A Response Guide for Sunken Oil Mats (SOMs): Formation, Behavior, Detection and Recovery

Prepared by:

Jacqueline Michel and Phil Bambach
Research Planning, Inc.
Columbia, South Carolina 29201

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List of Abbreviations

API°	API gravity
bbl	barrel
cSt	centistoke
DWH	*Deepwater Horizon* oil spill
GPS	Global Positioning System
mi	mile
mPa-s	milliPascal-second
NOAA	National Oceanic and Atmospheric Administration
OPA	oil-particle aggregate
OSAT	Operational Science Advisory Team

PPE   personal protective equipment
ppm   parts per million
ROV   remotely operated vehicle
SCAT   Shoreline Cleanup Assessment Technique
SOM   Sunken oil mat
SRB   Surface residue ball

Acknowledgments

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1. Introduction

Most oil spill response strategies are based on the concept that oil floats. However, oil does not always float. Sometimes it is suspended in the water column; sometimes it sinks to the bottom of the water body; and sometimes it does all three: floats, suspends, and sinks. The following terminology is used in this guide based on the American Petroleum Institute (2016) report on Sunken Oil Detection and Recovery:

- **Floating oil.** Spilled oil that is on the surface of the water.
- **Submerged oil.** Spilled oil that is in the water column, below the water surface, including oil that is in temporary suspension due to turbulence and will refloat or sink in the absence of that turbulence.
- **Sunken oil.** Spilled oil that is on the bottom of the water body.

Oil can sink and form sunken oil mats because:

1. The initial density of the oil is greater than that of the receiving water body (this process is more common in freshwater);
2. The initial density of the oil is lower than that of the receiving water body but the density of the oil increases as the floating oil weathers; or
3. Interaction with sediment (mostly sand) that causes the oil-sediment mixture to become heavier than the receiving water body.

This guide addresses the third type of sunken oil–oil that has mixed with enough sand either after stranding on a sand beach or mixing with sand suspended in the water column in the nearshore to cause the oil to sink and form **bulk** oil in the form of Sunken Oil Mats (SOMs). Following the *Deepwater Horizon* oil spill, SOMs (which were called submerged oil mats) formed across the Gulf Coast region but were found most commonly along the sand beaches of the Panhandle of Florida and coastal Alabama. SOMs were a constant source of reoiling of the beaches during the four years of the *Deepwater Horizon* oil spill response, and chronic reoiling has continued for years. The challenge of detecting and removing these SOMs led to more research into the formation process and persistence of SOMs.

This guide does **not** address oil that is transported to the seafloor via the process of marine oil snow sedimentation and flocculent accumulation (MOSSFA), which is the capture of oil droplets in the water column by the web-like, mucus-rich marine snow (Passow et al., 2012; Vonk et al., 2015). Under this process, oil is deposited as oiled fine-grained and organic-rich sediments over a large area of the deep sea floor and is generally not recoverable.

This operational guide includes: 1) a table of case histories where SOMs formed after oil spills; 2) a summary of the literature on SOMs; 3) a description of conditions necessary for SOM formation and persistence; 4) the most effective survey methods to detect SOMs; and 5) the most effective removal methods that also minimize environmental impact.

2. Case Histories

Table 1 is a summary of the spills where sunken oil mats have been documented. These case histories reflect the wide range of conditions under which SOMs can form. There are some commonalities among these spills:

1. All of the spills were of a heavy crude or heavy fuel oil, with two exceptions:
   - The Ixtoc 1 spill: The medium crude oil emulsified and weathered at sea as it was transported hundreds of miles (mi) along the coast. The oil observed off the coast of Texas was in the form of floating tarballs and large mats that were very viscous.
   - The *Deepwater Horizon* oil spill: The light crude oil traveled through 5,000 feet of water to reach the surface as an emulsion. The viscosities of two surface slicks collected from offshore barges in July 2010 ranged from 6,500-90,000 centistokes (Forth et al., 2015).
2. Often, the oil had weathered (and/or emulsified) at sea for days to weeks before stranding on the shoreline, increasing the oil's viscosity.
3. SOMs formed off exposed sand beaches with enough wave action to suspend sand in the surf zone and/or erode the oiled sand that had stranded on the beach.
4. At most of the spills where the oil mixed with sand suspended in the surf zone, the tidal range was less than 6 feet, and often less than 3 feet.
5. SOMs were often deposited in the trough between the beach and the first offshore bar, though they were also deposited in sheltered lagoons, estuaries, or deep parts of channels.
6. SOMs are patchy in size and distribution, making them difficult to locate and remove.
7. SOMs can become a source of chronic re-oiling of the adjacent beach.
8. There are two types of SOMs, defined on the amount of sand in the sunken oil mat: Oily SOMs and Sandy SOMs (discussed later).

Table 1. Case histories of spills where sunken oil mats occurred.

Spill Name/ Location	Spill Date	Oil Type/ Volume Spilled/API°	SOM Formation	Removal Method
SOM Case Studies in Exposed Coastal Marine Environments				
T/V *Eleni V,* United Kingdom	May 1978	Heavy fuel oil, 30,000 bbl/ 14.4 to 19	The oil quickly emulsified into large rafts that barely floated. Sand adhered to the mousse both offshore on sand banks and onshore after rolling in the surf. The oil fouled fishing nets trawled 1.5-8 mi offshore and was found on the seafloor 0.3 mi offshore. No reports of fouled gear after 1 year (Blackman and Law, 1980; Kaperick, 1995).	Chemical dispersants were used on floating oil in deeper waters. Stranded oil on sand and gravel beaches was mechanically removed. No mention is made of efforts to remove the tar-like oil deposits just offshore (Kaperick, 1995; Blackman and Law, 1980).
Ixtoc I/ Bay of Campeche, Gulf of Mexico	June 1979	Light crude/ 3,400,000 bbl/ API° not reported	Three months after the Ixtoc I blowout it was estimated at 16% of the oil remained in the nearshore bottom off the Mexican and Texas coasts. After the passage of a tropical storm in mid-September, 36 mats were found at the toe of the beach. The mats contained 8% oil, 15% water, and 77% sand. By 1 year later, only 19 mats were still visible. They likely formed as thick oil masses that mixed with sand during the storm. As of 2011, small mats were still located in the region (Gundlach et al. 1981; Tunnell, 2011).	No mention is made of efforts to remove the mats resulting from the spill (Gundlach et al., 1981; Hooper, 1981).
T/V *Alvenus*, Galveston Island, Texas	July 1984	Merey and Pilon crude/ 65,000 bbl/ 13.8 and 17.3	Release occurred after grounding in the Calcasieu Ship Channel. Oil stranded onshore six days later. The viscous oil mixed with sand in the surf zone and sank no further than 100 feet from the shoreline along 7.5 mi of the coast. There were over 1,000 bbl of sunken oil with a high sand content (Alejandro and Buri, 1987).	Multiple efforts to remove the sunken oil using vacuum, pumps, heavy machinery and manual methods were not effective. The oil was recovered as it broke up and was transported onto the beach over a 2 week period (Alejandro and Buri, 1987).
T/V *Nissos Amorgos*, Maracaibo, Venezuela	February 1997	Bachaquero crude/ 25,400 bbl/ 11.8	Oil stranded on the shoreline and also mixed with entrained sand in the surf zone that extended >1,000 feet from the shore. ~5% of the oil sank in nearshore troughs. The troughs shifted position over time, remobilizing the sunken oil. The sunken oil contained 30% oil (Moller, 1998).	Cores were used to delineate locations of sunken oil. Sunken oil was removed using tracked excavating machines working close to shore in water depths of 3 ft, over 2.5 to 6 months post spill (Moller, 1998).

Table 1. Case histories of spills where sunken oil mats occurred (cont.).

Spill Name/ Location	Spill Date	Oil Type/ Volume Spilled/API°	SOM Formation	Removal Method
SOM Case Studies in Exposed Coastal Marine Environments				
T/V *Erika*, France	December 1999	Heavy fuel oil/ 115,000 bbl/1.0025	Initial spill occurred approximately 60 mi off the coast of Brittany, France. After several weeks at sea the oil stranded along a 250-mi stretch of shoreline. Due to the long time at sea and continued exposure to wave action (storm conditions), viscosity and volume increased (emulsion with 30-50% water). Only 3% of the spilled oil was recovered at sea. Near the Pen Bron Channel an area of approximately 7,500 ft^2 was covered with what was described as an oil and sand mixture (Le Guerroué et al., 2003; Čović et al., 2013).	Barge-mounted excavators with screened buckets removed 800 tons over a 10-day period at low tide to minimize impacts to shell fisheries. Suction dredgers with blade cutters recovered the less oiled sand. The dredged material was pumped through onshore separation lagoons where the oil separated from the coarse sand and floated, allowing for recovery via skimming. The sunken sand was tested for oil content: if <1,000 ppm, the sand was stockpiled on the beach for surf washing; if >1,000 ppm, it was put back through the settling tanks. 5,500 tons of material were excavated in one month and 85% of the sand was returned to the site (Le Guerroué et al., 2003).
T/V *Volgoneff 248*, Turkey	December 1999	Heavy fuel oil/ 9,150 bbl/ 11.2	The vessel grounded during a storm; oil stranded on 3 mi of sand beach. The oil mixed with sand, mussels, and other debris and sank in depths 3-45 feet and was up to 1 foot thick, with ~25% oil content. The oil was extremely viscous and a source of chronic shoreline reoiling after storms (Moller, 2002).	Oil mats in shallow water were removed manually with spades and front-end loaders. In deeper water, divers cut the oil into pieces, placed them in bags and lifted them to the surface. In 275 days 2,135 bbl of oil were recovered, 23% of the spilled volume (Moller, 2002).
SE Florida Mystery Spill	August 2000	Heavy fuel oil/ Estimated 476 bbl/ API° unknown	Oil from an unknown source stranded along 25 mi of beach near Ft. Lauderdale. SOMs and patties that were as much as 4 inches thick were found mixed with seagrass and sand in the first nearshore trough. Tarballs on the shore were coated with sand.	Divers manually removed the oiled mat material (NOAA Hotline Reports).
Lebanon	July 2006	Intermediate fuel oil/ 60,000 to 90,000 bbl/ 11.8	Most of the oil from a bombed powerplant floated but some sank as it picked up sand after being stranded onshore (contained 20% oil) then eroded. Underwater video detected oil mats and oil "rope" formation had formed. The mats were 4-8 in thick and several yards wide.	The cohesive oil mat was lifted from the sand by hand-generated currents, then rolled like a carpet, cut into pieces and placed in bags. (Elsarji, 2008; Fichaut, 2008).

Table 1. Case histories of spills where sunken oil mats occurred (cont.).

Spill Name/ Location	Spill Date	Oil Type/ Volume Spilled/API°	SOM Formation	Removal Method
Deepwater Horizon, Gulf of Mexico	April-July 2010	Medium crude/ 3.2 million bbl/ 36.2	Oiled sand on the shoreline was eroded by wave action and deposited in the nearshore and/or by mixing of floating oil approaching the shoreline with sediment suspended by wave action. Located between the beach and first offshore bar along Gulf-facing beaches from LA to FL. Ranged in size from a few inches to mats up to 10 feet wide and 100s of feet long. 10-20% oil (OSAT-3, 2011; Dalyander et al., 2014).	Mechanical removal using long-reach backhoes, sometimes with sieves.
Ras Al Zour, Kuwait	August 2017	Heavy crude/ 35,000 bbl/ API° unknown	Oil came ashore and deposited in SOM form in the lower intertidal zone near the sand beaches of Ras Al Zour.	Light mechanical equipment was proposed to remove the lower intertidal mats.
SOM Case Studies in Sheltered Marine or Estuarine Environments				
Venoil/ Venpet, South Africa	December 1977	Heavy Iranian crude/ 140,000 bbl/ 29.6 Bunker fuel/ 17,500 bbl/ API° unknown	Oil came ashore in patches and was lying in pools in depressed portions of the reef as a sand/oil mixture up to 4 in thick. Some oil was deposited in an estuary where it moved as far as 1.25 mi upstream and formed a layer on the bottom to depths ~4.5 ft. It was a 75/15/10% water/oil/ sand mixture (Moldan et al., 1979).	The river mouth was closed by a manmade sand bar to prevent oil redistribution and suction pumps removed the accessible sunken oil mats (Moldan et al., 1979).
T/B *Bouchard 155*, Tampa Bay, Florida	August 1993	No. 6 fuel oil/ 8,000 bbl/ 10.5	The oil weathered offshore for 7 days then stranded during a storm event. The oil mixed with 7-15% sand by weight in the surf zone and sank in isolated troughs offshore and on an island inside Johns Pass. Over 58,540 ft^2 of oil mats and patties were identified.	Manual removal and vacuuming at very low tide. During dredging of Blind Pass 7 years later, oil fingerprinted as the 1993 spill was found. Oil mats up to 3 in thick, covered by up to 4 feet of sand were segregated from the clean sand and removed during dredging (Michel and Galt, 1995).
T/B *Morris J. Berman*, San Juan, Puerto Rico	January 1994	No. 6 fuel oil/ 190,000 bbl/ 9.5	Oil picked up ~ 2% sand in the surf zone and sank in protected areas ~ 90 mi E/W of the grounding site. Large amounts of oil/sand sank in a lagoon closed off by booms. During the day, as the water warmed and wave energy increased, some of the oil would break off, refloat on the surface and re-oil the adjacent shoreline (Hazmat Report 95-100).	Heavier oil accumulations were removed by diver-assisted vacuum systems, Archimedes screw pumps, and positive displacement piston pumps. Small dredges using centrifugal vane pumps and rotating dredge cutter heads were used to remove sunken oil from two sheltered lagoons. 3,450 bbl recovered (Ploen, 1995; Burns et al., 1995).

