the kind of sediment in the pit (Boulder, Cobble, Pebble, Granule, Sand, and Mud). Substrate classifications followed standard Wentworth scale. A slash between substrate codes indicated surface sediments vs subsurface sediments. The first code represented the most common substrate, followed by the second most common, and so forth. Finally, we recorded the GPS coordinates of the pit along with the pit location (e.g., A 4, R1) and took a photograph.

Sediment chemistry sampling

No chemical analysis of sediment samples was planned for this project; however, sediment samples were collected from oiled pits and archived for potential later analysis. Prior to collecting these samples, we ensured that our surroundings were free from possible sources of contamination. Samples were collected in 2 oz certified hydrocarbon-free jars using spoons previously rinsed with methylene chloride and wrapped in aluminum foil. Spoons were only used once. The finest grain sediments with oil were collected (silt, mud, sand, granules). Sediments have high water content, so we did not fill the jars to the top to prevent bursting when frozen. Any excess water was discarded. Samples were labeled with a sample identification number (SIN). Jar lids were also labeled with SIN and date. A GPS waypoint with longitude and latitude also was recorded for each oil sample. All data were recorded on chain of custody forms. Samples were stored in a cooler, frozen as soon as possible, and kept frozen at - 22 °C until shipping for prolonged storage at the Auke Bay Laboratory in Juneau, Alaska. Upon arrival the change in custody was noted on the chain of custody forms. All sampling equipment was thoroughly cleaned between samples using Joy detergent and a scrub brush, starting with the cleanest tool and working to the dirtiest. Spoons were returned to the laboratory for cleaning.

Photo documentation

Photo documentation of monitoring sites were taken of the start of site and column A, all oiled pits, all columns (A-E) starting at the top, along shore shot from column A across sites, from column E looking back across site, method examples (surveying, digging pits, etc.), and all MVD block starts in the upper left-hand corner where the stake was placed. Files were transferred from the camera to a laptop and labeled. Selected images can be viewed in Appendix A.

Statistical analysis

The goals of the analysis included determining the probability of encountering oil on each beach segment, estimating the area occupied by oiled patches, calculating the retention rate of oil since the last survey in 2015, evaluating the vertical distribution of the oil on the beaches, and assessing the frequency of residue classifications. We also compared these values to previously published values (Short et al. 2003, Short et al. 2005, Short et al. 2007, Boehm et al. 2008, Lindeberg et al. 2018). The probability of finding oil on the i^{th} beach segment, $\hat{p}_i$, was estimated as the ratio k_i/N_i where k_i is the number of pits contaminated with any subsurface oil and N_i is the total number of pits dug. Note that when calculating encounter probabilities, we included pits located on bedrock and other impervious surfaces to ensure comparability with previous analyses. We also provide data describing the encounter probabilities adjusted for the presence of impervious surfaces, $p_{i-adj,}$ by subtracting the number of pits located on bedrock outcrops from N_{i-adj}. The variance for $\hat{p}_i$ was estimated as $p_i(1-p_i)N_i^{-1}$. The observed $\hat{p}_i$ was combined with estimates for other surveys and plotted as a function of survey year. A linear regression was conducted on the plot to determine if the slope between $\hat{p}_i$ and year differed from 0.0.

The stratified random approach used allowed us to estimate the oiled area on each beach segment, $\hat{\tau}_i$. We compared these estimates with those calculated in the same way from the 2015 and 2005 surveys. First, we used the measurements of column width and the bounds of the vertical drop to estimate the total area of the block, A_k. $\hat{\tau}_k$, the oiled area of the k^{th} block is given by :

Equation 1. $$A_k \frac{\sum_{i=1}^{n_k} x_{ki}}{n_k}$$

where x_{ki} is the oiling status of the i^{th} pit in the block and n_k is the total number of pits dug in the block. Note that the adjustment takes on the value of 0, 0.5, or 1.0 depending on whether we observed oil in none, one, or both pits excavated in block *k.* Multiplying the adjustment by A_{ik} gives $\hat{\tau}_k$. The oiled block areas were summed to find $\hat{\tau}_i$. Variances for $\hat{\tau}_i$ were calculated as:

Equation 2. $$V\hat{a}r\ (\tau_i) = \sum_{k=1}^{B}(A_k)(A_k - O_k)\frac{s_k^2}{O_k}$$

Where s_i^2 is equal to:

Equation 3. $$\left(1 - \frac{\hat{\tau}_k - 1}{A_{ik} - 1}\right)\left[\frac{\left(\frac{\sum x_{ki}}{n_k}\right)\left(1 - \frac{\sum x_{ki}}{n_k}\right)}{n_k}\right]$$

We compared the oiled areas to estimates from the 2015 survey by constructing 95% confidence intervals for $\hat{\tau}_i$ and plotting them against similar intervals obtained in 2015.

