Exxon Valdez Oil Spill
Restoration Project Final Report

Evaluation of Oil Remediation Technologies for Lingering Oil from the *Exxon Valdez* Oil Spill in Prince William Sound, Alaska

Restoration Project 050778
Final Report

Jacqueline Michel, Zach Nixon, and Linos Cotsapas

Research Planning, Inc.
1121 Park Street
Columbia, South Carolina 29201

for

National Marine Fisheries Service
National Oceanic and Atmospheric Administration
11305 Glacier Highway
Juneau, Alaska 99801-8626

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Study History: Project 050778 was developed because lingering oil from the *Exxon Valdez* oil spill remains throughout Western Prince William Sound (PWS) and may have chronic effects on sea otter and sea duck populations in these areas. In studies conducted in 2001 and 2003 by the NOAA Auke Bay Laboratory, estimates were made of the amount of surface and subsurface oil remaining in PWS and the location of the oil in the intertidal zone. Most of the subsurface oil occurs in the middle intertidal zone and is less weathered than the surface oil. If the lingering oil is shown to be the source of on-going impacts, feasible remediation methods will be needed.

Abstract: The objective of this study was to identify and evaluate technologies for remediating the lingering oil in Prince William Sound. The 2001 survey data were processed geospatially to produce maps and statistics on the estimated area and volume of subsurface oil, by degree of oiling. Several sites were visited in the field. Eleven promising technologies were identified and evaluated using a scoring matrix for factors of effectiveness, implementability, and operations. Four technologies scored the highest out of maximum score of 240: Natural recovery (score of 161); Physical removal with landfill disposal (score of 142); Physical removal with landfarming (score of 140), and bioremediation (score of 145). These technologies were evaluated further using a scoring matrix for environmental factors considering: sediment recovery; intertidal community recovery; acute and chronic impacts during implementation; fish and wildlife disturbance during implementation; and amount of bioavailable oil remaining after termination of cleanup activities. Two technologies scored the highest out of maximum score of 100: Natural recovery (score of 70); and Bioremediation (score of 60). It should be noted that natural recovery scores were very high for many factors because no cleanup activities are undertaken (e.g., no personnel, no energy demand, no training). Costs for these two technologies were developed. Natural recovery costs included only bi-annual monitoring for 10 years, at a cost of $875,000. Bioremediation costs were estimated based on implementation on shoreline segments where the subsurface oil met the following criteria: any combination of LOR, MOR, or HOR in area greater than 100 m^2. We used the geospatial data for the 42 segments with known subsurface oil to calculate the costs for treating the 17 segments that met the oiling criteria, then extrapolated these costs for treating the volume of oiled sediments as calculated by Short et al. (2004). The total costs for bioremediation was $49,925,000. These costs do not include: 1) finding the rest of the subsurface oil to be treated; 2) government project management and oversight; and 3) multi-year application.

Key Words: *Exxon Valdez* oil spill, lingering oil, remediation

Project Data: None

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Acknowledgements

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EVALUATION OF OIL REMEDIATION TECHNOLOGIES FOR LINGERING OIL FROM THE *EXXON VALDEZ* OIL SPILL IN PRINCE WILLIAM SOUND, ALASKA

I. INTRODUCTION

Oil from the 1989 *Exxon Valdez* oil spill (EVOS) has persisted for over 12 years, as both surface and subsurface oil residues (Short et al., 2004). Surface oil primarily occurs as highly weathered residues that pose little continuing ecological risk. Subsurface oil, however, can occur as moderately weathered, bioavailable oil residues, and may be a source of continuing exposure to intertidal and aquatic resources in Prince William Sound (PWS). There have been numerous studies on the distribution and persistence of oil in Prince William Sound in the early years after the *Exxon Valdez* oil spill (Gibeaut and Piper, 1998; Neff et al., 1995; Gundlach et al., 1991; Boehm et al., 1995; Hayes and Michel, 1998). These studies were generally of two types:

1) SCAT (Shoreline Cleanup Assessment Teams) surveys where teams walked the shoreline to document the extent of visual oil, including digging of trenches based on the experience of the team to look for subsurface oil (surveys were conducted in 1989, 1990, 1991, and 1992); and
2) Multi-disciplinary surveys over time at selected sites.