Table 1. Case histories of spills where sunken oil mats occurred (cont.).

Spill Name/ Location	Spill Date	Oil Type/ Volume Spilled/API°	SOM Formation	Removal Method
SOM Case Studies in Sheltered Marine or Estuarine Environments				
M/V *Kuroshima*/ Dutch Harbor, Alaska	November 1997	Bunker C/ 930 bbl/ API° not reported	Oil was released from a freighter that grounded on the shore during a large storm. The oil mixed with sand in the surf zone and, due to the extreme storm conditions (hurricane force winds), was forced into Summer Bay Lake. The sunken oil ranged in size from 1 in. tar balls to mats up to 4 feet in diameter in water up to 30 feet. The mats contained >25% oil (Kane, 2003; Martin et al., 2003).	Divers removed the sunken oil by hand, placing it in mesh bags that were then lifted to the surface. Larger mats were cut into pieces then removed. Overall, 8.5 tons of oil were removed in 2 weeks (Kane, 2003; Martin et al., 2003).
SOM Case Studies in Fresh Water Environments				
Lake Wabamun, Canada	August 2005	No. 6 fuel oil/ 5,000 bbl/ 11.9	Oil from a train derailment flowed over land and into a freshwater lake where oil both floated and sank. Some of the sediment was picked up by the oil as it flowed over land before entering the lake. The sunken oil mixed with vegetation and coarse sediment. More sediment mixed with the oil when it was driven onto beaches by strong winds. The sunken oil formed tar balls as well as logs up to 1 foot in width and 15 feet in length and in some locations tar mats just offshore. Some oil refloated when separated from sand or vegetation (Fingas et al., 2006).	The sunken oil was mapped in part using viewing tubes from small boats in shallow water. Other methods used during the recovery effort included bottom grab samples, weighted snares, and trawl nets (Fingas et al., 2006; Sergy et al., 2011).

3. Literature Review Summary on Formation of SOMs

Most of the case studies only documented the occurrence of SOMs and did not provide much detail on the conditions under which they formed. There have been several studies and a review on the formation, behavior, and fate of SOMs during and since the *Deepwater Horizon* oil spill. During the response, the Unified Command formed the Operational Science Advisory Team – 3 (OSAT-3) to conduct directed studies to evaluate source(s), transport, and deposition of residual oil from the *Deepwater Horizon* spill; and to investigate if operational changes can be implemented to more effectively recover residual oil. Some of the key findings of the OSAT-3 (2011; 2013) reports related to SOM formation were:

- All evidence supports the premise that SOMs accumulated landward of the first sand bar. Hydrodynamic models were used to show that it "is not likely that enough sand reaches the

surface of the water column to mix with oil except in the zone of active wave breaking/runup (where sand and floating oil mix)."

- Heavy shoreline oiling does not equate to SOM formation.

The U.S. Geological Survey conducted hydrodynamic and sediment transport modeling to predict the erosion, burial, and movement of residual oil (called surface residue balls, SRBs) in the nearshore as the SOMs broke up over time (Plant et al., 2013). The modeling results suggested that large SRBs do not move very far alongshore, thus they were a good indication of the presence of offshore SOMs. They also determined that SRBs are less mobile compared with sand under non-storm wave conditions, thus they are likely to become buried and unburied under normal sand transport processes thereby lengthening the time SRBs may take to move onshore. The behavior of SRBs in future spills may be different than that observed during the *Deepwater Horizon*, based on the spill conditions.

Gustitus and Clement (2017) provide a review of the formation and fate of two types of oil agglomerates: microscopic agglomerates (oil-particle aggregates, or OPAs) and macroscopic sediment-oil agglomerates or sediment-oil mats. They provide a conceptual model for the formation of sediment-oil mats and discuss their physical characteristics and transport mechanisms.

4. Factors for Formation of SOMs

Based on the case studies and a review of the literature on SOMs, the following factors were identified as key to the formation (or not) of SOMs: 1) oil properties; 2) sand beach and nearshore morphology; and 3) sediment dynamics. Each of these factors are discussed below.

4.1 Oil Properties

One of the key oil properties leading to the formation of SOMs is viscosity, which is measured in centistokes (cSt) or milliPascal-second (mPa-s). Viscosity of common liquids are shown in Table 2.

Table 2. Dynamic viscosity (in centistokes, cSt) at 20°C for common liquids.

Water	1
Fresh medium crude oil	10
SAE 10 motor oil	100
Weathered medium crude	110
Fresh IFO-380	380
Glycerin or castor oil	1,000
Fresh heavy crude oil	1,500
Corn syrup	10,000
Molasses	100,000
Weathered heavy crude	475,000
Peanut butter	1,000,000

Low viscosity oils have low amounts of asphaltenes and resins, which are heavier components of oil and make the oil "sticky." Viscosity and adhesion (a laboratory measure of stickiness) are closely related, as shown in Figure 1. There are few measurements of adhesion for fresh or weathered oils, so it is not possible to predict this property for a specific oil. However, in general, if the oil has low viscosity, it will not adhere to sand suspended in the water column, and it will penetrate into the beach sediments after

stranding onshore, even when weathered. Highly weathered viscous oils form thick tarballs and large patties where sand coats the outside rather than mixing into the oil. SOMs are more likely to form from floating oil with viscosities of between ~10,000 and 100,000 cSt. Surface slick samples collected from two different offshore barges on 29 July and 19 July 2010 during the *Deepwater Horizon* had viscosities of 6,400 and 90,000 cSt (Forth et al., 2015). The floating oil likely continued to increase in viscosity as it was transported to shore.
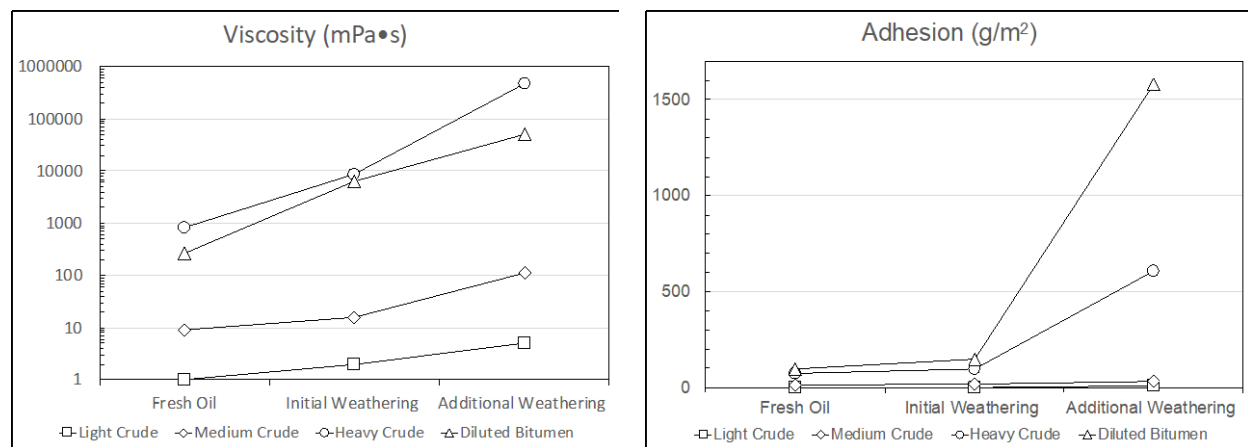
Figure 1. Viscosity and adhesion of typical crude oils for fresh and weathered (from data in NAS, 2016). Note the differences in the scales for each plot: Viscosity is plotted on a logarithmic scale because of the wide range, whereas adhesion is plotted on an arithmetic scale.

4.2 Sand Beach and Nearshore Morphology

Figure 2 shows a typical cross section of a sand beach along the northern Gulf of Mexico, defining the beach and nearshore morphology, and tidal zones. There can be multiple offshore trough and bar systems. Each trough and bar system gets deeper offshore. The first trough and bar system can move seaward during depositional periods and landward during erosional periods, which can bury and expose sunken oil over time. For SOMs to form, there needs to be an area in the nearshore where they can accumulate, such as in troughs, where wave energy is reduced. SOMs have also accumulated in lagoons formed by offshore rocky reefs (e.g., during the *Morris J.* Berman spill in Puerto Rico and the *Venoil/Venpet* spill in South Africa) and inside lakes and estuaries where suspended oil was transported into the sheltered waterbody by the flood tide, then deposited on the bottom during slack time (e.g., during the *Kuroshima* spill near Dutch Harbor and the *Venoil/Venpet* spill in South Africa).

SOMs can form in transverse bar and rip morphology regimes, meaning the bars are perpendicular and attached to the beach, separated by deeper rip channels. This regime is very common in the northern Gulf of Mexico as shorefaces transition from dissipative to reflective profiles as they recover from large hurricane events. In the Panhandle of Florida, the average wave height is 1.5 to 3 feet and the surf zone is on average 160 feet wide (Houser et al., 2013). SOMs can also form if oil comes ashore during storm events in which these conditions are temporarily simulated.
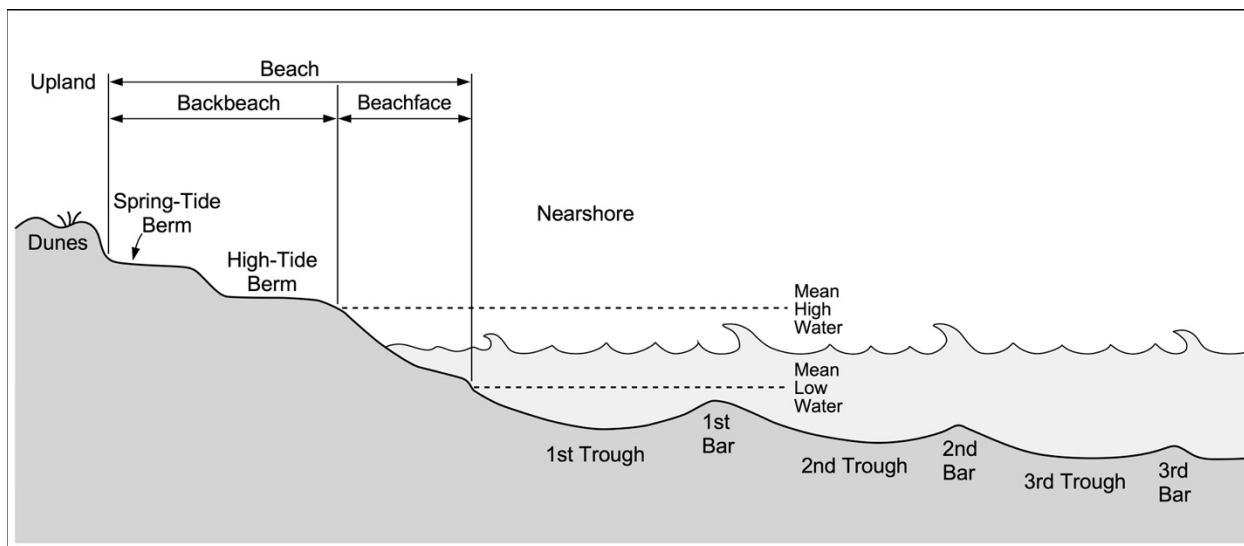
Figure 2. Sand beach and nearshore morphology and terminology.

Oil that is deposited on the backshore during high spring tides and storm conditions will be out of the reach of normal wave-remobilization, thus this type of stranded oil is not likely to contribute to formation of SOMs except following storms.

4.3   Sediment Dynamics

Oil-sand mixtures that can lead to the formation of SOMs are believed to occur by two distinct processes: 1) Floating oil interacts with sand suspended in the water column by waves breaking on shallow, nearshore bars, called **offshore entrainment**; and 2) Stranded oil on the shoreline that picks up sand and subsequently erodes from the beach during periods of high wave action, called **onshore sand uptake**. Each of these processes are described in more detail below.