We estimated the amount of oil retained between the 2015 and 2021 surveys following procedures described for previous surveys (Short et al. 2007, Lindeberg et al. 2018). The retention rate for a given beach, $\hat{\theta}_t$,

Equation 4. $$\hat{\theta}_t = \left(\frac{p_{2021}}{p_{2015}}\right)^{1/t}$$

and *t* is the number of intervening years between the 2021 survey and the previous survey and p_t is the encounter probability in year *t*. We calculated the variance for p_t as

Equation 5. $$\left(p_t(1 - p_t)\right)/N_t$$

To find the 95% confidence interval for $\hat{\theta}$ we bootstrapped 500 estimators of $\hat{\theta}_t$ to determine the standard error.

Finally, we evaluated the distribution of the oil on the beaches by contrasting the vertical distribution of the oiled pits with previous reports by proportion of all the oiled pits found in each of the vertical blocks. These proportions were plotted against the 95% confidence intervals reported by Lindeberg et al. (2018). We performed a similar analysis for the proportion of oiled pits identified as light oil residue (LOR), moderate oil residue (MOR), or heavy oil residue (HOR) and confidence intervals found in Lindeberg et al. (2018).

RESULTS

Oil was readily found in subsurface sediments sampled on all five of the beaches re-surveyed in 2021 and there was little evidence that encounter rates have changed. Overall, oil was encountered in 12.8% of the 188 pits sampled. While estimates of the encounter probabilities were lower on each of the surveyed beaches when compared with encounter rates from the 2015 survey (Lindeberg et al. 2018; Table 3), plots of the 95% confidence intervals for $\hat{p}_i$ with the same values from previous surveys revealed little evidence for a change over the last 20 years (Fig. 3). Confidence intervals for oil encounter rates largely overlapped for all surveys except for EL056C, which had disparate estimates for $\hat{p}_i$ in 2001 versus 2021. The relationship between $\hat{p}_i$ and time was negative for EL056, GR103B, and SM006B (Figure 3), however none of the slopes differed significantly from 0.0 ($P > 0.150$). Similar results were observed after adjusting the number of excavated pits by subtracting those on impervious substrates (Appendix A).

Table 3. Segment descriptions and the probability of encountering oil based on the number or pits randomly assigned sampled or adjusted for the number of pits located on impervious material. Encounter probabilities from 2015 are provided for comparison.

Segment	Length (m)	Pits dug	Number impervious pits	Number TR/LOR[a] pits	Number MOR[b] pits	Number HOR[c] pits	$\hat{p}_i$	$\hat{p}_{i\text{-}adj}$	$\hat{p}_{2015}$[d]
EL058B	80	40	4	0/2	2	0	0.10	0.11	0.33
EL056C	60	30	3	2/3	1	0	0.20	0.22	0.40
GR103B	100	40	5	0/1	0	0	0.18	0.22	0.12
KN114A	60	28	8	1/1	1	2	0.03	0.03	0.23
SM006B	100	50	10	6/2	0	0	0.16	0.20	0.20

[a]TR/LOR: Trace/light oil residue
[b]MOR: moderate oil residue
[c]HOR: heavy oil residue
[d.]Lindeberg et al. (2018)

