Journal of
Marine Science and Engineering

MDPI

Article

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

Jacqueline Michel * and Philip Bambach

Research Planning Inc., 1121 Park Street, Columbia, SC 29201, USA; pbambach@researchplanning.com
* Correspondence: jmichel@researchplanning.com

Abstract: Based on past spills, the conditions under which floating oil mixes with enough sand to form sunken oil mats (SOMs) are identified. SOMs form mostly during spills of heavy crudes or heavy fuel oils, but also highly weathered and viscous crude oils. They usually form when oil and sand are both suspended in the water column by breaking waves or by the erosion of heavily oiled sand from the beach. The oil–sand mixture needs an area in the nearshore where it can accumulate into mats, such as in troughs or inside lagoons, where wave energy is reduced. SOMs can be oily (>40% oil) or sandy (<<40% oil), with oily SOMs posing risks of the oil separating from the sand and refloating. Methods are described for SOMs detection and recovery based on their location, in either the surf zone or the open-water environment seaward of the surf zone. A matrix provides guidance on methods based on effectiveness and environmental impacts for different site conditions.

Keywords: sunken oil mats; SOMs; SOMs case histories; SOMs formation; SOMs detection; SOMs recovery; oil–sand interaction

check for updates

Citation: Michel, J.; Bambach, P. A Response Guide for Sunken Oil Mats (SOMs): Formation, Behavior, Detection, and Recovery. *J. Mar. Sci. Eng.* **2022**, *10*, 368. https://doi.org/10.3390/jmse10030368

Academic Editor: Kenneth Lee

Received: 10 February 2022
Accepted: 1 March 2022
Published: 4 March 2022

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 paper:

Floating oil: Spilled oil that is on the surface of the water.

Non-floating oil: Spilled oil that occurs as:

- 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 because:
    - The initial density of the oil is greater than that of the receiving water body (this process is more common in freshwater);
    - 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
    - Interaction with sediment (mostly sand) that causes the oil-sediment mixture to become heavier than the receiving water body.

Previous reports on "nonfloating" oil discussed both submerged and all types of sunken oil [1–3]. This paper addresses only 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 a bulk oil in the form of Sunken Oil Mats (SOMs) on the seafloor. This kind of bulk sunken oil can result in visible oil on the seafloor and, over time, buried oil layers. 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 Florida Panhandle 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 continued for years once cleanup operations were terminated. The challenge of detecting and removing these SOMs led to more research into their formation process and persistence.

This paper provides: (1) a summary 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 SOM removal methods that also minimize environmental impact.

2. Methods

2.1. Case Histories and Literature Review

We identified fifteen oil spills where sunken oil mats were reported (Table 1). These case histories reflect the wide range of conditions under which SOMs can form. There are some commonalities among these spills:

- All of the spills were of a heavy crude or heavy fuel oil, with two exceptions:
  - The Ixtoc-1 blowout and spill: The medium crude oil emulsified and weathered at sea as it was transported hundreds of kilometers (km) along the coast. The oil observed off the coast of Texas was in the form of floating tarballs and large mats that were extremely viscous [4].
  - The *Deepwater Horizon* blowout and spill: The medium crude oil traveled through 1500 m (m) of water to reach the surface as an emulsion. The viscosities of two surface slicks collected from offshore barges in July 2010 ranged from 6500–90,000 centistokes [5].
- Often, the oil had weathered (and/or emulsified) at sea for days to weeks before stranding on the shoreline, increasing the oil's viscosity.
- SOMs formed off exposed sand beaches, indicating the requirement of enough wave action that could suspend sand in the surf zone and/or erode the oiled sand that had stranded on the beach.
- At most of the spills where oil mixed with sand suspended in the surf zone, the tidal range was less than 2 m, and often less than 1 m.
- SOMs were deposited in the trough between the beach and the first offshore bar (e.g., *Alvenus*, *Nissos Amorgos*, SE Florida Mystery Spill, *Deepwater Horizon*). They were also transported by longshore currents and deposited in sheltered lagoons, estuaries, or in the deeper portions of channels (e.g., *Venoil/Venpet*, *Kuroshima*, *Erika*).
- SOMs were patchy in size and distribution, making them difficult to locate and remove.
- SOMs can become a source of chronic re-oiling of the adjacent beach (e.g., *Alvenus*, *Volgonef 248*, *Morris J. Berman*, *Deepwater Horizon*).

Table 1. Case histories of spills where sunken oil mats were documented, in chronologic order. Volumes are reported in metric tonnes (t). Density is reported as grams per cubic centimeter (g/cm^3).

Spill Name/ Location/Date	Oil Type/ Volume Spilled/Density	SOM Formation	Removal Method
T/V *Venoil/Venpet*, South Africa December 1977	Heavy Iranian crude/21,285 to 30,000 t/ 0.87 g/cm^3 Bunker fuel/3000 t/ density not reported	Oil came ashore in patches and was lying in pools in depressed portions of the reef as a sand/oil mixture up to 10 cm thick. Some oil was deposited in an estuary where it moved as far as 2 km upstream and formed a layer on the bottom to a depth up to 1.5 m, with 75/15/10% water/oil/sand [4].	The river mouth was closed by a manmade sand bar to prevent oil redistribution and suction pumps removed the accessible sunken oil mats [6].