The offshore entrainment process involves oil moving toward the shoreline and interacting with sand particles suspended in the water column by breaking waves that eventually become entrained in the oil, creating an oil-sand mixture that is denser than the receiving water and causing it to sink (Figure 3). The oil-sand mixture then accumulates in a lower energy collection point, most often in the trough between the shoreline and the sandbar nearest the shoreline, in the lowest intertidal or subtidal zone. Some of the oil-sand mixture can accumulate in the trough between the first and second bar, but in lesser amounts. If there is no place for the oil-sand mixture to accumulate, that mixture will be transported either offshore by the backwash of waves, or alongshore by currents. The mixture can eventually accumulate in a depositional area, such as inside a tidal inlet. Daylander et al. (2014) reported that, during the *Deepwater Horizon* spill, more SRBs were observed in the Pensacola Pass inlets and Little Lagoons inlets than in the surrounding Gulf-facing beach segments. Broken up SOMs can also continue to slowly spread as smaller "tarballs" that can become re-deposited on beaches down current. Using models coupled with observational data, Daylander et al. (2014) concluded that under typical calm conditions, cm-size SRBs are unlikely to move alongshore; however, SRB deposition on the beach increased in several days after the passage of a storm.

Sand/Oil Entrainment SOM Formation
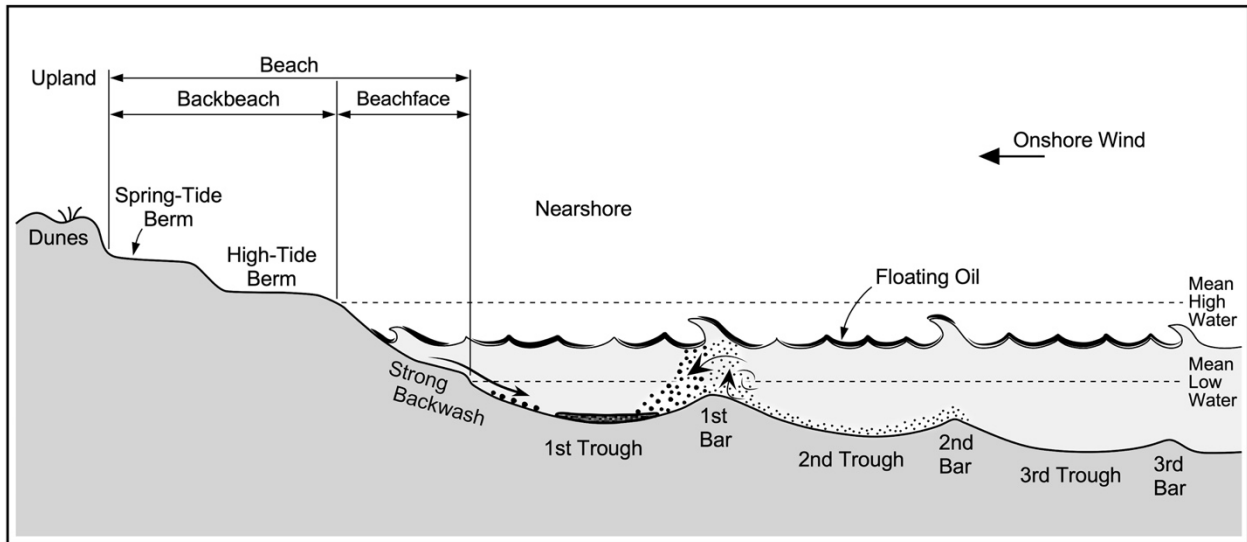
Figure 3. Schematic of the offshore entrainment process during SOM formation.

Several conditions increase the likelihood of SOMs formation by the offshore entrainment process:

1) Wave Exposure: Waves are the primary mechanism for suspension of sand in the water column. Along coastal areas with low wave exposure, there would not be enough energy to suspend sand except during storm events. Along coastal areas with high wave exposure, the waves would energetic enough to disperse the oil into small droplets that would not likely recoalesce into mats on the seafloor.

2) Presence of offshore bar(s): Sand suspended in the surf zone off sand beaches is rare above 2 feet from the bottom (Kana, 1979), meaning oil must reach a water depth of approximately 2 feet or less before the entrainment process can begin. This depth most often occurs as waves approach offshore bar(s). Offshore bars are indicated by breaking waves offshore (Figure 4).

3) Breaker Type: Plunging waves are the most likely to produce suspended sediment.

4) Distance Relative to Breaker Point: In plunging waves, concentration peaks within the first few feet of the breakpoint then decrease gradually toward the shore.

5) Slope: Increased slope increases entrainment on 1 to 3% grade beaches, meaning steeper-sloped beaches produced more entrainment and a greater chance for SOMs to form.

6) Wave Height: There is a greater concentration of sand in water in smaller waves, though larger waves create more entrainment overall, meaning the greater the wave height the more likely SOMs are to form.

7) Existence of a Trough: Once the sand has been entrained in the oil, a nearshore trough below wave base must exist so that the sand-oil mixture has a place to accumulate (Figures 3 and 4).

In the onshore sand uptake process, oil is deposited on the shoreline, where it mixes with beach sand. The mixture is denser than the adjacent water and, when re-suspended or eroded from the beach by increased wave action, can accumulate in the nearshore troughs (Figure 5). This process could occur on mixed sand and gravel beaches, particularly when the sand fraction occurs on the surface, such as when the sand is deposited on the shoreline after a storm. The wave exposure and sediment grain size conditions under which SOMs formation is likely and unlikely are shown in Figure 6.

Figure 4. Waves breaking on two offshore bars along the Florida Peninsula. There is a deeper offshore bar with slight breaking waves and a shallower nearshore bar with consistent breaking waves. The trough between the nearshore bar and the wave uprush on the beachface is where SOMs are most likely to accumulate.
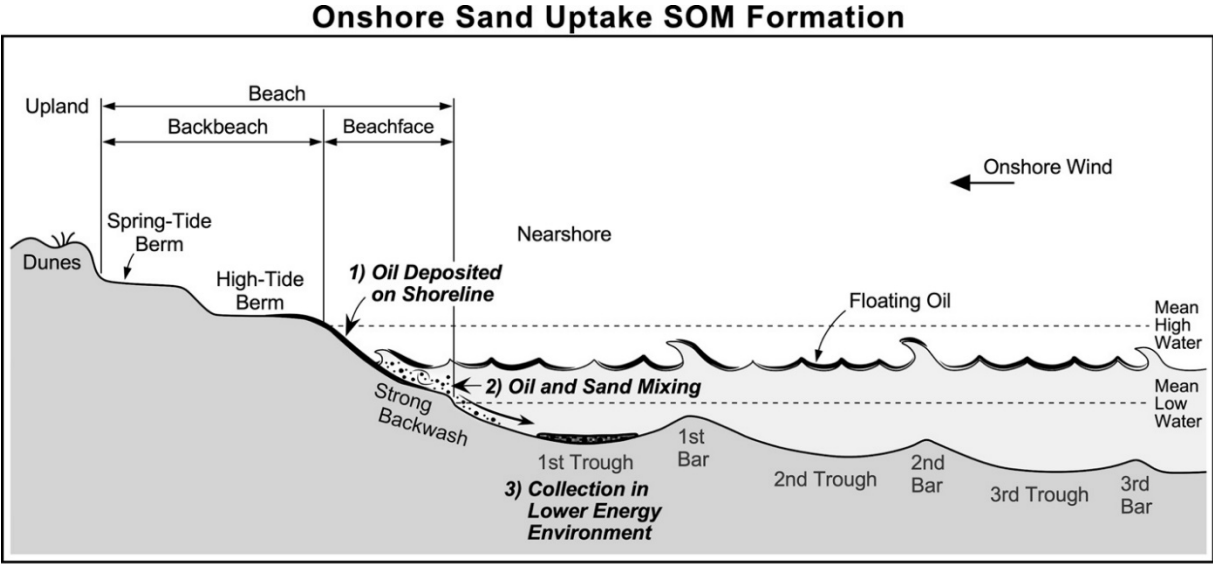
Figure 5. Schematic of the onshore sand uptake process during SOM formation.
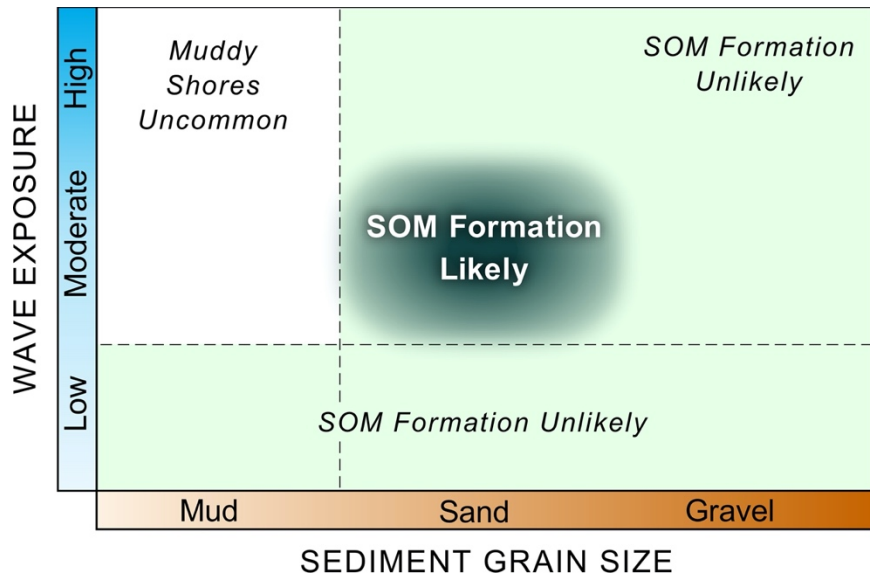
Figure 6. Wave exposure and sediment grain size conditions when SOM formation is likely or not. Based on initial sketch from John Harper, Coastal & Ocean Resources.

How oil mixes with the sand depends on the oil viscosity. Highly viscous oils do not penetrate into the sand but can become coated with enough sand to make them heavier than water (Figure 7 Left).

Less viscous oils that penetrate into the sand and oil deposited on sand can become buried by clean sand. These buried oiled layers can weather and increase in viscosity enough to form a cohesive mass that can survive the forces of wave action while they are being eroded from the beach. Subsequent erosional wave action can resuspend and transport the oil-sediment mixture to the subtidal zone where it sinks. Figure 7 (Right) shows a SOM off the coast of Florida during the *Deepwater Horizon* oil spill that clearly is an agglomeration of smaller "surface residue balls (SRBs)" that contain 10-20% oil.

Figure 7. Left: Venezuelan crude oil from the *Athos* reworked waves on a sand tidal flat in the Delaware River. The oil picked up a small amount of sand and submerged in the water column. However, the oil remained suspended by river currents and never accumulated as SOMs.
Right: SOM from the *Deepwater Horizon* formed by agglomeration of smaller surface residue balls that likely originally formed on the beach and were eroded by wave action (Snorkel SCAT).

A combination of these processes can also result in the formation of SOMs. All types of SOMs have the potential to be buried by clean sediments.

5. Oily SOMs vs. Sandy SOMs

SOMs can be divided into two subcategories: Oily SOMs and Sandy SOMs.

Oily SOMs can be defined as any sunken oil composed of >40% oil or oil emulsion by weight. Beach sand porosity is about 40%; therefore >40% oil would result in excess oil/emulsion between the sand grains. Often, the oil content was much higher, up to 98%. This type of mat is more likely to form with highly viscous oils where the sand attaches to the surface of large, thick oil, rather than the sand penetrating into the oil. Oily SOMs formed during 8 of the 15 spills listed in Table 1: *Eleni V, Erica*, SE Florida Mystery spill, *Venoil/Venpet, Bouchard 155*, *Morris J. Berman*, *Kuroshima,* and Lake Wabamun (see example in Figure 8). Oily SOMs formed in a wide range of settings. There does not appear to be a common set of conditions except for a high viscosity at the time that the oil becomes mixed with the sand. In two cases, the oil separated from the SOMs and floated to the surface on warm days. For example, at the *Morris J. Berman* oil spill, the oil picked up ~2% sand and sank in a sheltered lagoon. As daytime water temperatures increased, the oil became less viscous, separated from the sand, and floated to the surface (Figure 9). A similar behavior was observed at the Lake Wabamun spill (Fingas et al., 2006). Oily SOMs can also include a lot of vegetation and other organic material.

Figure 8 Left: Oily SOM is floating just below the surface from the Bouchard 65 in Tampa Bay, FL. Right: Oily SOMs in the form of rounded "tarballs" on the bottom of Lake Wabamun (Fingas et al., 2006).