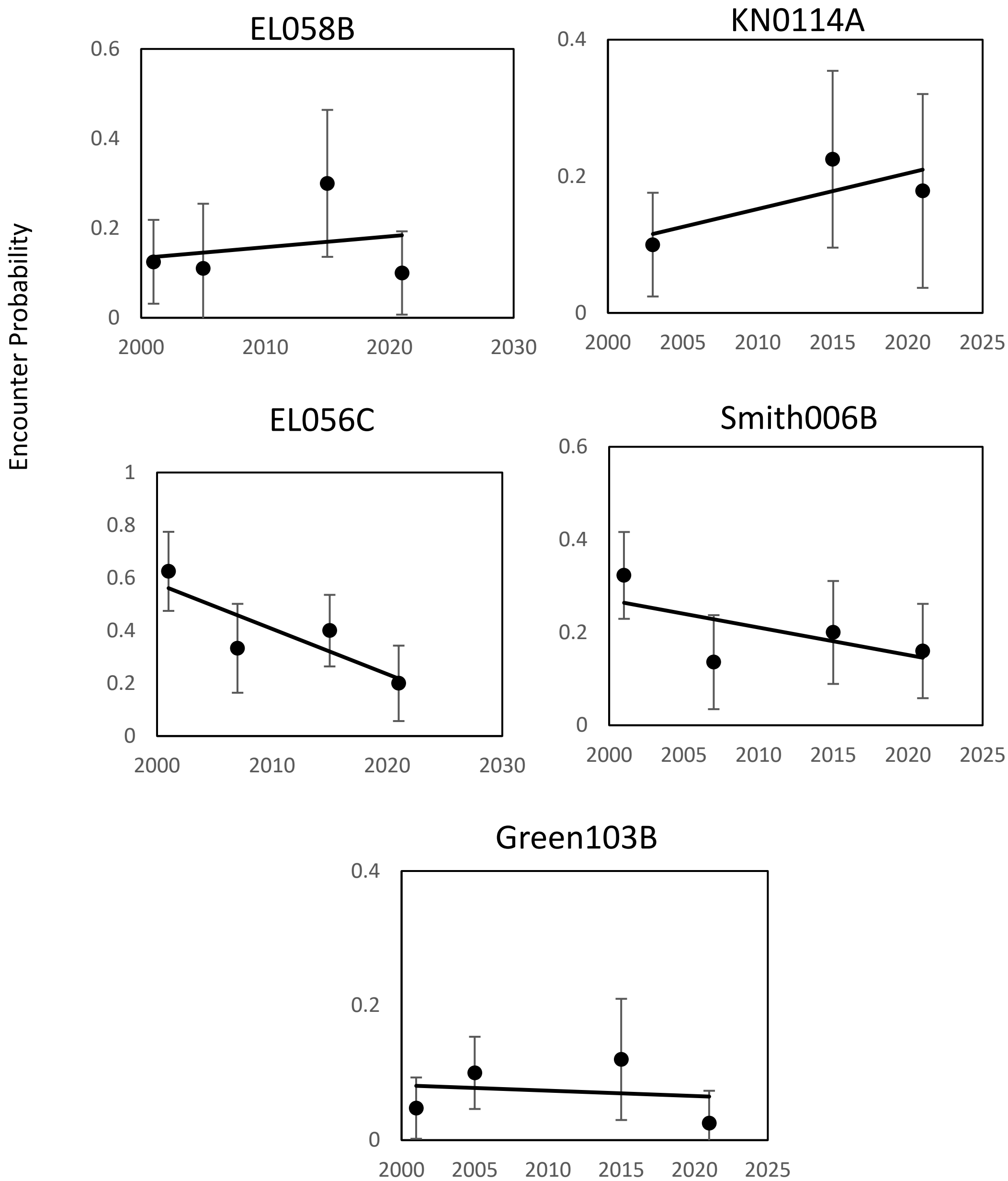

Figure 3. Temporal change in encounter probabilities for beach segments surveyed in 2021. Symbols depict 95% confidence intervals and lines were derived from linear regressions.

The estimated oiled areas, $\hat{\tau}_k$, decreased on each of the beaches relative to estimates from 2015. However, an average of 14% of the beach area surveyed was oiled compared with 11% in 2015. Values for $\hat{\tau}_k$ decreased the most on segments GR103B and EL056C (Fig. 4), decreasing by 87% and 64%, respectively on these segments. However, the point estimate for $\hat{\tau}_k$ on GR103B in