Table 1. *Cont.*

Spill Name/ Location/Date	Oil Type/ Volume Spilled/Density	SOM Formation	Removal Method
T/V *Eleni V*, Norfolk Coast, Eastern England, northern entrance to the English Channel May 1978	Heavy fuel oil, 5000 t/ 0.94–0.97 g/cm^3	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 in the water column 2.4–13 km offshore and was found on the seafloor 0.5 km offshore. No reports of fouled gear after 1 year [7,8].	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 [7,8].
Ixtoc I/Bay of Campeche, Gulf of Mexico June 1979	Light crude/475,000 t/density not reported	After the passage of a tropical storm in mid-September, 36 mats were found at the toe of the beaches along Padre Island, Texas. The mats contained 8% oil, 15% water, and 77% sand. One year later, 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 [4,9].	No mention was made of efforts to remove the mats resulting from the spill [4,10].
T/V *Alvenus*, Galveston Island, Texas July 1984	Merey and Pilon crude/~10,000 t/ 0.95 and 0.96 g/cm^3	Release occurred after grounding in the Calcasieu Ship Channel. The viscous oil mixed with sand in the surf zone and sank no further than 30 m from the shoreline along 12 km. 160 t of sunken oil with a high sand content [11].	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 deposited on the beach over a 2-week period [11].
T/B *Bouchard 155*, Tampa Bay, Florida August 1993	No. 6 fuel oil/1380 t/ 0.99 g/cm^3	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 5440 m^2 of oil mats and patties were identified [12].	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 7.6 cm thick, covered by up to 1.2 m of sand, were segregated from the clean sand and removed during dredging [12].
T/B *Morris J. Berman*, San Juan, Puerto Rico January 1994	No. 6 fuel oil/32,800 t/ 1.00 g/cm^3	Oil picked up ~2% sand in the surf zone and sank in protected areas ~140 km 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 to the surface and re-oil the adjacent shoreline [13].	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. 600 t were recovered [14,15].

Table 1. *Cont.*

Spill Name/ Location/Date	Oil Type/ Volume Spilled/Density	SOM Formation	Removal Method
T/V *Nissos Amorgos*, Maracaibo, Venezuela February 1997	Bachaquero crude/3600 t/ 0.98 g/cm^3	Oil stranded on the shoreline and also mixed with entrained sand in the surf zone that extended >300 m 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 [16].	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 1 m, over 2.5 to 6 months post spill [16].
M/V *Kuroshima*/ Dutch Harbor, Alaska November 1997	Bunker C/150 t/density not reported	Oil was released from a freighter grounded on the shore during a large storm. The oil mixed with sand in the surf zone and, due to hurricane force winds, was forced into Summer Bay Lake. The sunken oil ranged in size from 2.5 cm tar balls to mats up to 1.2 m in diameter in water up to 9 m deep. The mats contained >25% oil [17,18].	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. 8.5 tons of oil were removed in 2 weeks [17,18].
T/V *Erika*, France December 1999	Heavy fuel oil/20,000 t/ 1.00 g/cm^3	Initial spill occurred ~100 km off the coast of Brittany. After several weeks at sea the oil stranded along 400 km 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). Six months after the spill, sunken oil was found near the Pen Bron Channel, with 10,000 m^2 of patches up to 0.15 m and tarballs, including an area of ~700 m^2 with heavily contaminated sand [19,20].	Barge-mounted excavators with screened buckets removed 800 tons of the heavily oiled sand over a 10-day period for disposal. Suction dredgers with blade cutters recovered the less-oiled sand. The dredged material was pumped to onshore separation lagoons where the oil separated from the coarse sand and floated, allowing for recovery via skimming. The sand was tested for oil content: if <1000 ppm, the sand was stockpiled on the beach for surf washing; if >1000 ppm, it was put back through the settling tanks. 5500 tons of material were excavated in 1 month and 85% of the sand was returned to the site [19].
T/V *Volgonef 248*, Turkey December 1999	Heavy fuel oil/1578 t/ 0.99 g/cm^3	The vessel grounded during a storm; oil stranded on 5 km of sand beach. The oil mixed with sand, mussels, and other debris and sank in depths 1–14 m and was up to 0.3 m thick, with ~25% oil content. The oil was extremely viscous and a source of chronic shoreline reoiling after storms [21].	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 654 t of oil were recovered, 23% of the spilled volume [21].

Table 1. *Cont.*

Spill Name/ Location/Date	Oil Type/ Volume Spilled/Density	SOM Formation	Removal Method
SE Florida Mystery Spill August 2000	Heavy fuel oil/80 t/density not reported	Oil stranded along 40 km of beach. Mats and patties up to 10 cm 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 [22].
Lake Wabamun, Canada August 2005	No. 6 fuel oil/850 t/ 0.99 g/cm^3	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. Sand content ranged from 3.0 to 18.7% by weight. The sunken oil formed tar balls as well as logs up to 0.3 m in width and 4.5 m in length and in some locations tar mats just offshore. Some oil refloated when separated from sand or vegetation, and during daytime [23].	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 [23,24].
Lebanon July 2006	Intermediate fuel oil/10,000 to 15,000 t/ 0.98 g/cm^3	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 (10–20 cm thick and several meters wide) and oil "ropes" [25,26].	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 [25,26].
Deepwater Horizon, Gulf of Mexico April–July 2010	Medium crude/460,000 t/ 0.84 g/cm^3	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 tarballs few cm to mats up to 3 m wide and 30–60 m long containing 10–20% oil [27,28].	Mechanical removal using long-reach backhoes, sometimes with sieves [26].
Ras Al Zour, Kuwait August 2017	Heavy crude/6000 t/density not reported	Oil came ashore and deposited as SOMs in the lower intertidal zone near the sand beaches of Ras Al Zour (S. Zengel, 2017, pers. comm.)	Light mechanical equipment was proposed to remove the lower intertidal mats.

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 reports [27,29] 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.

Plant et al. [30] conducted hydrodynamic and sediment transport modeling to predict the erosion, burial, and movement of residual oil (called surface residue balls, SRBs) in the nearshore along the Gulf of Mexico as the SOMs broke up over time. The modeling results suggested that large SRBs would not move very far alongshore; thus, they were a good indication of the presence of SOMs in the nearshore. They also determined that SRBs were 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 that SRBs take to move onshore. The behavior of SRBs in future spills may be different to that observed during the *Deepwater Horizon*, based on the spill and sediment transport conditions.

Gustitus and Clement [31] provided 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 (SOAs) or sediment-oil mats. They provided a conceptual model for the formation of sediment-oil mats and discussed their physical characteristics and transport mechanisms. SOMs are macroscopic SOAs and not OPAs as defined by Gustitus and Clement [31]. We chose to use "sunken oil mat" over their "sediment-oil mat" terminology because "sunken oil mat" is more commonly used by spill responders and, in our opinion, better defines the type of bulk oil on the seafloor that has occurred in the case studies in Table 1.