Oily SOMs often accumulate in areas of low energy, away from waves and tidal currents. Examples include in an estuary after the *Venoil/Venpet* spill, inside of lagoons along the Puerto Rico coast after the *Morris J. Berman* oil spill (Figure 9), in the bottom of Blind Pass, Florida after the *Bouchard 65* spill in Tampa Bay, in Summer Bay Lake, Unalaska Island after the *Kuroshima* spill, and in a deep part of a channel after the *Ericka* spill. During the *Athos* spill in the Delaware River, where the oil picked up sand after stranding on a tidal flat (Figure 7), areas outside of the main channel and bathymetric lows were searched for sunken oil. However, the river currents were strong enough to keep the oil moving along the bottom, and no accumulations were found.
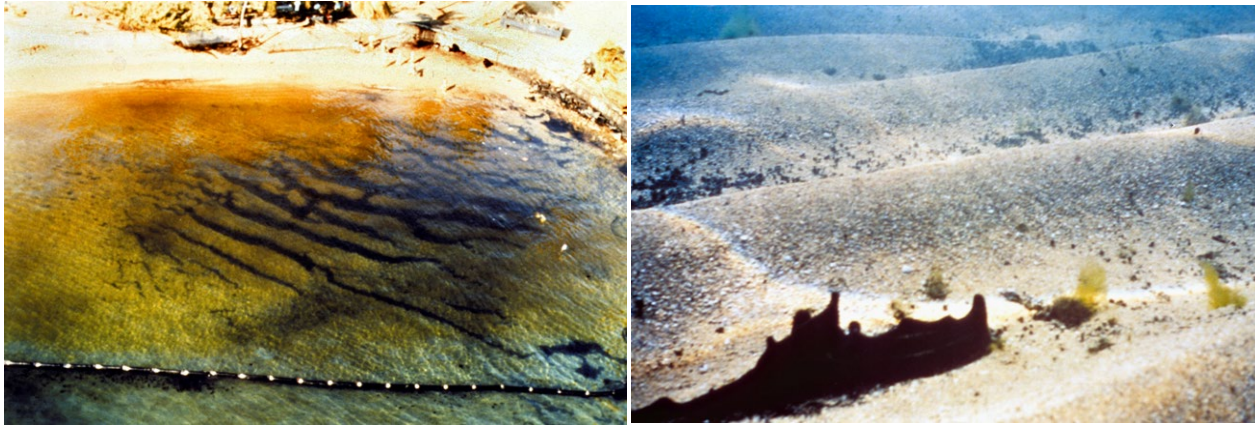
Figure 9. Left: Oily SOM accumulation in a protected lagoon at the *Morris J. Berman* oil spill, Puerto Rico. The oil accumulated in the troughs between the sand waves, and there is no oil on the shoreline, meaning that the oil mixed with sand in the offshore environment. Boom is ~125 feet long. Right: The oil, which was still lighter than the water, refloated as daytime water temperature increased and the oil viscosity decreased, allowing the oil to separate from the sand.

Oily SOMs with very little sand content can be mobile, moving around with the bottom currents. Figure 10 shows two images from underwater video of the sunken oil in Summer Bay Lake after the *Kuroshima* spill.

Figure 10. Left: Small SOM that was resuspended in the water column by the diver waving a hand over it and quickly settled back to the bottom. Right: This SOM is about 3 feet long and is covered by a layer of silt. Photographs courtesy of Polaris Applied Sciences, Inc.

Sandy SOMs are defined as any submerged oil mat composed of >60% sand by weight, meaning that the oil coats the sand grains but does not fill all of the available space between the sand grains. For this type of SOM to form, there needs to be large amounts of oil present in the nearshore zone. The oil interacting with sand in the surf zone is more likely to be smaller droplets (because of higher wave energy), or the oil stranded onshore penetrated into the sand before being eroded from the beach. In all cases, the oil must be viscous so that it strongly adheres to the sand.

Sandy SOMs formed during 7 of the 15 spills listed in Table 1: Ixtoc, *Alvenus*, *Nissos Amorgos, Volgoneff*, Lebanon, *Deepwater Horizon*, and Ras Al Zour, Kuwait. In most of these spills, the oil stranded on the sand beach before sinking, though mixing with sand suspended in the surf zone also occurred. These types of SOMs most often persist in the trough between the shoreline and the first bar just below standard wave base or at the toe of the beach.

The greatest occurrence of Sandy SOM formation was on the beaches of the Florida Panhandle and Alabama following the *Deepwater Horizon* oil spill. The SOMs were usually a yard wide, a few to tens of yards in alongshore length, and 1-10 inches thick. Examples are shown in Figure 11. The SOMs remained stationary, being buried and exposed by sand over time; however, pieces would break off the SOMs and be deposited on the adjacent shoreline as surface residue balls, causing chronic reoiling that continues as of 2019. During the *Deepwater Horizon* oil spill, one of the most common methods of detection was finding unexplained tarballs on the shoreline in locations surveyed in the recent past. Not just abundance but also the SRB shape. They would often appear angular or recently broken, indicating that the SRBs had not tumbled around enough yet to become oval or round. This pattern was so consistent that SOMs surveys were not conducted; a cleanup team would go out after most moderate weather events and remove the newly deposited SRBs (Greg Challenger, Polaris, pers. comm.).

Figure 11. Left: Sandy SOM found in the most landward trough following the *Deepwater Horizon* oil spill. Water depth is approximately 2 feet. Right: SOM composition is predominantly sand (Snorkel SCAT).

6. Survey Methods to Detect SOMs

Detection methods are summarized for two types of water environments:

1. Open-water environments that are seaward of the surf zone: Mainly offshore of beaches beyond the surf zone, inside of lagoons, estuaries, and lakes, and rivers; and
2. Surf zone environments: Mainly in the surf zone offshore of beaches, where breaking waves limit the use of vessels.

Detection methods are briefly described in the following section.

6.1 Acoustic Methods for Open-Water Environments Seaward of the Surf Zone

Acoustic methods for open-water environments seaward of the surf zone (Table 3) include:

- Side scan sonar
- Singlebeam and multibeam sonar

- Sub bottom profiler
- 3D scanning sonar
- Acoustic camera

Table 3. SOMs detection using acoustic methods for open-water environments seaward of the surf zone.

	Method	Operation	Advantages for SOM Detection	Considerations for SOM Detection	Prior Use
Acoustic Methods	Side Scan Sonar	Sonar (>350 kHz) towed by a vessel. Shows seabed texture, and backscatter anomalies can be viewed in real time to ID potential targets.	Rapid area coverage. Readily available. Software improvements allow real-time visualization and output as georeferenced map. Able to detect oil patch >1 m^2.	Minimum water depth is approximately 3 feet. Likely difficult to detect SOMs in the backscatter from muddy sediments. Requires ground truth for validation of sonar data. Will not be able to detect buried oil.	Promising results from a test at DWH
	Singlebeam and Multibeam Echo Sounder	Sonar (>350 kHz) pole-mounted on vessel.	Provides bathymetry maps showing low spots where SOMs could collect. Bathymetric data may be needed to support recovery Ops.	Resolution of bottom features is ~2-4 feet. Detection of SOMs difficult unless they are thick enough to show as a bathymetric anomaly.	DWH
	Sub Bottom Profiler	Vessel-mounted or towed, with sonar designed to penetrate strata below the surface in a narrow swath.	Potential for detection of buried SOMs, when used in conjunction with other sonars.	Poor data in organic-rich muds because of entrained gas. No experience in if/how SOM anomaly might appear.	Promising results from a test at DWH
	3D Scanning Sonar	Towed by a vessel. Multiple beams both horizontally and vertically ensonify the bottom and water column.	Creates 3D images from the backscatter at varying intensities.	Resolution of bottom features is ~2-3 feet. Detection of SOMs on the bottom may be difficult unless they are thick enough to show as an anomaly or in high backscatter contrast with the substrate.	Promising results from a test at DWH
	Acoustic Camera	Very high-frequency (>1,500 kHz) and high-resolution imaging sonar deployed by diver, on ROV, or mounted on the bottom.	Creates 3D monotone images from the backscatter that are very optical like in water of low visibility. Could be deployed at a fixed location to monitor SOMs remobilization.	Resolution is <1 foot. Narrow field of view so best used under low visibility settings to create images of SOMs distribution.	No

Detailed information on each acoustic method is provided in the American Petroleum Institute (2016) report on Sunken Oil Detection and Recovery, including survey rates. Therefore, such information is not repeated here. Harper et al. (2018) also provide information on survey methods and rates.

Underwater acoustic systems have greatly improved in the last few years, making them relatively easy to operate, and data can be reviewed in real time so that a survey pattern can be refined on-the-fly to focus on suspected SOMs. Since the passage of the U.S. Coast Guard Nonfloating Oil Classification for Oil Spill Response Organizations on 31 March 2016, many oil spill response organizations have sonar systems and experienced operators.

Side scan sonar is the most common approach at past spills to detect sunken oil anomalies (because of its high survey rate) and multibeam sonar to provide bathymetric data. Unlike bathymetric sonars, which record bottom depths, side scan sonar systems produce images of the acoustic reflectivity of the bottom. Side scan sonar imagery is used to infer subaqueous geology, substrate texture, sediment types and habitats. In general, rougher and harder materials (exposed rock, debris) tend to reflect acoustic energy, resulting in a higher return to the sonar and a brighter signature in side scan sonar images; softer and smoother materials (sunken oil, submerged vegetation, mud) tend to absorb more acoustic energy than they reflect, resulting in darker signatures in side scan sonar images. Objects that rise into the sonar's field of view may also produce acoustic "shadows", which can be used to estimate the height of the object. Figure 12 shows the side scan sonar image of sunken slurry oil combined with bathymetric data created to support removal operations during the *Apex 3508* spill of slurry oil that sank directly to the bottom (thus it was not included in Table 1).
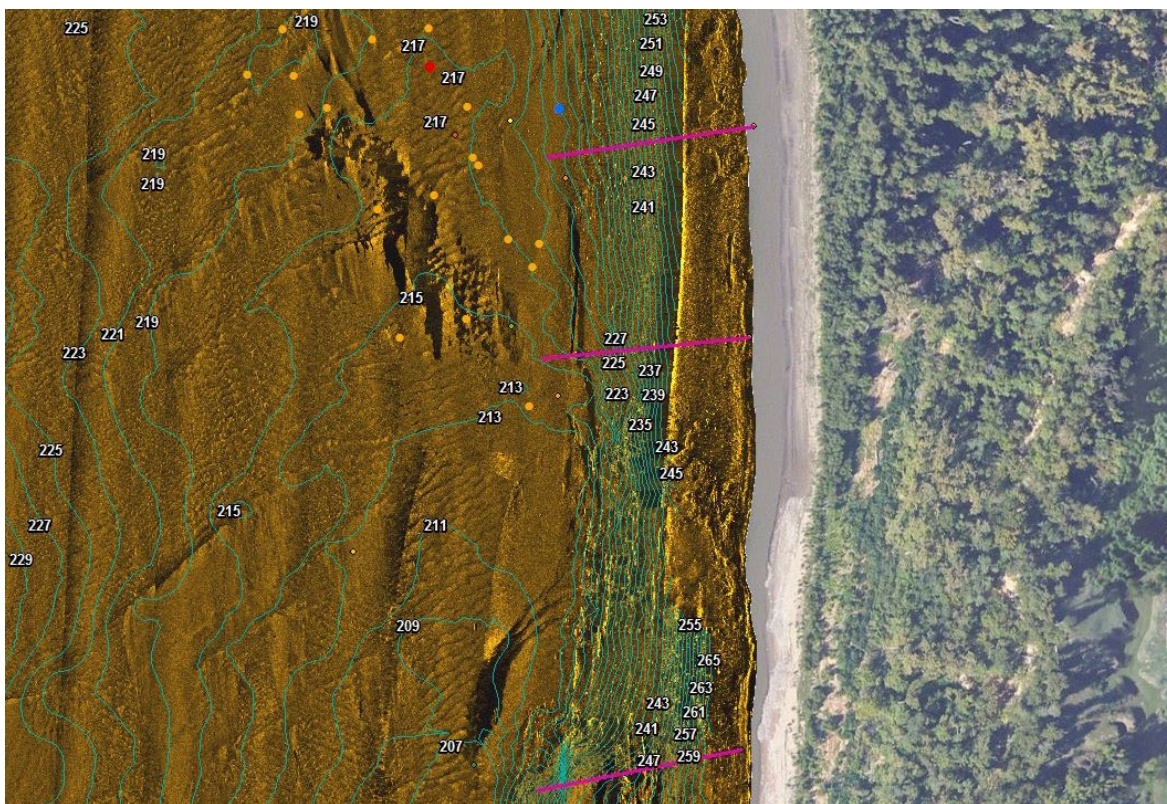
Figure 12. Side scan sonar images of sunken oil in the Mississippi River from the *Apex 3508* slurry oil spill that sank directly to the bottom in two locations, as indicated by the dark areas.

Singlebeam and multibeam sonars are used to generate bathymetric data that can be used to locate accumulation areas for SOMs as well as support removal operations. In Figure 12, the bathymetric map had a horizontal resolution of 1 foot, enabling complete interpretation of the side scan sonar imagery and precise delineation of the sunken oil on the riverbed.