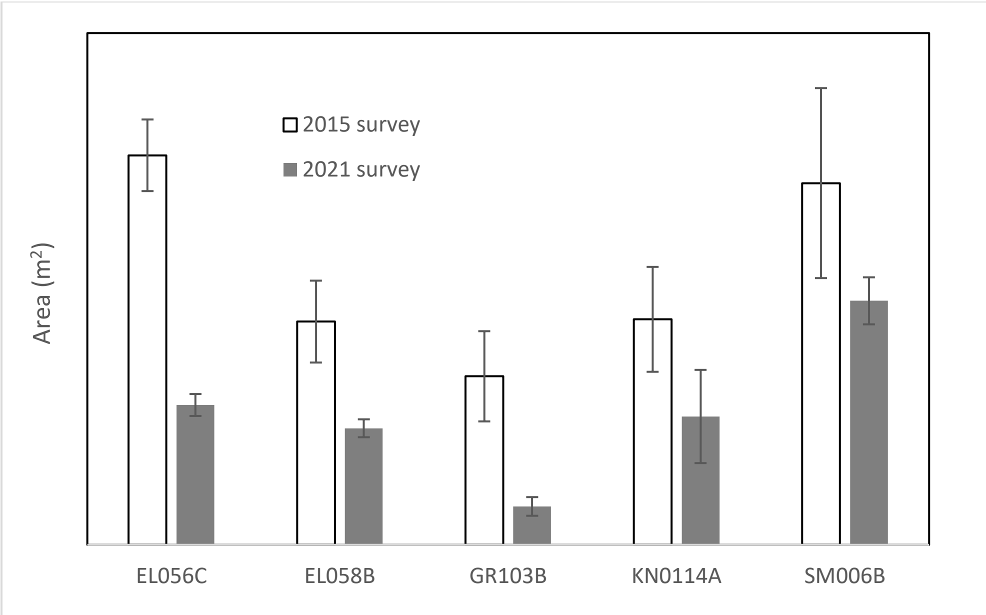

Figure 4. Estimated areas contaminated with oil on beach segments surveyed in 2015 and 2021. Error bars depict 95% confidence intervals.

2005 was 147 m^2 (Short 2007) and within the 95% confidence interval for the 2021 estimate. Moreover, oil occupied the greatest area on segment EL056C during 2015 and had the second greatest coverage in the 2021 survey. The converse was true for SM006B, and all other ranks were conserved between the two years. Coefficients of variation were less than 20% for all the segments indicating the adequacy of the sampling strategy.

Despite reductions in oiled areas, estimates of $\hat{\theta}_k$ revealed little loss of oil from the beaches. Values for $\hat{\theta}_k$ ranged from 0.77 to 0.96 and all the confidence intervals encompassed 1.0 (Fig. 5). GR103B had the lowest estimated retention with $\hat{\theta}$ equal to 0.77 ± 0.25. In contrast, EL056C had a retention rate of 0.89 ± 0.13 indicating nearly 90% of the oil observed in 2015 was still there in 2021. It is worth noting that estimates of $\hat{\theta}_k$ for the period between 2001 and 2015 indicated an increase in oil at GR103B and that there was evidence of oil loss at EL056C between 2005 and 2015 (Lindeberg et al. 2018). There was little if any evidence that oil is degrading on the surveyed beaches.

There was also little indication of any change in the spatial distribution of the oil or the distribution of residue types. Of the oiled pits, 75% had trace oil or lightly oiled residues (LOR), compared to 17% of the oiled pits being moderately oiled (MOR) and 8% heavily oiled (HOR). These values were nearly identical to the previous surveys (Fig. 6). The vertical distribution of oil patches on the surveyed beaches did not differ from previous surveys (Fig. 3). The subsurface oil was most abundant in the lower/middle of the intertidal (MVD 4: 37.5%) with the next highest percentage being found in the middle of the intertidal (MVD 3: 20.8%). Only 8.3% of the oiled pits were found in the lowermost section of surveyed beaches (MVD 5) compared with

16.7% in the highest (MVD 1). The next highest section, MVD 2, also contained 16.7% of the oiled pits.