2.2. Factors for Formation of SOMs

Based on the case studies and a review of the literature, 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 is discussed below.

2.2.1. Oil Properties

Oil density is one of the key properties determining whether SOMs will form; 13 out of the 15 case studies were spills of heavy oils with densities usually greater than 0.95 g/cm^3. Another key oil property leading to the formation of SOMs is viscosity. High viscosity oils have higher 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 related [32]. There are few measurements of adhesion for fresh or artificially weathered oils and particularly heavy fuel oils [33], so it is difficult to predict this property for a specific oil once spilled. Furthermore, recent research has shown the importance of the effects of photooxidation on floating oil properties, such as the studies by Ward et al. [34] that found there was a 7-fold increase in viscosity and 6-fold increase in adhesion when *Deepwater Horizon* oil was exposed to simulated sunlight. In general, oils with a low viscosity also have a low adhesion [34]; thus, slicks of lighter oils are not likely to adhere to sand when both oil and sand are suspended in the water column; however, lighter oils can penetrate into beach sediments after stranding onshore as a function of the sediment grain size, even when weathered. Surface slick samples collected from two different offshore barges on 29 July and 19 July 2010 during the *Deepwater Horizon* had viscosities of 6400 and 90,000 centistokes (cSt) [5]. The floating oil likely continued to increase in viscosity as it was transported to close to shore. Based on these data and observations from the spills listed in Table 1, a rule of thumb is that SOMs are more likely to form from floating oil with viscosities between ~10,000 and 100,000 cSt. Lower viscosity reduces the potential for oil to adhere to the sand

and to form cohesive sand–oil layers or tarballs; at higher viscosities, it is more difficult for enough sand to penetrate into the oil and make it denser than water.

2.2.2. Sand Beach and Nearshore Morphology

Figure 1 shows a typical cross section of a sand beach along the northern Gulf of Mexico, defining the beach and nearshore morphology. There can be multiple offshore trough and bar systems deepening 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 (e.g., the *Nissos Amorgos* [16], *Deepwater Horizon* [27,28], and SE Florida Mystery spills [22]). SOMs have also accumulated in lagoons formed by offshore rocky reefs (e.g., *Morris J. Berman* [13–15] and *Venoil/Venpet* [6] spills) 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 tide (e.g., *Kuroshima* [17,18] and *Venoil/Venpet* [6] spills).

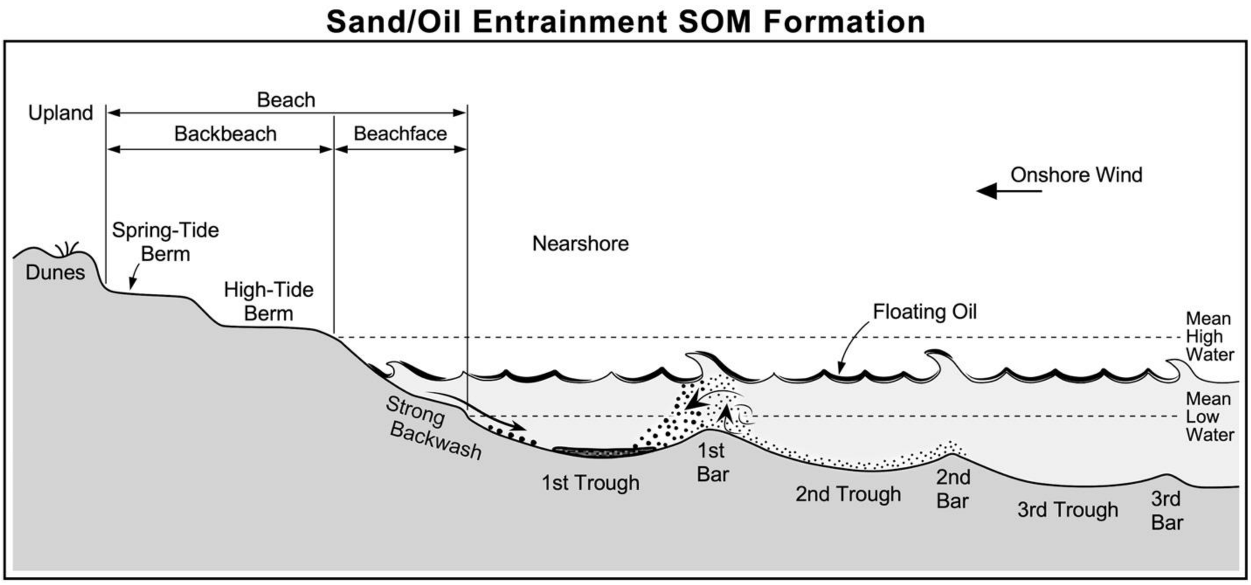

Figure 1. Schematic of the offshore entrainment process during SOM formation where sand and floating oil are suspended together by breaking waves over offshore bars, then accumulate in the trough where the energy is lower. There can also be the erosion of oiled sand from the adjacent beach.

2.2.3. Sediment Dynamics

Based on the case studies in Table 1, oil–sand mixtures that can lead to the formation of SOMs occurred by two distinct processes: (1) Floating oil interacts with sand suspended in the water column by waves breaking on shallow, nearshore bars, referred to as 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, referred to as 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, causing it to sink (Figure 1). The oil–sand mixture then accumulates in a lower energy collection point, most often in the trough between the shoreline and the first bar. 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, it will be transported either offshore by the backwash of waves, or alongshore by currents. The mixture can eventually accumulate other low-energy areas, such as inside a tidal inlet. Daylander et al. [28,35] reported that, during the *Deepwater Horizon* spill, more

SRBs were observed in down-current inlets than in the surrounding Gulf-facing beaches. 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. [28] concluded that, under typical calm conditions, centimeter-sized SRBs were unlikely to move alongshore; however, SRB deposition on the beach increased in several days after the passage of a storm.