Sub bottom profiler methods were tested during the *Deepwater Horizon* tactical SOMs detection program. One SOM was detected by acoustic dropout and later confirmed (Gulf Coast Incident Management Team, 2011). Figure 13 shows the imagery for that SOM detection. This method has not been used at any other spill.
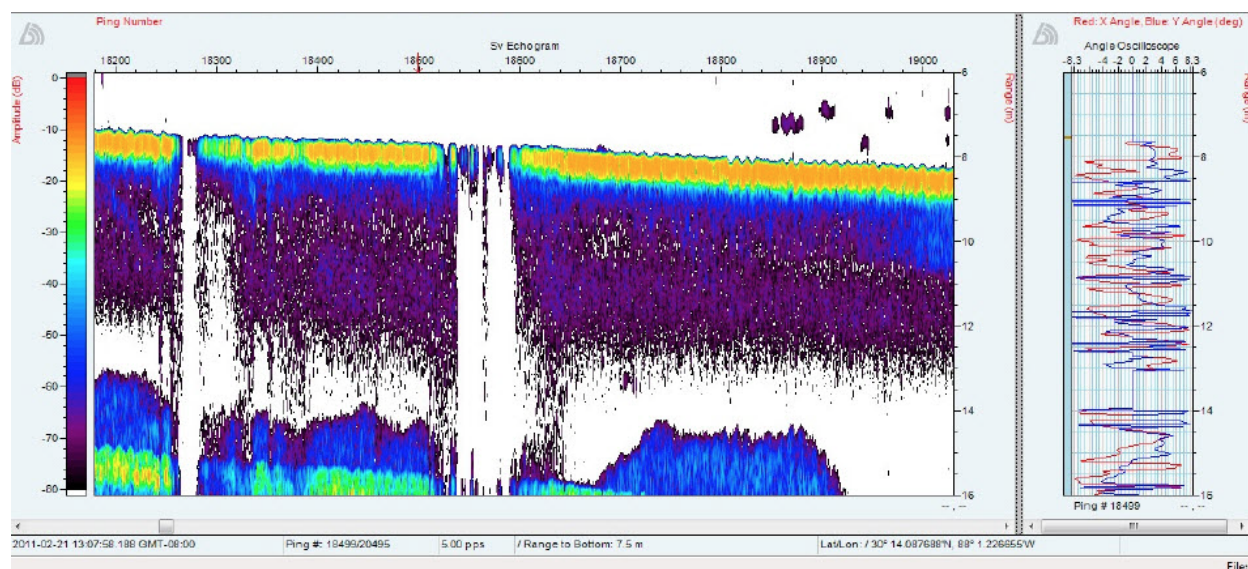
Figure 13. A seabed trace showing the seabed surface over time (horizontal axis) and penetration into the sediments from a sub bottom profiler tested during the *Deepwater Horizon* response. The center of the image shows the "dropout" of the return signal caused by a SOM on the surface (Gulf Coast Incident Management Team, 2011).

3D scanning sonar was also tested during the Deepwater Horizon response, where it was able to detect tar particles moving up and down in the water column (Gulf Coast Incident Management Team, 2011). With increased availability of 3D scanning sonar systems, and the high visual quality of the imagery, use of these systems will likely increase, depending on the site conditions. Figure 14 shows how detailed and visually informative the imagery can be.

Acoustic cameras are very high-frequency and high-resolution imaging sonars that provide an acoustic image very similar to an optical video system in real time and has the ability to detect contacts of varying specific gravity, such as entrained oil, in the water column (American Petroleum Institute, 2016). The benefit is that they can generate images in very high turbidity conditions. Such a system could be mounted on the seafloor to monitor movement or burial of SOMs over time.

All acoustic detection methods require ground-truth validation of potential SOM targets using methods such as diver observations, still or video camera (in clear water), sampling, or towed sorbents.
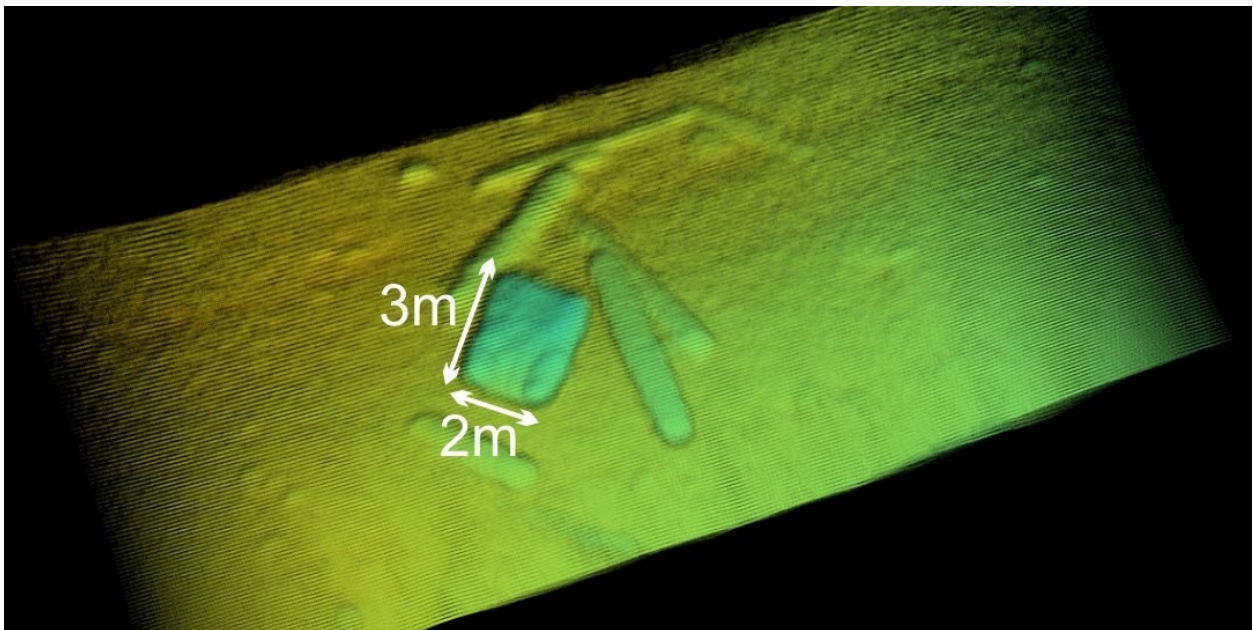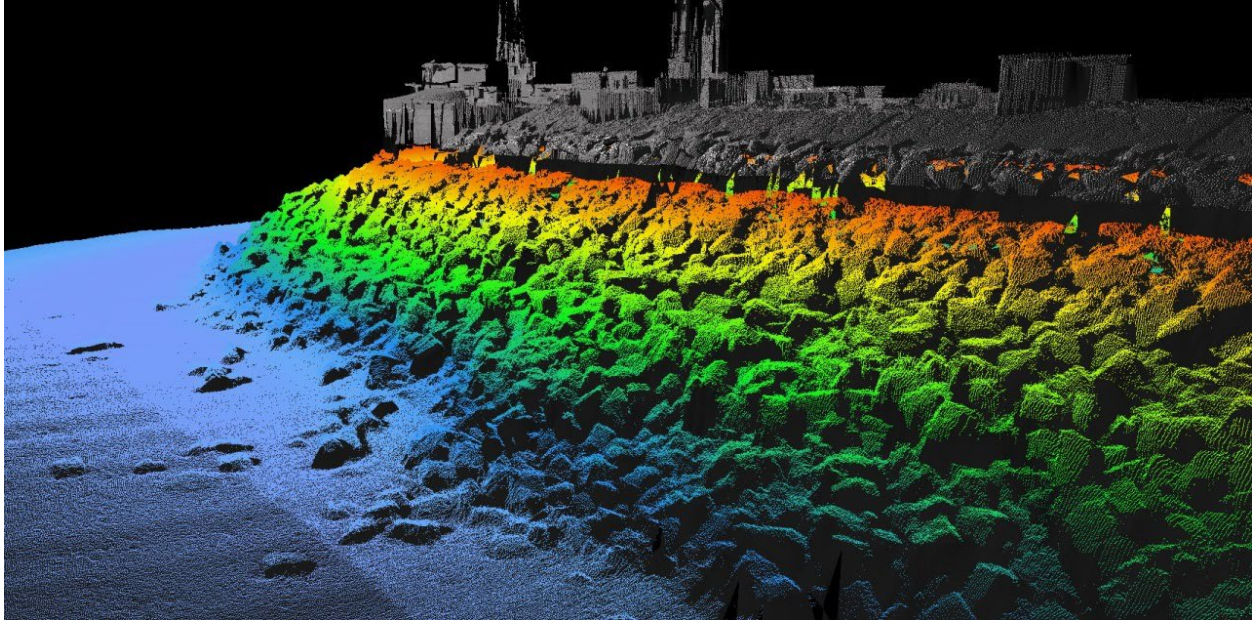
Figure 14. 3D scanning sonar images. Top: Breakwater. Image courtesy of CodaOctopus. Bottom: Image of debris on the seafloor showing the level of detail possible. Image courtesy of Baird.

6.2 Visual Methods for Open-Water Environments Seaward of the Surf Zone

Visual methods for open-water environments, seaward of the surf zone (Table 4) include the following:

- Digital still camera
- Video camera
- Aerial observation
- Diver observation
- Surface viewing

Digital and video camera images provide high detail on the bottom conditions and distribution of the oil, though over relatively small areas in clear water. Therefore, they are most useful to confirm potential targets once the presence of SOMs has been determined. For example, Figure 9 (Right) shows that the sunken oil is located in the sand wave troughs, and it is separating from the sand as the water temperatures increased during the day at the *Morris J. Berman* spill in Puerto Rico.

Figure 15 shows screen shots from the video of SOMs in Summer Bay Lake, Unalaska Island after the *Kuroshima* spill of Bunker C fuel oil. The oil appears light colored because of silt on the surface. The water temperature was 34°F, but the SOMs were still semi-fluid and would slowly migrate down slopes in the lake. Videos showed that some of the smaller SOMs were readily resuspended when the diver waved a hand over them (Figure 10), indicating that they were only slightly negatively buoyant.

Figure 15. Screen shots from the video of SOMs in Summer Bay Lake, Unalaska Island after the *Kuroshima* spill in November 1997. The SOM on the left is about 4 feet long and 1.5 feet wide. Photographs courtesy of Polaris Applied Sciences, Inc.

Aerial observations are limited to clear, shallow water. Figure 9 (Left) shows SOMs in a sheltered lagoon from the *Morris J. Berman* spill in Puerto Rico. Aerial observations were not able to distinguish SOMs from the multiple false positives in the surf zone along the Florida and Alabama beaches during the *Deepwater Horizon* oil spill.

Diver observations are frequently used to locate and confirm SOMs in water conditions that are safe for diving operations. Divers can measure the SOM thickness and estimate length and width. They can take samples and describe bottom conditions. Even under low-visibility conditions, divers have been able to locate SOMs by feel. Divers can work in water depths from 5 to 190 feet. Martin et al. (2003) describe the systematic survey of Summer Bay Lake using Shoreline Cleanup Assessment Technique (SCAT) methods by scientific divers during the *Kuroshima* spill. With water temperatures of 34°F, the oil was viscous and not sticky underwater, thus posed limited risks to SCUBA divers in the water. SCUBA divers were used during sunken slurry oil spill in Quintero Bay, Chile in 2016 from a submarine pipeline (Piraino et al., 2017). A systematic SCUBA survey was conducted along transects that were tracked using AquaMap™ transducers and using standard SCAT procedures.

Table 4. SOMs detection using visual methods for open-water environments seaward of the surf zone.

	Method	Operation	Advantages for SOM Detection	Considerations for SOM Detection	Prior Use
Visual Methods	Digital Still Camera	Deployed by divers, on a ROV, or dropped from a vessel to take pictures at specific locations. Images can be georeferenced.	Very high-resolution images that can be georeferenced.	Discrete images do not provide continuous images of the water bottom. Water turbidity limits effectiveness. Can get fouled by oil because must be operated close to the bottom.	Lebanon
	Video Camera	Deployed by divers or on a ROV. Images can be georeferenced.	High-resolution images that can be georeferenced. Can show behavior of SOMs in currents, presence of biota, etc.	Turbidity limits the effectiveness. Can get fouled by oil because it is operated close to the bottom.	DWH, Lake Wabamun, *Kuroshima*, Lebanon
	Aerial Observation	Trained individuals search for SOMs by aerial observation using the flight path and GPS to collect data points.	Large areas can be searched in a short period of time.	Buried oil cannot be detected by aerial observation. Only feasible in very clear water. Seaweed, seagrass, and schools of fish can look like SOMs.	*Morris J. Berman*, Lake Wabamun
	Diver Observation	Commercial divers search for SOMs visually or in no visibility conditions can detect SOMs by feel. Position of the diver can be georeferenced.	Divers can measure SOM thickness and extent as well as provide direct feedback regarding bottom conditions. Divers can collect samples and describe/photograph what the samples represent and the bottom conditions.	The amount of time the diver can spend at the bottom is based on depth. The divers umbilical cord may force the support vessel to reposition, and high winds/waves may prevent safe dive operations. Water visibility is a key factor. It is difficult to get an accurate position of a diver on the bottom, so may not be able to relocate the SOM for subsequent removal.	*Alvenus*, *Kuroshima*, *Erika*, *Volgoneft 248*, Lebanon, *Morris J. Merman*, DWH
	Surface Viewing	Observers inspect the bottom directly or using underwater viewers, collecting data along pre-determined transects using GPS to collect data points.	Limited equipment and resources needed; observers can quickly determine if SOMs are present.	Method is only effective in clear, shallow water and during daylight hours. This method is not effective for buried SOMs.	Lake Wabamun, *T/B Bouchard 155*

Standard SCUBA gear does not provide adequate protection in contaminated water environments. American Petroleum Institute (2016) provides a detailed discussion of the safe operations for diving in oiled water, including use of surface-supplied air diving and non-porous dry suits.