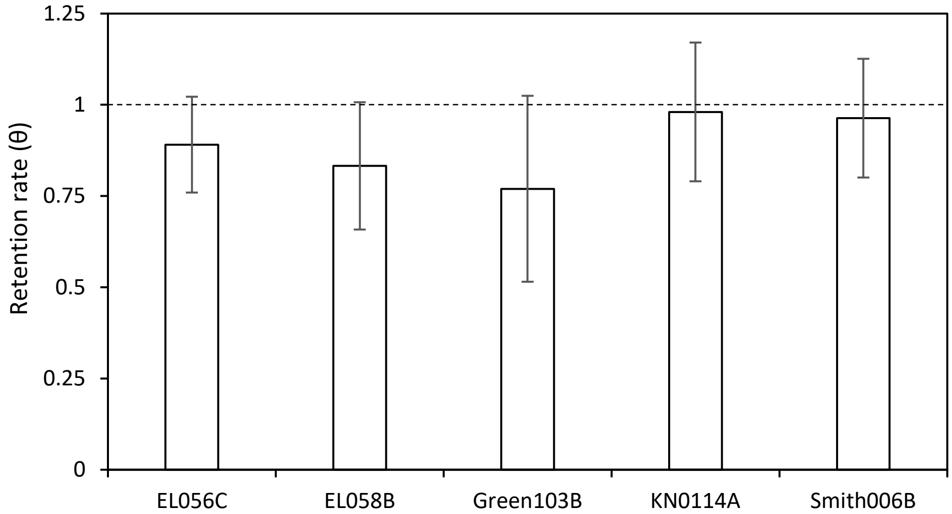

Figure 5. Estimated proportion of oil retained on survey beach segments between 2015 and 2021. Bars show 95% confidence intervals and the dashed horizontal line depicts a value of 1.0, which indicates complete retention.

From the 2021 survey, allocating half of the MVD 3 pits to the upper half of the beach results in an estimated 43.7% of the oil in the upper intertidal and 56.2% in the lower intertidal. The distribution of oiled pits was similar to 2015 survey results, where 38% of the oil was in the upper intertidal and 62% in the lower intertidal.

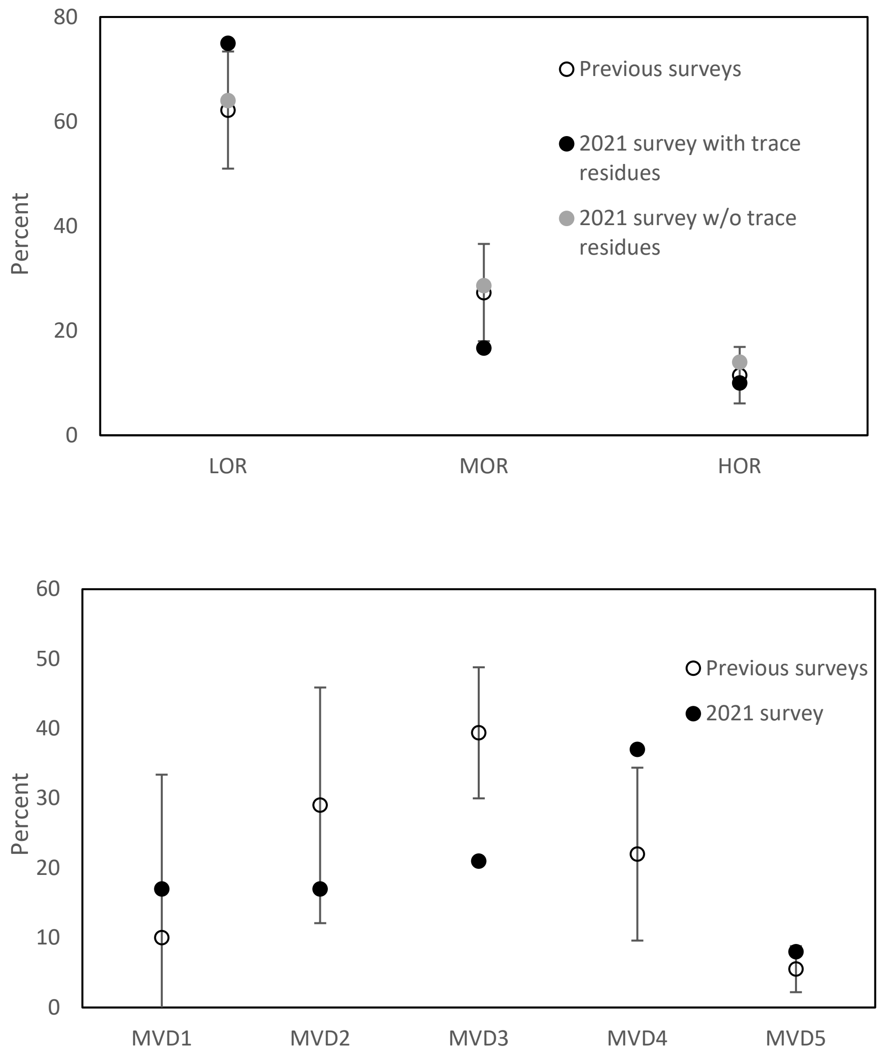

Figure 6. Spatial distribution of oil contaminated pits in previous surveys and the 2021 survey (top panel). Error bars show the 95% confidence interval based on previous surveys and solid symbols show the percentage of oiled pits for each vertical drop in the 2021 survey comparison. The frequency distribution of oil residues (bottom panel) is shown in a similar manner, showing 95% confidence intervals based on previous surveys and observations from the 2021 survey.