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

(1) Wave Exposure: Waves are the primary mechanism for suspension of sand in the water column adjacent to sandy shorelines. 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 be 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 0.75 m from the bottom [36], meaning that oil must reach this depth or less before the entrainment process can begin. This depth most often occurs as waves approach and break on the offshore bar(s).
(3) Breaker Type: Plunging waves produce higher concentrations of suspended sand, compared to spilling waves [37].
(4) Distance Relative to Breaker Point: In plunging waves, suspended sand concentration peaks within the first meter of the breakpoint then decreases gradually toward the shore [36].
(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 [36].
(6) 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 1 and 2).

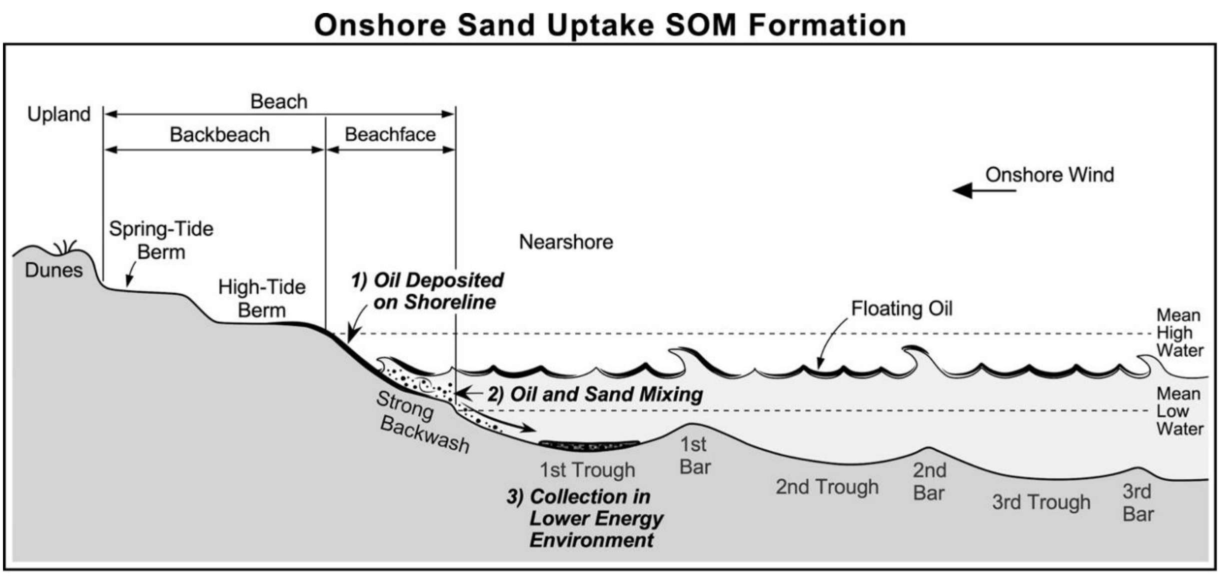

Figure 2. Schematic of the onshore sand uptake process during SOM formation, where stranded oil heavily penetrates into the sand beach and is later eroded during high-wave (plunging) conditions and is deposited by the backwash in the first trough.

In the onshore sand uptake process (Figure 2), oil is deposited on the shoreline, where it either penetrates the sand or is coated with sand when rolled around in the swash zone. If the mixture is denser than the adjacent water and is re-suspended or eroded from the beach by increased wave action, it is likely to accumulate in the nearshore trough (Figure 2). Though this process is most common on sand beaches, it could occur on mixed sand and gravel beaches, particularly when the sand fraction is on the surface, such as when the sand is deposited on the shoreline after an erosional event. The wave exposure and sediment grain size conditions under which SOMs are likely and unlikely to form are shown in Figure 3. SOMs are unlikely to form under high wave conditions, which tend to disperse the oil or transport beach sediments seaward, or under low wave conditions, when there is low suspension of sand in the surf zone or erosion of oiled sand from the beach. SOMs are unlikely to form from interaction with sediments composed of mud, because not enough fine-sediment will bind with the oil to form a cohesive mat, or with gravel, because gravel is so large and is suspended only by very large waves that will disperse the oil.

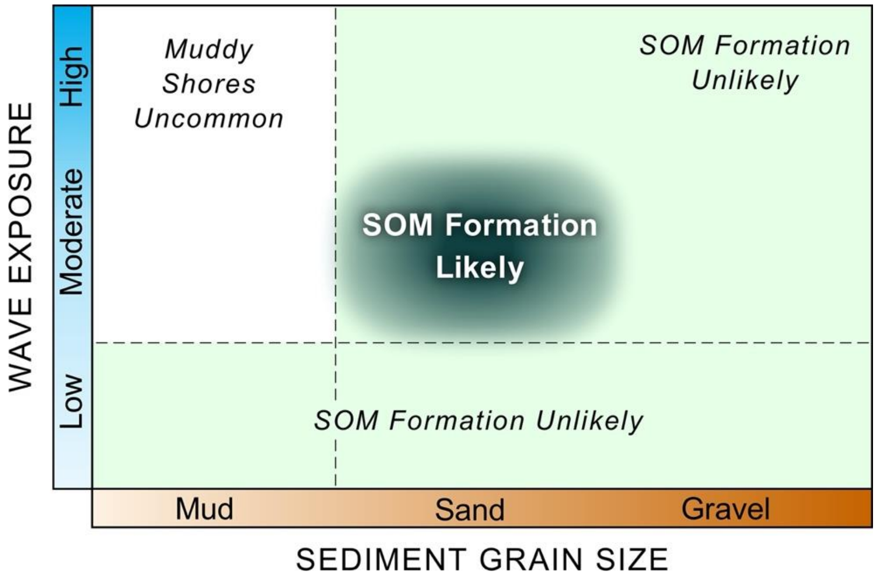

Figure 3. Wave exposure and sediment grain size conditions when SOM formation is likely or not. Based on initial sketch from John Harper, Coastal and Ocean Resources.