Surface viewing methods are limited to clear, shallow water. Surface viewing can be conducted from boats under low wave conditions. For example, Figure 16 shows use of viewing tubes during the Lake Wabamun spill in Canada.

During the *Deepwater Horizon*, the original concept of "Snorkel SCAT" was that the SOMs could be located by wading into the surf zone during low wave conditions and visualizing the oil on the surface using diver masks. However, the SOMs were intermittently buried and exposed, requiring the use of shovels to delineate the extent of the SOMs observed.

Figure 16. The surface viewing method during the Lake Wabamun oil spill. Photograph courtesy of Owens Coastal Consultants.

6.3 Sampling Methods for Open-Water Environments Seaward of the Surf Zone

Sampling methods for open-water environments seaward of the surf zone (Table 5) include the following systems:

- Grab sampler
- Core sampler
- Towed sorbents

Grab samplers can be deployed off a small vessel using a winch to retrieve the sample, as shown in Figure 17 (Left). Deployment and recovery in deeper water requires heavier equipment, as shown in Figure 17 (Right). The grab sampler can be dropped and retrieved by hand, but this method often results in poor sediment recovery. Another limitation of some grab samplers is that the contents are dumped into a container for inspection, making it difficult to determine the oil thickness and burial depth. The grab sampler has to be cleaned after each retrieval.

Figure 17. Left: Ponar grab sampler; Right: Van Veen grab sampler. Note that the area sampled is small.

Core samplers allow detection of the depth and thickness of SOMs. Their biggest limitations are: small area sampled (2-6 inches in diameter); potential for compaction of the core, particularly in soft sediments; and having to extrude or cut the core liner before making observations. Coring in deep water requires a frame and winch to deploy the core tube, as shown in Figure 18 (Left). Cores can be taken in shallow water by wading (Figure 18, Right), though it can be difficult to push the core tube into compact, sandy sediments and then to pull it out without losing the sediment inside the core. Poor sediment retrieval and compaction are common problems.

Vibracoring is a coring method where a source of mechanical vibration is attached to a steel core barrel. The vibrations facilitate penetration into water-saturated sediments, to depths up to 20 feet. When carefully done, compaction can be minimal. A rigid plastic liner can be used inside the core. The cores have to be maintained upright until they are cut open for description and sampling. SOMs are usually not buried deep enough to warrant assessment using vibracoring.

The biggest limitations of coring methods are: 1) very small area sampled, and 2) that the cores have to be split open for inspection, which can delay use of the results in determining where to core next to refine the distribution of any SOMs. Coring is the only direct method to detect buried SOMs in offshore settings.

Table 5. SOMs detection using sampling and other methods for open-water environments seaward of the surf zone.

	Method	Operation	Advantages for SOM Detection	Considerations for SOM Detection	Prior Use
Sampling Methods	Grab Sampler	Set of jaws is shut when sampler reaches the bottom or bucket rotates into the sediment when it reaches the bottom. Location can be georeferenced.	Relatively easy to handle and operate, readily available, and versatile in terms of substrate type. Manual recovery limits amount of sediment and water removed from the environment.	Not effective for SOMs buried below ~8 inches. May be difficult to collect sediments in hard-packed sand, thus requiring a heavier sampler and winch for deployment and retrieval. Sediment structure and oiled layers may not be preserved.	*Volgoneff 248*, SE Florida Mystery Spill. *Kuroshima*
	Core Sampler	A core tube or box core is driven into the sediment by gravity, pistons, or vibration and recovered using a winch or crane from a vessel. Location can be georeferenced.	Box cores can collect sediments 1-3 feet deep, gravity cores up to 1-5 feet, and vibracores 1-20 feet. Thus, they are the best way to detect buried SOMs.	Method has limited spatial detail. Very slow and labor intensive. Cores have to be split open or extruded for observation, which delays data turnaround.	*Nissos Amorgos*
	Towed Sorbents (V-SORS)	Sorbents are attached to chains and dragged along the bottom then brought to the surface for visual analysis. Transects can be georeferenced.	Able to cover a large distance. Can be used in vessel traffic lanes. High confidence it maintains bottom contact.	Requires a large vessel with a crane. Highly dependent on wave conditions. Cannot determine where along the trawl the SOM occurred, or the distribution/thickness of the SOM. Cannot detect buried SOMs.	*DWH*
Other Methods	Induced Polarization	A controlled electrical current is introduced into the water using transmit electrodes; the induced voltage is measured using non-polarizing receiver electrodes. Deployed from a vessel and towed close to the seabed. The distance between transmit and receiver electrode pairs determines penetration depth. Transects can be georeferenced.	Can detect hydrocarbons in the water column, on the bottom, and buried below the surface. Operators can perform on-the-fly interpretation with real-time displays.	Operator training standards are currently more rigorous than other systems. Aerially range limited to 40 feet in the current configuration, but good subsurface penetrations. Only one system currently available. There are no field data showing ability to detect SOMs.	Field trials at Superfund site with creosote/tar showed promise.

Figure 18. Left: Core samplers deployed from a vessel with a heavy frame and winch. Photograph courtesy of the Dann Blackwood, U.S. Geological Survey, Woods Hole, MA. Right: Push coring in shallow water. Photograph courtesy of WaterMark.

Towed sorbents have been frequently used for sunken oil detection (American Petroleum Institute, 2016). The oil has to be sticky enough to adhere to the sorbents as they are dragged along the bottom. Thus, they may not be effective for Sandy SOM detection. Other considerations are towed sorbents do not provide information on the distribution of SOMs along the distance of tow, the thickness of the SOMs, buried oil, or bottom conditions. Towed sorbents can be assembled from readily available materials and provide rapid information on the presence of sticky oil on the bottom. Long transects can be used to search for SOMs, followed by shorter transects to pinpoint the location. Figure 19 shows the different types of towed sorbent systems used at past spills.

Figure 19. Left: Towed sorbent deployed using a header pipe to increase the surface areas sampled during the *Athos* spill in the Delaware River. Right: Towed sorbents deployed during the spill of a heavy fuel oil in the Ohio River. Photographs courtesy Mark Ploen, QualiTech.

Induced polarization is a promising technology for detecting SOMs both on the surface and buried (Wynn et al., 2017). However, as summarized in Table 5, there are no field data that show the actual performance of this method.

6.4   Sampling Methods for Surf Zone Environments

Assuming that wave conditions are not suitable for vessel operations, sampling methods for surf zone environments (Table 6) include the following systems:

Visual Methods:

- Aerial observations
- Surface viewing

Sampling Methods:

- Core/box sampler
- Shovel sampler

Aerial observations of SOMs in the surf zone may be effective in very clear water and low wave conditions. Large areas can be quickly covered. However, water turbidity and the inability to detect buried SOMs are major limitations. In past spills, false positives have included cloud shadows, seaweed, worm tube colonies, clay and peat outcrops, schooling fish, and submerged aquatic vegetation.

Surface viewing of oil in the surf zone may also be effective in clear water and low wave conditions. Viewing tubes may be more difficult to manage while standing in even low surf conditions Any type of survey that requires teams to enter oiled water will require special personal protective equipment (PPE).

Core/box/grab samplers can be deployed at wading depths in the surf zone, under low wave energy conditions. The biggest limitation with coring of any kind is that the cores have to be brought to shore and extruded to allow description and sampling, which can delay use of the results in determining where to core next to refine the distribution of any SOMs. Also, penetration and recovery can be very difficult in compact sand and underwater.

Shovel samples were selected as the most effective method for detecting of SOMs during the *Deepwater Horizon* response because of the shallow water location of the SOMs and often calm wave conditions allowed entry by the teams. Called "Snorkel SCAT" during the *Deepwater Horizon* response, teams worked in up to waist-deep water. They wore snorkel gear and used a shovel with a narrow blade (sharp shooter) to dig to depths of about 18 inches and quickly brought the shovel full to the surface (Figure 20). The Snorkel SCAT team during the *Deepwater Horizon* response consisted of seven members, one GPS operator, two shovel technicians, one data recorder, two boat crewmen on the safety boat, and one communications technician (OSAT-3, 2013). As seen in Figure 20, the PPE for *Deepwater Horizon* field team did not have to include protection against oil suspended in the water column because the SOMs were very sandy and contained 10-20% weathered oil.

Selection of survey locations would be based on the amount and type of new oil depositing on the adjacent shoreline. Shovel samples allow rapid determination of the presence and depth of SOMs, and the team can readily expand the search area to delineate the areal extent and depth of burial. Under ideal conditions, the survey teams work closely with Operations so that removal can occur as soon as an area of SOMs is found. This close timing of delineation and removal is of particular importance for SOMs along the outer coast because of the potential for rapid burial.

Table 6. SOMs detection methods in the surf zone.

	Method	Operation	Advantages for SOM Detection	Considerations for SOM Detection	Prior Use
Visual Methods	Aerial Observation	Trained individuals search for SOMs by aerial observation using the flight path and GPS to collect data points.	Large areas can be searched in a short period of time.	Water visibility is a limiting factor. Most effective under low wave conditions. Buried oil cannot be detected. Seaweed, seagrass and schools of fish can look like SOMs. Needs ground truthing.	*Bouchard 65, Morris J. Berman,* DWH
	Surface Viewing	Viewing tubes are hand-held in shallow water to observe the seabed. Each location or transect can be georeferenced.	Can improve visual observations of any surface oil and bottom features. Data can be collected at point locations or along transects.	Not able to detect buried oil. May be difficult to maintain steady views in wave action. Resuspension of oily SOMs in the surf may contaminate workers and equipment.	Lake Wabamun
Sampling Methods	Core/Box/Grab Sampler	A core tube or box/grab sampler is driven into the sediment and retrieved by hand. Core tubes are 2-4 inches in diameter; box samplers collect a square or rectangle ~ 100 square inches. Each location can be georeferenced.	Hand-deployed box cores can collect a sample up to ~1 feet thick, core tubes ~3 feet. However, deep core tubes may be difficult to retrieve and may require a tripod to extract the core.	Very slow and labor intensive, with limited spatial detail. Box/grab samplers may be difficult to penetrate into compact sand. The material in the samplers may have to be dumped into a container so may not be able to describe oil distribution with depth. Core tubes can have poor recovery in sand and some compaction. Core tubes have to be returned to shore and extruded/cut open to observe oil distribution.	DWH
	Shovel Sample	Referred to as "Snorkel SCAT" during DWH, survey teams use a narrow blade shovel to dig into the sand down to 18 inches and bring the material to surface to visually detect the presence of SOMs. Each location can be georeferenced.	Team can work in unison with removal operations to quickly remove identified SOMs, which is very important off exposed sand beaches because of rapid burial by sand bar and shoreline migration.	Method has limited spatial detail (only the width of the shovel blade); though once a SOM is found, can be readily delineated. Very slow and labor intensive. Can provide information on oil distribution with depth.	DWH, Southeast Florida Mystery Spill

Figure 20. "Snorkel SCAT" SOM detection during the *Deepwater Horizon* response.

7. Effective Methods to Recover SOMs

Recovery methods are summarized by the same environments as the survey methods.

- Open-water environments that are seaward of the surf zone: Mainly offshore of beaches beyond the surf zone, inside of lagoons, estuaries, and lakes, and rivers; and
- Surf zone environments: Mainly in the surf zone offshore of beaches, where breaking waves limit the use of vessels.

Recovery methods are briefly described in the following section.

7.1 Vessel-Oriented Recovery Methods for Open Water Environments Seaward of the Surf Zone

Vessel-oriented recovery methods for open-water environments seaward of the surf zone (Table 7) include the following removal techniques:

- Hydraulic suction dredging
- Diver-directed pumping and vacuuming
- Barge-mounted excavator/clamshell dredge
- Airlift pneumatic dredging
- Towed sorbents
- Trawls and Nets

As with the detection methods, detailed information on each vessel-oriented recovery method is provided in the American Petroleum Institute (2016) report on Sunken Oil Detection and Recovery. Therefore, such information is not repeated here.