DISCUSSION

For more than 30 years since EVOS, it has been possible to find oil lingering in the sediments of specific beaches in PWS (Lindeberg et al. 2018, Nixon and Michel 2018). Initially, these beaches were heavily oiled and tidal action drove the oil deep beneath the cobble/boulder armor into nutrient-poor, anoxic sediments (Nixon and Michel 2015, Sharifi et al. 2011). It remains in these locations and has experienced little weathering since making landfall (Lindeberg et al. 2018). Surveys conducted in 2021 confirmed the presence of oil on five of these beaches. Point estimates of oil encounter probabilities ($\hat{p}$) were lower than those reported for the 2015 survey, but there was no evidence of a statistical difference. Similarly, the 95% confidence intervals for oil retention rates, $\hat{\theta}$, between 2015 and 2021 overlapped 100%. These results seem to be at odds with the decreased estimates of oiled areas between 2015 and 2021, however this is likely a product of the inherent variability in the area estimates. Comparison of areas estimated in 2021 with those reported earlier than 2015 are consistent with conclusions that there has been no appreciable loss of oil on these beaches. Similarly, the frequency with which different intensities of oiling and the vertical distribution on the beach is unchanged since surveys began in 2001.

The only evidence for a decrease in oil came from the analysis of oiled areas, which were found to be lower on each of the five beaches compared with the 2015 survey. Yet, the 2021 beaches averaged 14% oiled compared with 11% in 2015. The oiled area on EL056B was nearly identical to the 2005 estimate (~350 m^2) (Short et al. 2007). Similarly, the 2021 estimate for GR103B (120 m^2) was much closer to the 2005 estimate (~350 m^2) than the 2015 estimate (527 m^2). It is unlikely that oil areas increased between 2005 and 2015. A more likely explanation for reduced oil areas in 2021 is that oiled area estimates are highly variable because only two pits are dug per block. Recall from equation 1, that the oil in the k^{th} block is assumed to cover either the entire area, half of the area, or none of the area depending on the status of the two pits dug in the block. In a 100 m^2 block that has a true oil coverage of 18% (i.e., $p_k = 0.18$), the model would estimate complete coverage of the block 3% of the time, half coverage 33% of the time and no coverage 67% of the time. In no case would the model predict 18% of the area was oiled. Thus, one survey may estimate the oiled area as 50% while the next might find no oil. The true value of 18% would only be found after averaging the estimates of multiple surveys. In the case of PWS, only 2 to 3 such surveys have been completed for each beach segment. Employing a greater number of pits per block would offer the ability to better resolve the estimated areas.

Estimates of retention rates provide little if any evidence of decreasing subsurface oil since surveys began in 2001. Estimates of $\hat{\theta}_k$ are ratios of encounter rates and values of 1.0 indicate that the value $\hat{p}$ observed in one year is equal to that of the previous survey. In contrast, areas are calculated using the number of oiled pits observed to adjust the block area and then summing across blocks. Any detected loss of oil at a site would likely be due to repeated site disturbance and re-excavation of oiled areas resulting in mobilization of the trapped oil and not natural weathering. For example, a history of re-excavation (Short et al. 2004, 2006, 2007, Boehm et al. 2008, Michel et al. 2010) and intensive experimental remediation (Boufadel and Bobo 2011) are most likely explanations for the significantly different estimates of $\hat{p}_i$ between 2001 and 2015 at EL056C. There have been 20 winters between the initial survey for SSO and the most recent survey and no trend in $\hat{p}_i$ has been detected on any of the beaches. Consequently, we conclude that there is no evidence of natural weathering taking place.