How oil mixes with sand depends on the oil viscosity. Highly viscous oils may not penetrate into fine- to medium-grained sand, but can become coated with enough sand to make them heavier than water. Viscous oil deposited on top of the sand can become buried by clean sand. These buried oiled layers can form a cohesive mass that can survive the forces of wave action while they are eroding from the beach. Subsequent erosional wave action can resuspend and transport the oil-sand mixture to the subtidal zone where it sinks. A combination of these processes can also result in the formation of SOMs. Low viscosity oils do not adhere strongly to the sand; thus do not form cohesive layers and the oiled sand is broken up by wave action.

3. Results

3.1. Oily SOMs vs. Sandy SOMs

Based on the case studies in Table 1, we propose that SOMs can be characterized as oily SOMs or sandy SOMs.

We define oily SOMs as being composed of >40% oil or oil emulsion by weight. Beach sand porosity is roughly 40% [37]; therefore >40% oil would result in excess oil/emulsion between the sand grains. Oily SOMs formed during eight of the fifteen case study spills listed in Table 1: *Eleni V*, *Erika*, SE Florida Mystery spill, *Venoil/Venpet*, *Bouchard 155*, *Kuroshima*, *Morris J. Berman*, and Lake Wabamun (see examples in Figure 4). In these spills, the oil content of the oily SOMs 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 particles, rather than the sand penetrating into the oil. 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 became 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 [15]. A similar behavior was observed at the Lake Wabamun spill [22]. Oily SOMs can also include a lot of vegetation and other organic material.

(**A**)

(**B**)

(**C**)

(**D**)

Figure 4. (**A**): Oily SOM floating just below the surface from the Bouchard 65 in Tampa Bay, FL. (**B**): Oily SOMs in the form of rounded "tarballs" in reed beds on the bottom of Lake Wabamun; some of these would rise and release sheens during the day [23]. (**C**): 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 ~38 m long [15]. (**D**): Close up photograph of the SOM in C; 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 [13].

Oily SOMs often accumulate in areas of low energy, away from waves and 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, 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 *Erika* spill (see Table 1 for more details and references). Oily SOMs with very little sand content can be mobile, moving around with bottom currents. During the *Athos* spill in the Delaware River, where the oil picked up sand after stranding on a tidal flat, areas outside of the main channel and bathymetric lows were searched for sunken oil [38]. However, the river currents were strong enough to keep the oil moving along the bottom (as documented by placing strings of sorbents throughout the water column), and no accumulations were found [38].

Sandy SOMs are composed of <40% oil by weight, meaning that oil coats the sand grains but does not fill all of the available space between the sand grains. 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 seven of the fifteen case history spills in Table 1: Ixtoc-1, *Alvenus*, *Nissos Amorgos*, *Volgonef 248*, 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 or at the toe of the beach (where the intertidal beach slope decreases, usually at the low-tide water level).

The greatest occurrences of sandy SOMs were on the beaches of Alabama and the Florida Panhandle following the *Deepwater Horizon* oil spill. The SOMs were on average a meter wide, a few to tens of meters in alongshore length, and 0.5–4 cm thick, though there could be much thicker accumulations [27]. Examples are shown in Figure 5. The SOMs remained stationary, being buried and exposed over time; however, pieces would break off the SOMs and deposit on the adjacent shoreline as SRBs, causing chronic reoiling [27,29]. During the *Deepwater Horizon* spill, one of the most common methods of detecting SOMs was finding unexplained SRBs 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 in the surf zone to become rounded (G. Challenger, 2020, pers. comm.) This pattern was so consistent that in-water SOM surveys were not conducted in later years. Instead, SCAT teams would identify areas of newly deposited SRBs after moderate weather events, and a cleanup team would be deployed to remove the newly deposited SRBs (G. Challenger, 2020, pers. comm.)

(**A**)

(**B**)

Figure 5. (**A**): Sandy SOM found in the most landward trough closest to the beach following the *Deepwater Horizon* oil spill. Water depth is approximately 1 m. (**B**): SOM formed as the accumulation of pieces of smaller SOMs, recovered during removal operations in 2014; it contains ~90% sand. Source: *Deepwater Horizon* SCAT Program.

3.2. Survey Methods to Detect SOMs

Detection methods are summarized for two types of water environments:

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

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

Acoustic methods for detection of SOMs in open-water environments seaward of the surf zone are summarized in Table 2.

Table 2. 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 1 m. Likely difficult to detect SOMs in the backscatter from muddy sediments. Requires ground truth for validation of sonar data. Not able to detect buried oil.	Promising results from a field test at *Deepwater Horizon* (Florida and Alabama); Large tank studies with patches of sunken oil on sand substrate [38,39]
	Single beam 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 operations.	Resolution of bottom features is ~0.5–1 m. Detection of SOMs difficult unless they are thick enough to show as a bathymetric anomaly.	Promising results from a field test at *Deepwater Horizon*
	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 field test at *Deepwater Horizon*
	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 ~0.6–1 m. 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 field test at *Deepwater Horizon*; Large tank study with patches of sunken oil on sand substrate [40]
	Acoustic Camera	Very high-frequency (>1500 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 <0.3 m. Narrow field of view so best used under low visibility settings to create images of SOMs distribution.	No

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. 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 is used 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. 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.

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

Visual methods for detection of SOMs in open-water environments, seaward of the surf zone are summarized in Table 3.

Table 3. 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 it 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.	*Deepwater Horizon*, 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. Berman*, *Deepwater Horizon*
	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. Not effective for buried SOMs.	Lake Wabamun, *Bouchard 155*

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 using other methods.

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.

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

Sampling methods for SOMs in open-water environments seaward of the surf zone are summarized in Table 4. 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. Induced polarization is a promising technology for detecting SOMs both on the surface and buried [41]. However, as summarized in Table 4, there are no field data that show the actual performance of this method.