Hydraulic suction dredging technology has increased considerably in recent years allowing for more accuracy in dredge positioning and stability. Even so, the accuracy of this technique is still dependent on wind speed, currents, positioning system accuracy, and operator skill. Because SOMs can be challenging to detect and can become buried by clean sediment or migrate over time, dredge operators will sometimes "over dredge" or, in other words use overlapping cuts, to ensure the target SOM was entirely removed. Divers may be used to guide the dredge to concentration areas.

Table 7. SOM removal using ship-oriented methods for open-water environments seaward of the surf zone.

	Method	Operation	Advantages for SOM Removal	Considerations for SOM Removal	Prior Use
Vessel-Orientated Operations	Hydraulic Suction Dredging	Cutter/auger head is lowered into the sediment and dragged along the seabed. The collected SOM and sediments are pumped into a recovery tank on a barge or onshore for separation and treatment.	May be effective for thick SOMs in a well-defined area, thereby reducing the potential for generating large amounts of contaminated sediments. Effective for buried SOMs.	Generates large amounts of contaminated water and sediment for decanting, and dewatering and handling of solids. May be difficult to find waste-handling sites close to the dredged location.	*Erika, Morris J. Berman*
	Diver-Directed Pumping and Vacuuming	Centrifugal or positive-displacement pumps are located at or below the water surface and are attached to a diver-directed suction hose. Vacuum transfer unit on a barge or shoreline and divers direct nozzle to recover each SOM.	Divers can selectively recover SOM material, reducing the amount of waste generated. Hot water can be introduced to reduce viscosity. Likely most effective on Oily SOMs that are less viscous. Effective for buried SOMs.	Generates large amounts of water and sediment that require treatment. Only positive displacement pumps can handle high viscosity material. Not effective for buried SOMs. Special requirements for oiled water diving.	*Venoil/Venpet, Bouchard 155, Morris J. Berman*
	Barge-Mounted Excavator/ Clamshell Dredge	Consists of an excavator or clamshell dredge removing SOMs and dumping them into a recovery tank on a barge.	Effective for solid or semi-solid material. Much lower waste generation compared to dredge/pump. Can track progress with geo-referenced locational data. Effective for buried SOMs.	This method requires a large vessel or barge if in unprotected water. Has a small coverage area for each scoop. Limited to ~20 feet water depth.	*Erika, Volgoneff*
	Airlift pneumatic dredge	Compressed air is transferred via a hose down to a tube extending from the vessel to the seafloor. A diver directs the air flow up the tube. The rising air expands and creates a strong current in the tube, which lifts the SOMs to the surface where they are transferred to containers on the vessel.	In good visibility,, the diver can selectively remove individual patches or larger accumulations. The diver can adjust the air flow and reduce it when re-positioning. Can be used to selectively remove overburden prior to removing SOMs. The deeper the water, the greater the airlift current.	May be hard for divers in full protective gear to handle the tube in water greater than 50 ft. Generates moderate amounts of contaminated water. Requires compressed air at increasing pressures and volume at increased depth. Solid pieces of debris can block the flow in the tube, which can result in sudden buoyancy that can suddenly lift the diver upwards.	*Bouchard 155*, used for recovery of sunken insoluble chemicals and black carbon slurry oil

Table 7. SOM removal using ship-oriented methods for open-water environments seaward of the surf zone (cont.)

	Method	Operation	Advantages for SOM Removal	Considerations for SOM Removal	Prior Use
Vessel-Orientated Operations	Towed Sorbents	Sorbents are attached to chains and dragged on the bottom to recover oily SOMs.	Can be used in active vessel traffic lanes. Can be used to confirm compliance with cleanup endpoints.	Sandy SOMs may not attach to the sorbents. Not effective for buried SOMs.	Degussa Engineered Carbons spill of HFO in Ohio River
	Trawls and Nets	Trawls or nets of different mesh sizes are dragged along the bottom to recover SOMs.	This system is readily available in areas with commercial fisheries. Fishermen have experience using these nets.	Oily SOMs could drain out of the net when lifted off the bottom. Nets can snag on debris, rock or other obstructions. May have to use clean nets after each trawl.	Lake Wabamun

Suction dredging will generate large amounts of water, sediment, and oil that will require complex systems to process the different waste streams for treatment and disposal. Thus, over dredging can become costly where processing and disposal costs for the waste stream are high. This method maybe most effective where SOMs are thick, within a well-defined area, and where the logistics allow handling and separation of large amounts of water, sediment, and oil.

Suction dredging was used during the *Erika* spill, where 5,500 tons of sediment were dredged and transported by pipeline to shore for treatment. The treatment included digging of two "lagoons" behind the shore for separation of the oil, water, and sediments (Le Guerroue et al., 2003). During the *Morris J. Berman* response, finding a pool or basin large enough to handle the dredged material volumes was a critical element; fortuitously there was a swimming pool in an abandoned sports complex adjacent to the lagoon to be dredged (Burns et al., 1995). In both of these spills, dredging was only feasible because there were options for handling of the large amount of dredged materials close to the dredged site. Figure 21 shows the suction dredge system used during the response to the Enbridge Pipeline spill in the Kalamazoo River. So much water was generated that, at the peak of the response, over 200 frac tanks were positioned in a "Frac Tank City" (USEPA, 2016).

Figure 21. Integrated a hydraulic cutterhead dredge with a positive-displacement pump that was used during the response to the Enbridge Pipeline spill of diluted bitumen into the Kalamazoo River (USEPA, 2016).

Diver-directed pumping and vacuuming is a common method for bulk oil removal from the bottom of a water body. Factors to consider include water depth (thus the duration a diver can spend on the bottom), water visibility so they can target the SOMs, and bottom currents. Divers need to be trained to regulate flow to minimize the amount of water and unoiled sediment removed. The method is not effective for buried SOMs but may be effective for patchy SOMs where the diver can turn on the nozzle for each patch, reducing the amount of water and sediment generated for treatment. Figure 22 shows the system used during the *Morris J. Berman* response.

Figure 22. Barge-mounted vacuum transfer unit with diver-directed pumping during the *Morris J. Berman* oil spill response.

Barge-mounted excavator/clamshell dredge can be an efficient method for SOM recovery that generates much less waste material, with minimal water collection. The biggest limitations are sea conditions and water depth. Figure 23 shows the environmental clamshell dredge used during the *Apex 3508* spill of a heavy slurry oil.

Airlift pneumatic dredging is commonly used for selective exposure and recovery of items on the seafloor, such as archaeological artifacts. This method uses simple and readily available materials: air compressor, hose, tube with a control nozzle, and air flow controller. It can be highly selective, removing individual targets. While slower, this method is less intrusive than conventional suction or cutter head dredging. It requires compressed air at corresponding increased pressure to increased water depth. Figure 24 shows an example.

Towed sorbents may be effective method for recovery of oily SOMs but not for Sandy SOMs. Yhe oil must be sticky enough for the SOMs itself to adhere to the sorbent. Though this method is most often used for sunken oil detection, it can be used as a final "polishing" method to recover oil remaining after

Figure 23. Environmental clamshell dredge used during the *Apex 3508* oil spill response to recover sunken liquid oil (no SOMs present) in the Mississippi River.
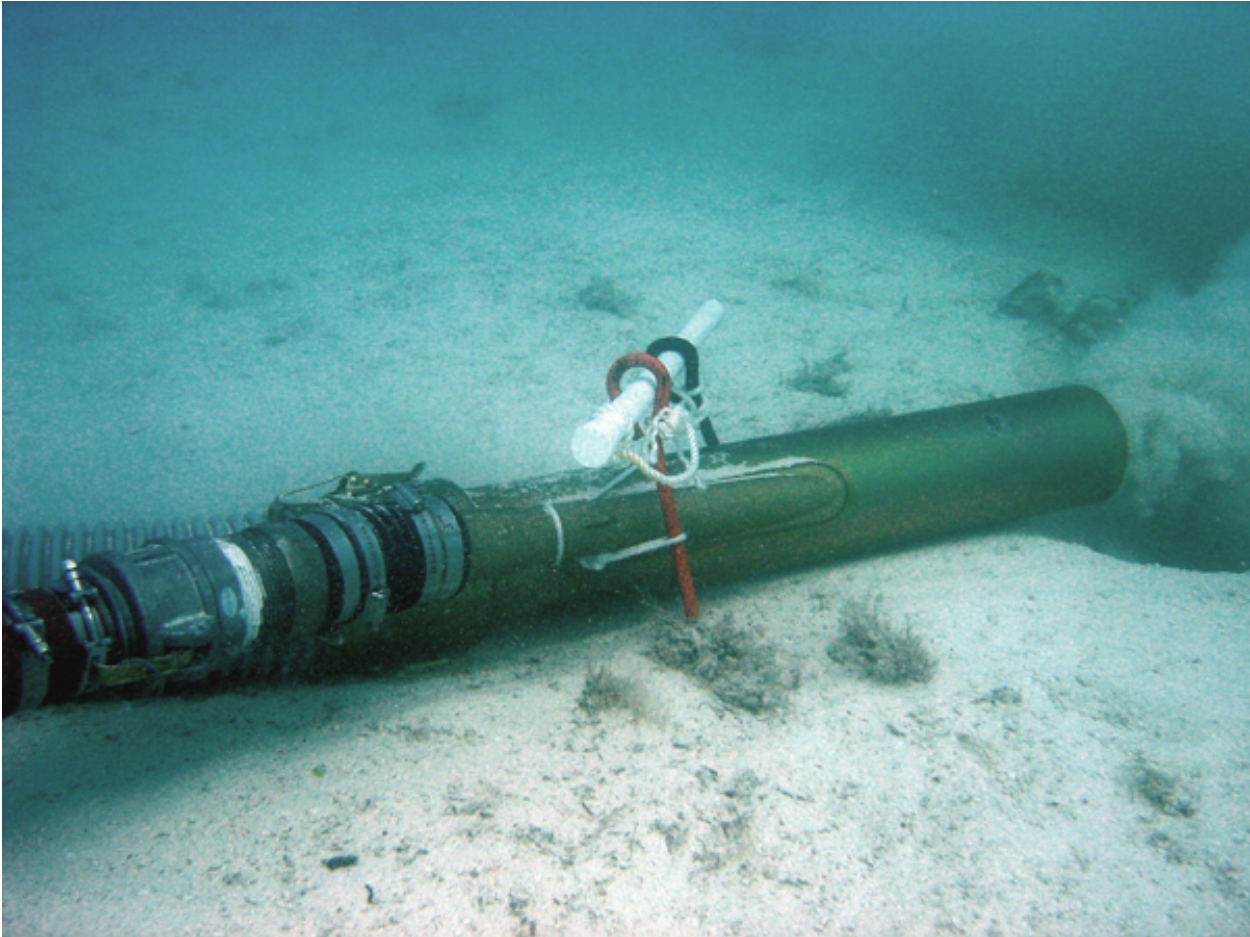
Figure 24. Pneumatic airlift dredge. Photograph courtesy of Brenda Altmeier, NOAA.

completion of other methods. It can also be used to confirm compliance with cleanup endpoints (e.g., no more than XX% oil on the sorbent when towed for xx distance). Figure 25 shows the use of towed sorbents to detect and attempt recovery of sunken oil following the *Hebei Spirit* oil spill. Very little oil was recovered, mostly in the form of oil droplets, suggesting that there was little or no sunken oil, but only small amounts of oil droplets associated with bottom sediments.
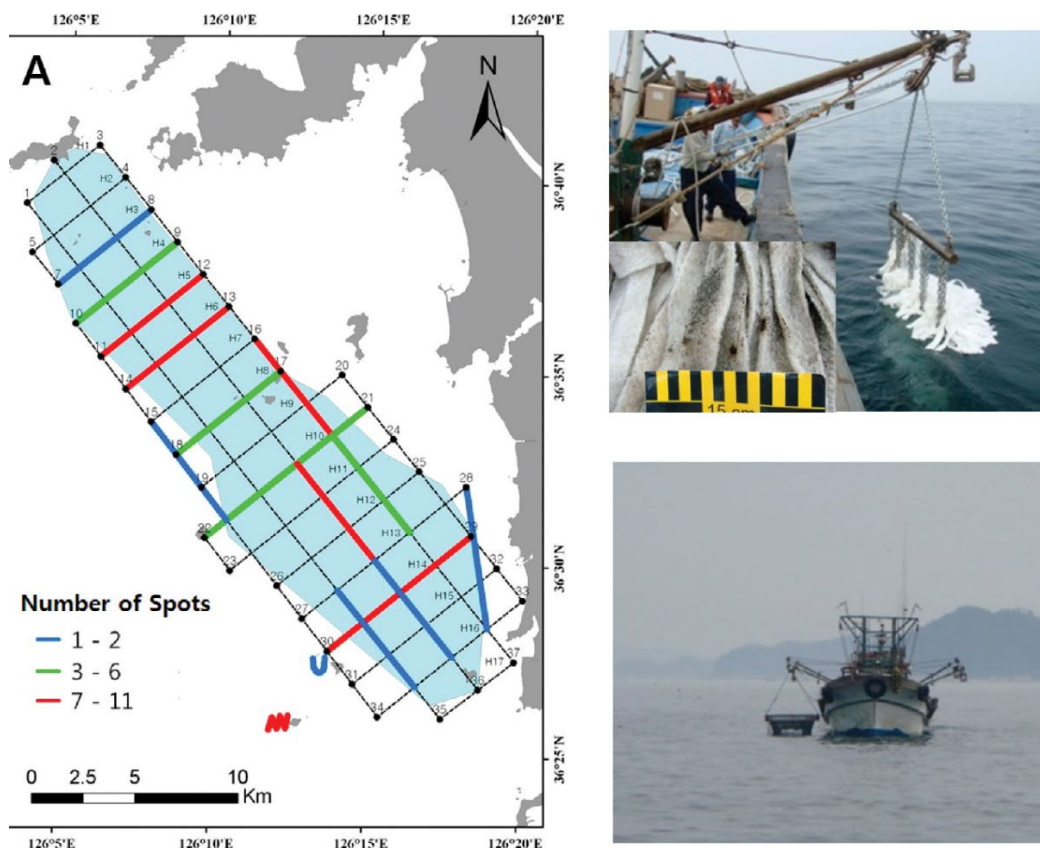
Figure 25. Left: Towed sorbent survey results for the 2007 *Hebei Spirit* spill in South Korea. Right: Sorbents being lowered into the water to locate and remove sunken oil (Yim et al., 2012)*.*