In 2001, the EVOS Trustee Council funded a study to quantify the extent of oil residues in PWS (known as the “big dig”). The key results of this study, published by Short et al. (2004), included:

- There were an estimated 11.3 hectares of lingering oil in PWS as of 2001
- Of this, 7.8 hectares were estimated to be gravel beaches contaminated with subsurface oil, containing an estimated 56,000 kilograms of oil
- Most of the subsurface oil was visually described as lightly oiled residue (62%) or oil film (11%); only 21% was described as moderately oiled, and 6% as heavily oiled
- Most of the subsurface oil was moderately weathered, with a median concentration of polynuclear aromatic hydrocarbons (PAH) of 68.6 μg/g (excluding the samples described as having only an oil film)
- All of the subsurface oil was fingerprinted as matching oil from the *Exxon Valdez*
- More oil was found in the mid- and lower-intertidal zones than in the upper-intertidal zone
- Most of the subsurface oil occurred in sheltered embayments

Based on the 2001 studies, further field work was funded: the objective of SCAT II was to assess the bioavailability of the lingering oil, and of SCAT III was to more accurately estimate the amount of oil remaining in the northern Knight Island area where otters seem to be recovering slowly. Another objective of SCAT III was to confirm the hypothesized distribution of subsurface oil in the lower intertidal zone (Jeff Short, pers. comm., 2005). These study results have not yet been published. However, review of the data provided to us showed that, of 662 pits excavated in the lower intertidal zone at 32 beach segments, 51 pits on 14 beaches contained subsurface oil, with 6 pits containing heavily oiled residue, 17 with moderately oiled residue, 16 with lightly oiled residue, and 12 with oil film.

Because the lingering subsurface oil is thought to pose continuing risks to intertidal resources, the EVOS Trustee Council decided to conduct a study to identify and evaluate currently available remediation technologies that may be applicable to lingering oil in PWS. The goal of the study was to:

> Determine if there are feasible, effective, and environmentally sound cleanup methods that can speed the removal of subsurface oil over that of natural recovery.

Using an objective and well-documented evaluation process, potential technologies would be evaluated and screened, then the most promising methods would be assessed for cost and environmental benefit or trade-off.

This work is important because of concerns that lingering oil continues to expose intertidal and aquatic resources to EVO and is a factor in the recovery of injured resources. As long as the oil persists, particularly the subsurface oil which is only moderately weathered and still bioavailable, there will be concerns about its effects. Also, users of intertidal resources, including subsistence users, will continue to be concerned about the safety of these resources. However, it is important to note that our analysis did not evaluate whether or not there actually are impacts resulting from the lingering oil in PWS, or what types of lingering oil pose the greatest potential risk. Such an analysis is very complex, and it is outside the scope of work of this study to conduct a full risk assessment and analysis of the risk reduction resulting from treatment of the lingering oil. The final decision must take into account the effects of the oil now in place and balance that against the benefit and risks of further cleanup. A rigorous risk assessment/risk reduction assessment would explicitly include uncertainties both with the remediation effectiveness and also with the reduction of risks to living resources and resource uses (and users). These uncertainties would be merged and the complete assessment, including the final uncertainties, would be purveyed to the decision makers so they will understand (and be able to convey) what uncertainty they are accepting as they make their decision. Additional work is needed to test and refine the proposed remediation technologies. Such studies will reduce the uncertainty but never eliminate it because of the highly variable conditions at each shoreline segment. During implementation, monitoring for both effectiveness and effects will be necessary, to confirm assumptions made during the risk assessment process. Our task was to identify and evaluate the feasibility of promising remediation technologies to remove the lingering oil, which is just one step in this overall risk assessment process.

II. METHODS OF STUDY

A. General Approach

The general study approach consisted of four tasks:

Task 1. Conduct spatial analysis of the data on subsurface oil in PWS collected by Short et al. (2004).

Task 2. Conduct limited fieldwork to review analyses by Short et al. (2004) on oil distribution at selected sites.

Task 3. Generate a list of promising cleanup technologies that may effect the removal of submerged oil, including natural recovery.

Task 4. Evaluate and screen technologies for applicability to the subsurface oil conditions and habitats in PWS.

The methods for each task are summarized in the following sections.

B. Spatial Analysis of Subsurface Oil in PWS

1. Subsurface Oil Data

The spatial distribution of oiling within and among beach segments surveyed during the 2001 SCAT surveys was analyzed to produce results that would support evaluation and selection of remediation strategies. A short summary of the methods and data generated by Short et al. (2004) is provided, so that our analytical approach can be better understood.