Table 4. 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.	*Volgonef 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 0.3–1 m deep, gravity cores up to 0.3–1.3 m, and vibracores 0.3–6 m. 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 the sorbent 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.	*Deepwater Horizon*; has been successful for heavy oils that sank to the seafloor [2,38]

Table 4. *Cont.*

	Method	Operation	Advantages for SOM Detection	Considerations for SOM Detection	Prior Use
Other Methods	Induced Polarization	A controlled electrical current is introduced into the water using transmit electrodes; the induced voltage is measured with 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 [41].

3.2.4. Sampling Methods for Surf Zone Environments

Assuming that wave conditions are not suitable for vessel operations, sampling methods for SOMs in surf zone environments are summarized in Table 5.

Shovel samples were selected as the most effective method for detection of SOMs during the *Deepwater Horizon* response because of the shallow water location of the SOMs and calm wave conditions allowed surf zone entry by the teams. Called "Snorkel SCAT" during the *Deepwater Horizon* response, teams worked in up to waist-deep water [26]. They wore snorkel gear and used a shovel with a narrow blade to dig to depths of about 45 cm and quickly brought the shovel full to the surface. 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 readily expanded 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 exposed beaches because of the potential for rapid burial.

3.2.5. Effective Methods to Recover SOMs

Vessel-oriented recovery methods for SOMs in open-water environments seaward of the surf zone are summarized in Table 6. Use of clamshell dredges minimizes the amount of co-collected water and clean sediment, and current geo-referencing technologies allows tracking of each "bite" of the clamshell. Towed sorbents would be most effective to determine the presence of residual oil, perhaps as one measure of meeting cleanup endpoints.

Table 5. 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 be false positives. Needs ground truthing.	*Bouchard 65*, *Morris J. Berman*, *Deepwater Horizon*
	Surface Viewing	Viewing tubes are hand-held in shallow water from boats 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 2–10 cm in diameter; box samplers collect a square or rectangle ~700 cm^2. Each location can be georeferenced.	Hand-deployed box cores can collect a sample up to ~0.3 m thick, core tubes ~1 m. 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 may occur. Core tubes have to be returned to shore and extruded/cut open to observe oil distribution.	*Deepwater Horizon*
	Shovel Sample	Referred to as "Snorkel SCAT" during *Deepwater Horizon*, survey teams use a narrow blade shovel to dig into the sand to 45 cm depths 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.	*Deepwater Horizon*, Southeast Florida Mystery Spill

Table 6. SOM removal using vessel-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 ~12 m water depth.	*Erika*, *Volgonef 248*
	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 15 m. 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.	

Recovery methods for SOMs in surf zone environments are summarized in Table 7. Excavators have proven to be an effective method for SOM recovery when they are located close enough to shore to allow the arm of the excavator to reach the sunken mats. 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.

Table 7. 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.	*Deepwater Horizon*
Mechanical	Submersible 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 [42]
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.	*Deepwater Horizon*, Lebanon, *Volgonef 248*, 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.

In some cases, the decision may be made to allow wave action to break up the SOMs and deposit them on the beach, which is listed as "Come Ashore/Natural Erosion" in Table 7. This option may be appropriate for recovery of patchy and smaller SOMs after active recovery methods have a diminishing effectiveness. The biggest concern is that chronic re-oiling of the adjacent shoreline can continue for months to years, depending on the storm frequency, intensity, and location and amount of SOMs in the area. SRBs from broken-up SOMs associated with the *Deepwater Horizon* spill continued to come ashore in Alabama for at least a decade after cleanup operations were terminated [43].

3.2.6. Selection of SOMs Removal Methods

Selection of SOMs removal method(s) will be based on many factors. Table 8 is a matrix that lists some of 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. Towed or trawled systems could hang up on bottom obstructions. 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 for treatment. American Petroleum Institute [1] has a detailed discussion on waste stream management during sunken oil response operations.

Table 8. Matrix to evaluate SOMs removal methods.

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 (m)										
- <1.5 m	Yellow	Red	Green	Green	Yellow	Yellow	Green	Green	Green	Green
- 1.5–12 m	Green	Green	Green	Green	Green	Yellow	Red	Yellow	Green	Green
- 12–25 m	Red	Green	Green	Yellow	Green	Yellow	-	-	-	-
- >25 m	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										
- <1.5 m	Green	Yellow	Green	Yellow	Green	Green	Green	Green	Yellow	Green
- >1.5 m	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										
- <0.1 m^2	Red	Green	Yellow	Green	Yellow	Yellow	Yellow	Red	Green	Green
- >0.1–1 m^2	Yellow	Green	Green	Green	Green	Yellow	Green	Green	Green	Green
- >1 m^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

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

4. Summary

The purpose of this work was to provide responders with a better understanding of when SOMs might form, guidance on possible methods for their detection and removal, and evaluation of these methods for different site conditions. Documentation of SOM formation at past spills is minimal, with only fifteen spills with even limited information. Based on these spills, SOMs formation requires viscous oil, wave action to suspend sand and relatively large amounts of oil together in the surf zone or to erode cohesive oiled sand from the shoreline, and a place for the oiled sediments to accumulate, such as in nearshore troughs, or where alongshore currents transport them in sheltered waterbodies. The understanding of when and how SOMs form would be greatly improved with better documentation during spills when they occur. Mesocosm studies in large wave tanks could provide insights into how oil properties, wave types, and sand suspension in breaking waves interact to form SOMs. Effective detection and removal methods vary by site conditions, particularly if they are located in waters allowing vessel operations, or in the surf zone where land-based methods are the only options. Current detection technologies are best refined during field operations.