Trawls and nets have not yet been found to be an effective means of SOM removal. Figure 26 shows an example of a beam trawl with a fine mesh. One of the larger concerns is that the nets/trawls may snag on debris or entangle wildlife. During the *Deepwater Horizon* oil spill, a test was conducted in August-September 2010 using shrimp vessels that were rigged to drag shrimp nets to collect floating oil residue balls, oil mats, or submerged oil in the water column (*Deepwater Horizon* Unified Incident Command Gulf Coast Incident Management Team, 2010). Three vessels worked in unison along a common course covering the 3 nautical mile line from Cat Island, Mississippi to Bay County, Florida, for a total of 231 miles. The vessels were spaced approximately 50 to 100 yards apart. However, no oil from the *Deepwater Horizon* spill was detected this far offshore.

Figure 26. A bottom trawl such as the one above may be an effective SOM recovery method if the SOM is not buried very deeply. Photograph courtesy of Discover Oceanography.

The biggest limitations for use of trawls and nets to recover SOMs are leakage, particularly for Oily SOMs, and the fact that the nets usually cannot be cleaned once oiled and have to be replaced frequently (with increased waste generation). It may be difficult to drag the trawl into the location of SOMs. Multiple trawls across the SOMs could also break up larger patches into smaller pieces that are more mobile.

7.2   Recovery Methods for Surf Zone Environments

Recovery methods for surf zone environments (Table 8) include the following systems:

Mechanical:
- Excavator
- Submersible dredge

Manual:
- Physical removal

Passive (as the SOMs are deposited on the adjacent shoreline):
- Come ashore / natural erosion

As with the detection methods, detailed information on each surf zone method is provided in the American Petroleum Institute (2016) report on Sunken Oil Detection and Recovery (excluding the sub-dredge method). Therefore, such information is not repeated here.

Excavators have proven to be an effective method for SOM recovery when the SOMs are located close enough to shore to allow the arm of the excavator to reach the sunken mat. The longer the arm of the

excavator and the more enclosed the bucket of the excavator, the more effective the method is in removing SOMs. Under ideal conditions, the survey team delineates SOMs in close coordination with Operations so that SOMs are removed as soon as they are delineated. Figure 27 shows the excavators that were used during the *Deepwater Horizon* response.

Table 8. SOM recovery methods in surf zone environments.

	Method	Operation	Advantages for SOM Removal	Considerations for SOM Removal	Prior Use
Mechanical	Excavator	Mechanical removal consists of an excavator scooping up the SOM material in the nearshore zone and placing it on a temporary mat for disposal.	This method is effective for recovery of solid or semi-solid material because it can be removed with little associated water.	Has a small coverage area. The excavator reach is limited to the length of the arm, so it is highly likely that some SOMs cannot be reached by an excavator on the beach.	DWH
Mechanical	Sub-mersible dredge	Remote-controlled vehicle that crawls along the bottom, pumping material via a hose to separator tank. Operator uses cameras and acoustical imaging to direct the pump.	This method could potentially be effective in the surf zone where excavators cannot reach.	Current designs have a large cutterhead	Prototype tested by USCG R&DC and showed promise.
Manual	Physical Removal	Involves two methods: 1) use of workers at wading depths in the water to remove SOMs by hand or using hand tools such as shovels, rakes, pitch forks or hand nets; and 2) use of divers in deeper water to collect SOMs and place them in bags that are lifted to the surface for handling by a boat crew.	This method requires a labor force and hand tools. Very selective recovery, limiting the amount of unnecessary water and sand.	The method is slow and labor intensive. It is restricted to shallow water and waves and current limit operations. This method also requires good water visibility.	*DWH*, Lebanon, *Volgoneff*, Southeast Florida Mystery Spill, *Kuroshima*
Passive	Come Ashore/ Natural Erosion	Involves letting natural processes break down the SOMs over time and deposit them on the adjacent shoreline.	Minimizes waste generation and habitat disturbance.	SOMs may remain in the environment for an unknown period of time, causing chronic re-oiling of adjacent shorelines.	Most every spill to a certain extent.

Figure 27. Long armed excavator removing SOMs along the Gulf coast during the *Deepwater Horizon* response. The excavator has a screened bucket welded to the front edge, which allows water and clean sand can drain out before the SOM material is placed on a tarp on the shoreline

Submersible dredges can reach locations in the surf zone that excavators may not be able to. Figure 28 shows an example. This technology was tested by the USCG Research and Development Center in 2012 (Fitzpatrick et al., 2013) and showed promise.

Physical removal by manually picking up SOMs using shovels, nets, rakes, etc., may be the most effective SOM recovery method if the volume of the SOMs are relatively small and the surf is small enough that it does not pose a hazard for wading workers during the recovery process.

Divers can also remove oil in deeper water, placing solid SOMs in bags and nets. They can use lift bags to get the waste material to the surface for handling and transport for shore-based disposal. American Petroleum Institute (2016) provides detailed guidance on diving in oiled water.

One of the primary benefits of physical removal is that the amount of wastes generated is very small compared to all other removal methods.

Figure 28. Submersible dredge. The cutter head for this one has as a diameter of about 1.5 feet but smaller cutter heads can be used (Eddypump.com).

<u>Come ashore/natural erosion</u> can be considered depending on the amount of SOMs present and use of the adjacent shoreline. In high energy environments where high erosion rates occur, allowing natural processes to break down the SOMs may be the quickest and most effective method for recovery onshore or dissipation into the environment. The biggest concern is that chronic re-oiling of the adjacent shoreline can extend for months to years. Surface residue balls from broken-up SOMs from the *Deepwater Horizon* spill have continued to come ashore in Alabama for years (Clement et al., 2017).

It may be appropriate to establish beach profile stations to monitor beach erosion and deposition patterns, relative to the distribution of SOMs. Time-series data as shown in Figure 29 can indicate where oil could be buried by beach accretion and when it could be released by beach erosion.
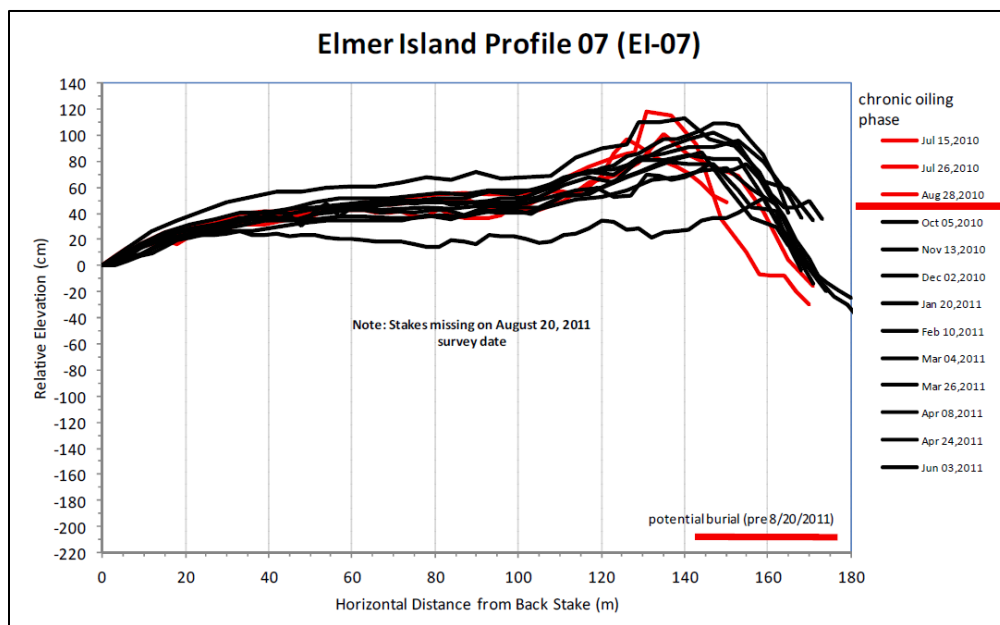
Figure 29. Example profile from *Deepwater Horizon* showing that after August 2010, the beach built out by nearly 100 feet (far right side of figure) after the oil stopped coming ashore, indicating the potential for SOM formation and burial.

7.3   Selection of SOMs Removal Methods

Selection of SOMs removal method(s) will be based on many factors. Table 9 is a matrix that lists these factors and ranks them for each removal method in terms of effectiveness and potential impacts. Potential environmental impacts in sensitive benthic habitats, such as submerged aquatic vegetation and coral reefs, will restrict the use of intensive removal methods such as dredging. Waste stream management can be complex, particularly for Oily SOMs where the recovered oil can be released from the sand and requires systems to separate the sand, water, and oil fractions for treatment. The American Petroleum Institute (2015) report has a detailed discussion on waste stream management during sunken oil response operations.

Table 9. Matrix to evaluate SOMs removal methods.

Green = Effective/Least Impact; Yellow = May be Effective/Some Impact; Red = Not Likely to be Effective/Greatest Impact; - = Not Applicable

Factors	Vessel-Oriented Recovery Methods for Open water Environments Seaward of the Surf Zone						Recovery Methods for Surf Zone Environments			
	Hydraulic Suction Dredge	Diver-Directed Pump/Vacuum	Barge-Mounted Excavator/Clamshell Dredge	Pneumatic Airlift Dredge	Towed Sorbents	Trawls and Nets	Excavator	Submersible Dredge	Physical Removal	Come Ashore/Natural Removal
Water Depth (ft)										
- < 5 ft	Yellow	Red	Green	Green	Yellow	Yellow	Green	Green	Green	Green
- 5-40 ft	Green	Green	Green	Green	Green	Yellow	Red	Yellow	Green	Green
- 40-80 ft	Red	Green	Green	Yellow	Green	Yellow	-	-	-	-
- > 80 ft	Red	Green	Yellow	Red	Yellow	Yellow	-	-	-	-
Water Current										
- < 2 knots	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
- > 2 knots	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Green
Water Visibility										
- < 5 ft	Green	Yellow	Green	Green	Green	Green	Green	Green	Yellow	Green
- > 5 ft	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
Availability	Green	Green	Green	Green	Green	Green	Green	Yellow	Green	Green
Bottom Obstruction	Red	Green	Yellow	Yellow	Red	Red	Yellow	Yellow	Green	Green
SOM Patch Size										
- < 1 ft^2	Red	Green	Yellow	Green	Yellow	Yellow	Yellow	Red	Green	Green
- > 1-10 ft^2	Yellow	Green	Green	Green	Green	Yellow	Green	Green	Green	Green
- > 10 ft^2	Green	Green	Green	Green	Green	Yellow	Green	Green	Green	Green
Oily SOMs	Green	Green	Green	Green	Green	Yellow	Green	Green	Green	Green
Sandy SOMs	Green	Green	Green	Green	Yellow	Yellow	Green	Green	Green	Green
Buried SOMs	Green	Yellow	Green	Green	Red	Red	Green	Green	Green	Green
Sensitive Habitat	Red	Green	Yellow	Green	Yellow	Yellow	Yellow	Red	Green	Yellow
Removal Rate	Green	Yellow	Green	Yellow	Red	Yellow	Green	Green	Yellow	Yellow
Waste Generation	Red	Yellow	Yellow	Yellow	Yellow	Red	Green	Yellow	Green	Green

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