Short et al. (2004) identified three categories of gravel beaches in western PWS that had been described as heavily or moderately oiled during SCAT surveys from 1989 to 1993, for a total shoreline length of 116.6 kilometers (km). Beach segments of 100 or less meters (m) in length were randomly selected from the different categories, so that 91 beach segments totaling 7.9 km were sampled. In the field, each segment was divided into up to eight columns that were 12.5 m wide. Each column was then divided into six blocks at 0.5 m vertical tidal elevation intervals. Thus, there were 48 blocks per 100 m segment of beach. Two 0.25 m^2 quadrats were randomly placed within each block. Each quadrat was evaluated for surface (within the top 5 centimeters [cm]) and subsurface oil, using the standard SCAT oil classification terms. Subsurface oil was described in pits excavated to 0.5 m depth as no oil (NO), oil film (OF), and light, moderate, or heavy oil residue (LOR, MOR, HOR, respectively). In total, 6,775 pits were excavated and described. The segment location and length, column and block data, pit location within the segment, and field observations on oiled intervals and type were entered into spreadsheets.

Our re-analysis of these data involved creation of Geographic Information Systems (GIS) data layers for each beach segment so that spatial analyses could be conducted. The data were received as MS Excel spreadsheets and were preprocessed as follows:

1) Data imported into Access database format, then to CSV text files.
2) 3D GIS point files generated for surfaces of all beaches based upon block characteristics
3) 3D GIS raster grids generated from the surface point files
4) GIS point files generated for all pits for all beaches based upon coordinates within blocks

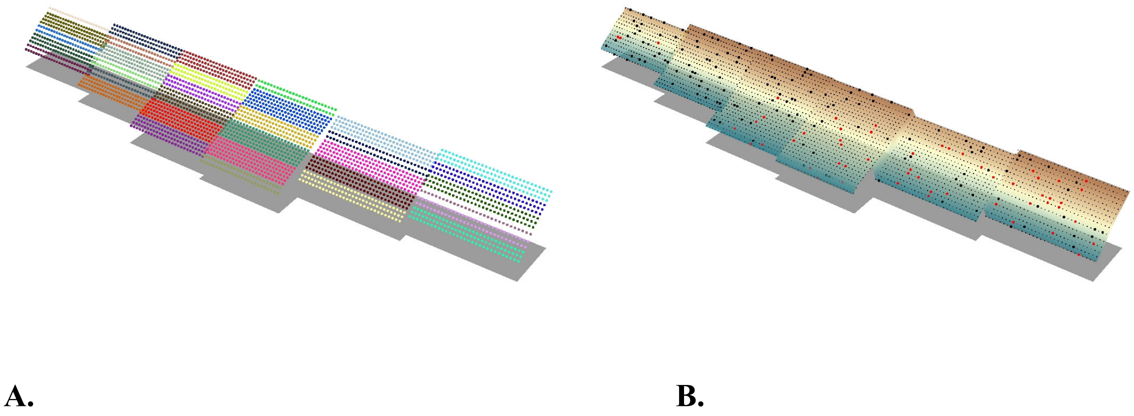


FIGURE 1. 3D view of data representing a single beach segment (KN0117A). 3D beach surface points at 0.5 m spacing (2x vertical exaggeration) generated from raw block data with blocks in different colors (**A**) and a 3D beach surface raster grid with pit locations superimposed (**B**).

All spatial data were created using a common spatial reference system based upon the survey grid.

2. Estimating Spatial Autocorrelation of Point Data by Segment

The next step was to determine if it was possible to discern patterns in the oil distribution within a beach segment. The oil distribution is a key factor in the evaluation of feasible remediation actions and their costs. Furthermore, the volume of oiled sediments in PWS that Short et al. (2004) estimated was extrapolated from the 7.9 km of shoreline sampled. Thus, the actual locations of oiled areas to be considered for remediation are not known beyond the beach segments where subsurface oil was found.

Moran’s Index is a statistic that indicates spatial autocorrelation. A Moran's Index value near +1.0 indicates clustering; an index value near -1.0 indicates dispersion. We calculated Moran’s Index for individual point datasets representing pits only for segments with at least one recorded incidence of subsurface oiling. Of the 91 segments in the database, 42 segments were recorded as having subsurface oiling. Each pit was assigned an ordered numeric indicator value according to its maximum subsurface oiling descriptor, as shown in Table 1.