Author Contributions: Conceptualization, J.M.; Writing, J.M. and P.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Multi-partner Research Initiative of Fisheries and Oceans Canada, via the Memorandum of Agreement MECTS-#3975272-v3-OFSCP with the National Oceanic and Atmospheric Administration, dated 2018.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: This research was supported by the Multi-partner Research Initiative of Fisheries and Oceans Canada and the National Oceanic and Atmospheric Administration (NOAA). We appreciate the support of Carl Childs of NOAA in coordination of the funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. American Petroleum Institute. *Sunken Oil Detection and Recovery*, 1st ed.; API Technical Report 1154-1; American Petroleum Institute: Washington, DC, USA, 2016; Available online: http://www.oilspillprevention.org/oil-spill-research-and-development-cente (accessed on 2 March 2022).
2. Michel, J.; Hansen, K.A. Chapter 13: Sunken and submerged oil. In *Oil Spill Science and Technology*; Fingas, M., Ed.; Elsevier: Amsterdam, The Netherlands, 2017; pp. 731–758. [CrossRef]
3. National Research Council. *Nonfloating Oil Spills: Risk and Response*; National Academy Press: Washington, DC, USA, 1999; 75p.
4. Gundlach, E.R.; Finkelstein, K.; Sadd, J.L. Impact and persistence of Ixtoc I oil on the south Texas coast. In Proceedings of the 1987 International Oil Spill Conference, Atlanta, GA, USA, 2–5 March 1981; pp. 477–488.
5. Forth, H.P.; Morris, J.M.; Lay, C.R.; Lipton, J.; Mitchelmore, C.L.; Suttles, S.E. *Characterization of Oil and Water Accommodated Fractions Used to Conduct Toxicity Texting in Support of the Deepwater Horizon Natural Resource Damage Assessment*; Technical Report Prepared for NOAA; NOAA: Seattle, WA, USA, 2015; DWH-AR0155415-0049; 48p.
6. Moldan, A.; Chapman, P.; Fourie, H.O. Some ecological effects of the *Venpet-Venoil* collision. *Mar. Pollut. Bull.* **1979**, *10*, 60–63. [CrossRef]
7. Blackman, R.A.A.; Law, J. The ELENI V oil spill: Fate and effects of the oil over the first twelve months. Part I: Oil in waters and sediments. *Mar. Pollut. Bull.* **1980**, *11*, 199–204. [CrossRef]
8. Kaperick, J.A. *Oil Beneath the Water Surface and Review of Current Available Literature on Group V Oils: An Annotated Bibliography*; Report HMRAD 95-8; National Oceanic and Atmospheric Administration, Hazardous Materials Response and Assessment Division: Seattle, WA, USA, 1995; 34p.
9. Tunnell, J.W. Ixtoc I oil spill impacts, short-term and long-term. In *Gulf of Mexico Oil Disaster Symposium*; National Council for Science and the Environment: Washington, DC, USA, 2011.
10. Hooper, C.H. (Ed.) *The IXTOC I Oil Spill: The Federal Scientific Response*; NOAA Hazardous Materials Response Project: Boulder, CO, USA, 1981; 208p.
11. Alejandro, A.C.; Buri, J.L. *M/V Alvenus*: Anatomy of a major oil spill. In Proceedings of the 1987 International Oil Spill Conference, Baltimore, MD, USA, 6–9 April 1987; pp. 27–32.
12. Michel, J.; Galt, J.A. Conditions under which floating slicks can sink in marine settings. In Proceedings of the 1995 International Oil Spill Conference, Long Beach, CA, USA, 27 February–2 March 1995; pp. 573–576.
13. U.S. Coast Guard. *Tank Barge Morris J. Berman Spill, Submerged Oil Recovery Operations*; San Juan, PR, USA, 1994; 104p.
14. Ploen, M. Submerged oil recovery. In *Second International Oil Spill Research and Development Forum*; International Maritime Organization: London, UK, 1995; pp. 165–173.
15. Burns, G.H.; Kelly, S.; Benson, C.A.; Eason, T.; Benggio, B.; Michel, J.; Ploen, M. Recovery of submerged oil at San Juan, Puerto Rico 1994. In Proceedings of the 1995 International Oil Spill Conference, Long Beach, CA, USA, 27 February–2 March 1995; pp. 551–557.
16. Moller, T.H. Summary of the *T/V Nissos Amorgos* oil spill. In *Unpublished Document Distributed at the NRC Workshop on Nonfloating Oil Spills, on 20 August 1998*; International Tanker Owners Pollution Federation Limited: London, UK, 1998; p. 1.