This conclusion is consistent with the reports describing the hydrocarbon composition of the oil (Lindeberg et al. 2018). Those reports found that little evidence of meaningful change in the oil composition since making landfall in 1989. Short et al. (2004) reported that subsurface oil on these and other beaches had median weathering index (Short and Heintz 1997) equal to 3.3 with a range of 0.94-12.1. Twelve years later, Lindeberg et al (2018) examined a subset of these beach segments and reported a median index of 2.9, with a range of 0.0-6.3. Oil not removed by physical factors is often remediated by microbial degradation (Venosa et al. 2010), however, oiled beaches in PWS have low dissolved oxygen levels in subsurface layers, which significantly slows microbial degradation by orders of magnitude (Boufadel et al. 2010, Guo et al. 2010, Li and Boufadel 2010, Xia et al. 2011). Coincidently, the frequency of LOR, MOR and HOR residues is unchanged. If sequestered oil was being mobilized or otherwise degraded, we would expect the relative proportions of these residues to change. This observation is remarkable in that these frequencies have been reported by independent survey crews making qualitative assessments of residue quality over multiple decades. Furthermore, the vertical distribution of the oiled pits is unchanged with most oil found in the lower intertidal. The absence of changes in vertical distribution since 2001 demonstrates that wave action on residues is constrained by beach armoring and protective small scale geomorphic features (Owens et al. 2008, Hayes et al. 2010, Michel et al. 2016). Otherwise, these lower sections, which are most exposed to high energy wave action, would have fewer residues. These observations reveal that the primary avenue by which sequestered oil is mobilized is currently through anthropogenic disturbance, but potentially in future via natural events, such as storms or earthquakes.

CONCLUSIONS

These findings demonstrate the presence of subsurface oil on all five of the surveyed beaches and indicate it persists in the volumes, locations and weathering states that were first identified in 2001. Previous estimates indicate 0.25% to 0.6% of the original mass of spilled oil remains sequestered on beaches throughout the spill zone (Taylor and Reimer 2008, Nixon and Michel 2018). Sequestration under armored surfaces is still protecting the oil from weathering, allowing it to maintain its potential toxicity, but the absence of any significant loss indicates it is minimally bioavailable. Outside of anthropogenic disturbance, the potential for mobilization and bioavailability would require an unusual natural event. Observations of the prolonged persistence of spilled oil in subsurface sediments have been documented following other spills and, in some cases long-term ecological effects of persistent oil have been identified (e.g., Bodkin et al. 2014) but this is the only attempt to quantify the rate at which oil is being lost over a long-term time period. Viewing this survey in the context of previous surveys makes it clear that claims made after the spill that beaches would clean themselves (Page et al. 1995) were overly optimistic and we now know subsurface EVO can persist in the environment on a decadal scale in some sites.

ACKNOWLEDGEMENTS

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Online resources

EVOSTC Long-Term Monitoring Program –
http://www.evostc.state.ak.us/index.cfm?FA=projects.gulfwatch

Gulf Watch Alaska – http://www.gulfwatchalaska.org/

Gulf of Alaska Data Portal – http://portal.aoos.org/gulf-of-alaska.php

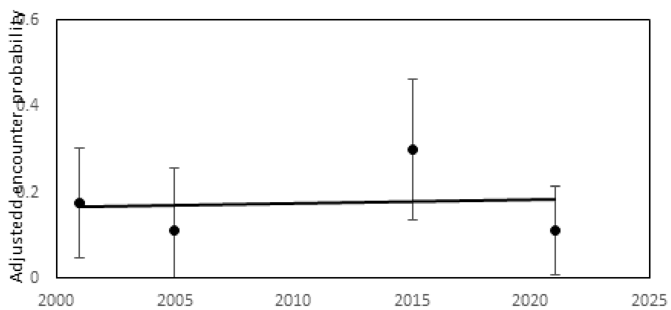
Lingering Oil project webpage –
http://www.gulfwatchalaska.org/monitoring/lingering- oil/lingering-oil-weathering-and-tracking/

APPENDIX A

Eleanor Island
EL058B
60.562026 N -147.573476 W

Results of surveys

Year	Pits	Pits on Bedrock	Oiled Pits	1 m Vertical Drops	Reference
2001	48	14	6	3	Michele et al. 2010
2005				5	Short et al. 2007
2015	30	0	9	5	Lindeberg et al. 2017
2021	40	4	4	5	This report



95% confidence intervals $\hat{p}_{i\text{-}adj}$ as a function of time with regressed line. $R^2 = 0.009$, slope = 0.001.

Distribution of oiled pits

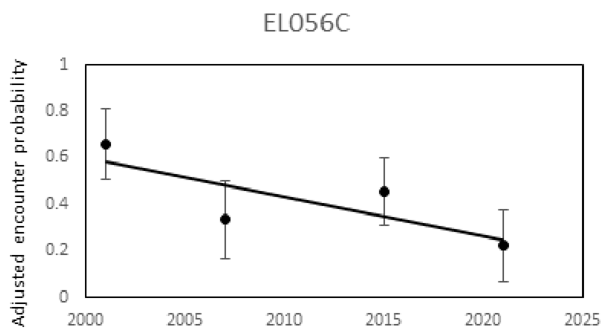
MVD	LOR	MOR	HOR
1	0	0	0
2	0	1	0
3	1	0	0
4	1	1	0
5	0	0	0