17. Kane, D.A. Recovery of submerged oil from an Alaska lake. In Proceedings of the 2003 International Oil Spill Conference, Vancouver, BC, Canada, 6–11 April 2003; pp. 713–718.
18. Martin, C.A.; Mauseth, G.S.; Suggs, R.D. Underwater cleanup assessment program during the M/V *Kuroshima* incident, April 1998. In Proceedings of the 2003 International Oil Spill Conference, Vancouver, BC, Canada, 6–11 April 2003; pp. 1275–1278.
19. Le Guerroue, P.; Poupon, E.; Merlin, F.X.; Cariou, G. Recovery of sunken and buried oil in coastal water during the *Erika* spill. In Proceedings of the 2003 International Oil Spill Conference, Vancouver, BC, Canada, 6–11 April 2003; pp. 551–558.
20. Čović, I.; Šimunac, A.; Veža, J.; Slišković, M.; Jelić-Mrčelić, G. Methods of pollution removal after Tanker *Erika* Accident. *Trans. Marit. Sci.* **2013**, *2*, 41–48. [CrossRef]
21. Moller, T.H. Recovery of sunken oil in the Sea of Marmara. In Proceedings of the Third Research and Development Forum on High-Density Oil Spill Response, Brest, France, 11–13 March 2002; International Maritime Organization: London, UK, 2002; pp. 337–345.
22. National Oceanic and Atmospheric Administration. Incident News Reports for Golden Beach Mystery Spill. 2000. Available online: https://incidentnews.noaa.gov/incident/9962#! (accessed on 3 March 2022).
23. Fingas, M.; Hollebone, B.; Fieldhouse, B. The density behaviour of heavy oils in freshwater: The example of Lake Wabamun spill. In *Presentation and Paper for the 2006 Freshwater Spill Symposium*; U.S. Environmental Protection Agency: Washington, DC, USA, 2006.
24. Sergy, G.A.; Lamarche, A.; Owens, E.H.; Reimer, P.D.; Zrum, L. Nearshore surveys following the Lake Wabamun Oil Spill. In Proceedings of the 34th Arctic and Marine Oilspill Program Technical Seminar, Banff, AB, Canada, 4–6 October 2011; pp. 19–34.
25. Elsarji, M. How a local NGO succeeded in cleaning up the Lebanon oil spill, 2006. In Proceedings of the 2008 International Oil Spill Conference, Savannah, GA, USA, 4–8 May 2008; pp. 327–330.
26. Fichaut, B. Massive use of berm relocation and surf washing during the 2006 Jyeh oil spill (Lebanon): The accurate response for beaches cleanup. In Proceedings of the 2008 International Oil Spill Conference, Savannah, GA, USA, 4–8 May 2008; pp. 331–338.
27. Operational Science Advisory Team (OSAT-3). *Summary Technical Report for Submerged Oil Mat Tactical Plan, Phase 1 Execution*; Deepwater Horizon Unified Command: New Orleans, LA, USA, 2011; 77p.
28. Dalyander, P.S.; Long, J.W.; Plant, N.G.; Thompson, D.M. Assessing mobility and redistribution patterns of sand and oil agglomerates in the surf zone. *Mar. Poll. Bull.* **2014**, *80*, 200–209. [CrossRef] [PubMed]
29. Operational Science Advisory Team (OSAT-3). *Summary Report: Investigation of Recurring Residual Oil in Discrete Shoreline Areas and Other Indicators in the Eastern Area of Responsibility*; Deepwater Horizon Unified Command: New Orleans, LA, USA, 2013; 54p. + Appendices A to F.
30. Plant, N.G.; Long, J.W.; Dalyander, P.S.; Thompson, D.M.; Raabe, E.A. Application of a Hydrodynamic and Sediment Transport Model for Guidance of Response Efforts Related to the Deepwater Horizon Oil Spill in the Northern Gulf of Mexico along the Coast of Alabama and Florida: U.S. Geological Survey Open-File Report 2012–1234. 2013; 48p. Available online: http://pubs.usgs.gov/of/2012/1234/ (accessed on 3 March 2022).
31. Gustitus, S.A.; Clement, T.P. Formation, fate, and impacts of microscopic and macroscopic oil-sediment residues in nearshore marine environments: A critical review. *Rev. Geophys.* **2017**, *55*, 1130–1157. [CrossRef]
32. National Academies of Sciences, Engineering, and Medicine. *Spills of Diluted Bitumen from Pipelines: A Comparative Study of Environmental Fate, Effects, and Response*; The National Academies Press: Washington, DC, USA, 2016; 144p. [CrossRef]
33. Wang, Z.; Hollebone, B.P.; Fingas, M.; Sigouin, L.; Landriault, M.; Smith, P.; Noonan, J.; Thouin, G.; Weaver, J.W. *Characteristics of Spilled Oils, Fuels, and Petroleum Products: 1. Composition and Properties of Selected Oils*; U.S. Environmental Protection Agency: Washington, DC, USA, 2003; EPA/600/R-03/072.
34. Ward, C.P.; Armstrong, C.J.; Conmy, R.N.; French-McCay, D.P.; Reddy, C.M. Photochemical oxidation of oil reduced the effectiveness of aerial dispersants applied in response to the *Deepwater Horizon* spill. *Environ. Sci. Technol.* **2018**, *5*, 226–231. [CrossRef]
35. Dalyander, P.S.; Plant, N.G.; Long, J.W.; McLaughlin, M. Nearshore dynamics of artificial sand and oil agglomerates. *Mar. Poll. Bull.* **2011**, *96*, 344–355. [CrossRef]
36. Kana, T.W. Suspended Sediment in Breaking Waves. Unpublished Ph.D. Dissertation, Geology Department, University of South Carolina, Columbia, SC, USA, 1979; 153p.
37. Román-Sierra, J.; Muñoz-Perez, J.J.; Navarro-Pons, M. Beach nourishment effects on sand porosity variability. *Coast. Eng.* **2014**, *83*, 221–232. [CrossRef]
38. Michel, J. Spills of nonfloating oil: Evaluation of response technologies. In Proceedings of the 2008 International Oil Spill Conference, Savannah, GA, USA, 4–8 May 2008; pp. 261–267.
39. Parthiot, F.; de Nanteuil, E.; Merlin, F.X.; Zerr, B.; Guedes, Y.; Lurton, X.; Augustin, J.M.; Cervenka, P.; Marchal, J.; Sessarego, J.P. Sonar detection and monitoring of sunken heavy fuel oil on the seafloor. In Proceedings of the Interspill 2004, Trondheim, Norway, 14–17 June 2004; Available online: https://www.interspill.org/wp-content/uploads/2021/11/465_PARTHIOT.pdf (accessed on 3 March 2022).
40. Hansen, K.A.; Fitzpatrick, M.; Herring, P.R.; VanHaverbeke, M. *Heavy Oil Detection (Prototypes)*; Report CG-D-08-09; U.S. Coast Guard Research and Development Center: Groton, CT, USA, 2009; 42p. + Appendices.

41. Wynn, J.; Williamson, M.; Frank, J. Sequestered oil pollution mapping, and tracking active oil breakouts in sensitive rivers, bays, and estuaries by induced polarization. In Proceedings of the 2017 International Oil Spill Conference, Long Beach, CA, USA, 15–18 May 2017.
42. Fitzpatrick, M.; Tebeau, P.A.; Hanson, K.A. *Development of Bottom Oil Recovery Systems-Final Project Report*; Report No. CG-D-09-13; U.S. Coast Guard Research and Development Center: Groton, CT, USA, 2013; 35p. + Appendices.
43. Arekhi, M.; Terry, L.G.; John, G.F.; Clement, T.P. Environmental fate of petroleum biomarkers in *Deepwater Horizon* oil spill residues over the past 10 years. *Sci. Total Environ.* **2021**, *791*, 148056. [CrossRef]