EL058B viewed from top of column A towards column D

Eleanor Island
EL056C
60.55095 N -147.57880 W

Results of surveys

Year	Pits	Pits on Bedrock	Oiled Pits	1 m Vertical Drops	Reference
2001	40	2	25	3	Michele et al. 2010
2007	30	0	10	4	Boehm et al. 2008
2015	50	6	20	5	Lindeberg et al. 2017
2021	30	0	6	5	This report



95% confidence intervals $\hat{p}_{i\text{-}adj}$ as a function of time with regressed line. $R^2 = 0.619$, slope = -0.017.

Distribution of oiled pits

MVD	LOR	MOR	HOR
1	1	0	0
2	0	1	0
3	0	0	0
4	3	0	0
5	1	1	0

EL056C viewed from top of column B towards the water

Green Island
GR1003B
60.300479 N -147.364841 W

Results of surveys

Year	Pits	Pits on Bedrock	Oiled Pits	1 m Vertical Drops	Reference
2001	84	66	4	3	Michele et al. 2010
2005				5	Short et al. 2007
2015	50	13	5	5	Lindeberg et al. 2017
2021	40	7	1	5	This report

95% confidence intervals $\hat{p}_{i\text{-}adj}$ as a function of time with regressed line. $R^2 = 0.663$, slope = -0.007.

Distribution of oiled pits

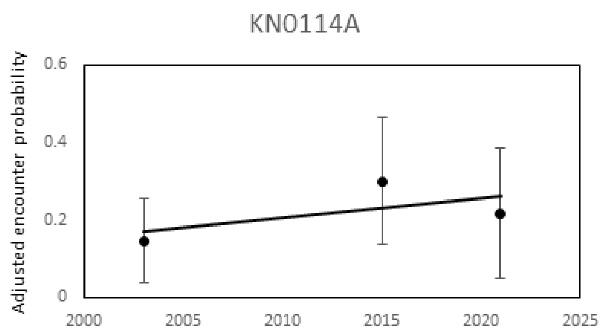
MVD	LOR	MOR	HOR
1	1	0	0
2	0	0	0
3	0	0	0
4	0	0	0

GR103B viewed from top of column A towards column E

Knight Island
KN0114A
60.48472 N -147.72361 W

Results of surveys

Year	Pits	Pits on Bedrock	Oiled Pits	1 m Vertical Drops	Reference
2003	60	19	6	3	Michele et al. 2010
2015	40	10	6	5	Lindeberg et al. 217
2021	28	5	5	5	This report



95% confidence intervals $\hat{p}_{i\text{-}adj}$ as a function of time with regressed line. $R^2 = 0.386$, slope = 0.005.

Distribution of oiled pits

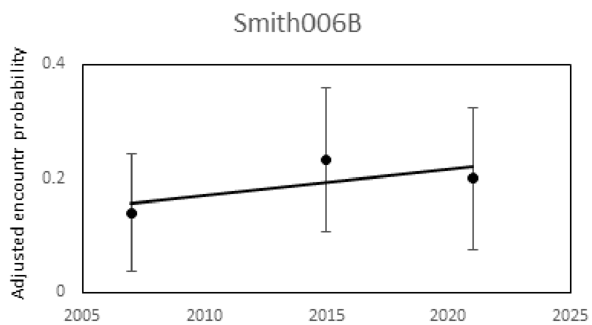
MVD	LOR	MOR	HOR
1	0	0	0
2	0	0	1
3	2	1	1
4	0	0	0
5	0	0	0

KN0114A viewed from top of column C towards column A

Smith Island
SM006B
60.51917 N -147.40389 W

Results of surveys

Year	Pits	Pits on Bedrock	Oiled Pits	1 m Vertical Drops	Reference
2001	96	22	31	3	Michele et al. 2010
2007	44	1	6	4	Boehm et al. 2008
2015	50	7	10	5	Lindeberg et al. 2017
2021	50	10	8	5	This report



95% confidence intervals $\hat{p}_{i\text{-}adj}$ as a function of time with regressed line. $R^2 = 0.492$, slope = 0.005.

Distribution of oiled pits

MVD	LOR	MOR	HOR
1	2	0	0
2	2	0	0
3	0	0	0
4	4	0	0
5	0	0	0

SM006B viewed from column A towards column E