TABLE 1. Oiling characteristics and indicator values.

Maximum Subsurface Oiling Descriptor	Code	Indicator Value
Oil film	OF	1
Lightly oiled residue	LOR	2
Moderately oiled residue	MOR	3
Heavily oiled residue	HOR	4

High positive spatial correlation (Moran's I values above 0 and approaching 1) indicates that oiled pits tended to be clustered together rather than distributed in a spatially random fashion. The clustering of oiled pits has implications in both the further modeling of spatial distributions, and in evaluating differences in cleanup feasibility between and across segments. The relationship between Moran's I and the amount of oil within a beach segment (as represented by the total area underlain by subsurface oil) is presented in Figure 2. Note that beach segments with large amounts of oil tend to have more autocorrelation, as might be expected. In general, segments in the upper right hand quadrant of the graph would be better cleanup targets with relatively large amounts of oiled pits that are relatively close together.

Figure 3 shows plan-view maps of the location of the pits and their subsurface oiling for four specific oiled segments, and the Moran's I value for the segment. The width of the segment varies as a function of the beach slope, so steep beaches appear narrow and flat beaches appear wide on these plots. These segments were selected to show the patterns of oil distribution for

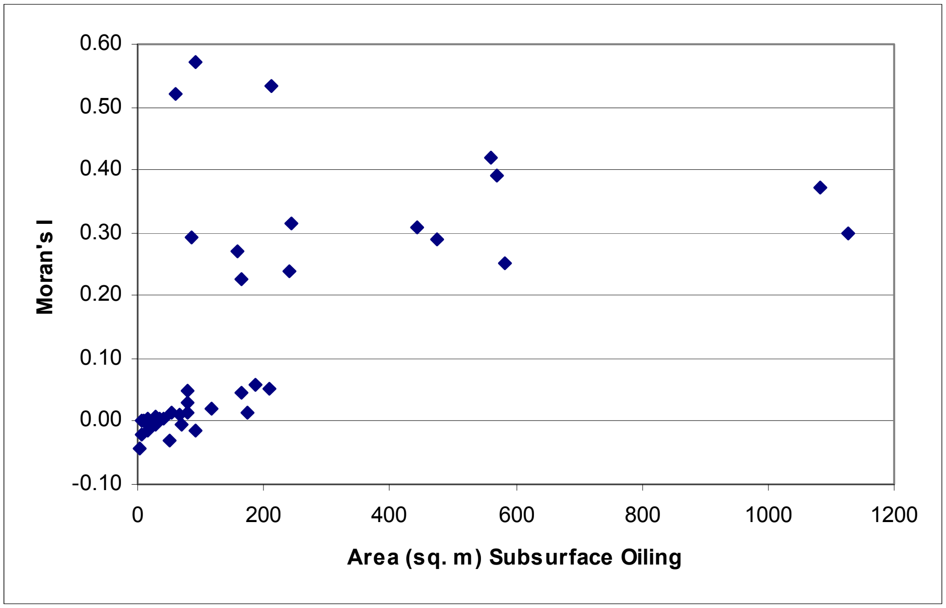
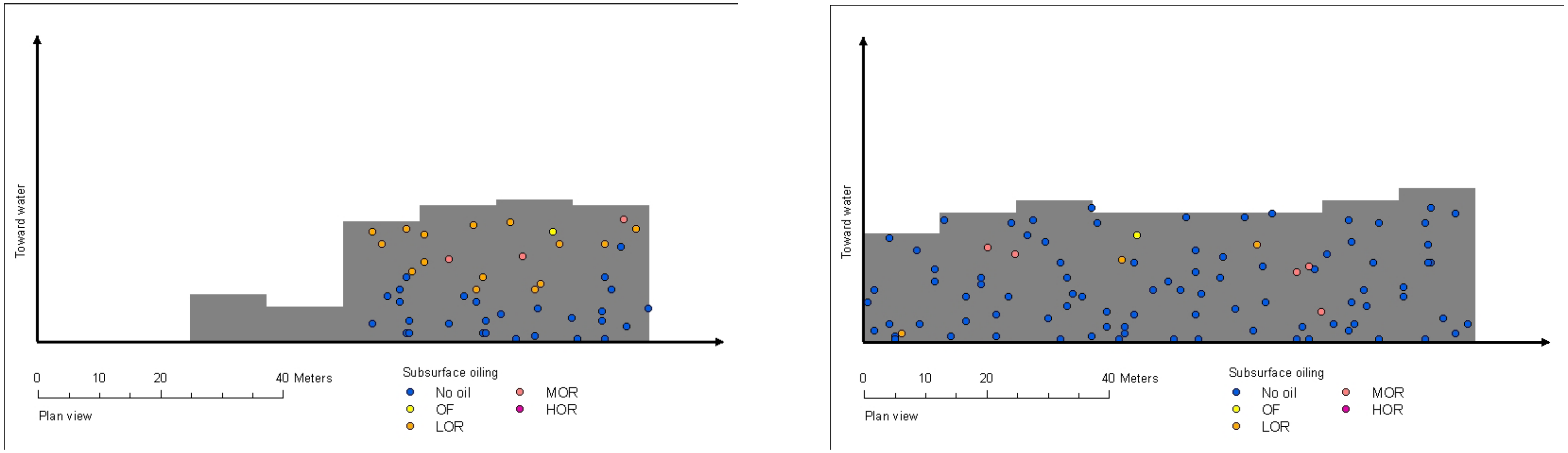
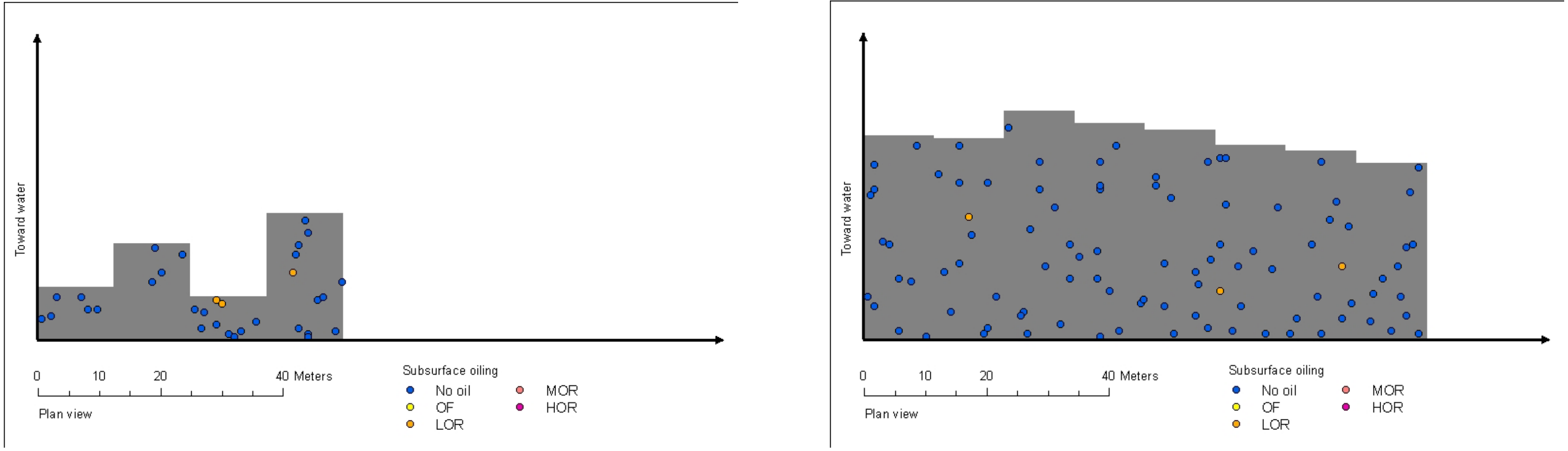


FIGURE 2. Moran's I values vs. area of subsurface oiling for the 42 beaches that contained subsurface oil.



A. KN0109A (Moran's I: 0.418) **B. LA018A1 (Moran's I: 0.058)**



C. KN0506A (Moran's I: 0.522) **D. LA020D (Moran's I: -0.006)**

FIGURE 3. Planimetric maps, pit locations by oiling descriptor, and Moran's I values for segments (**A**, **B**) with relatively large amounts of subsurface oiling, and (**C**, **D**) with lesser amounts. Although the beach slopes vary, the y-axis represents an elevation drop of 3meters.

segments with different amounts of subsurface oil. Figure 3A shows a beach segment on Knight Island where mostly LOR was found consistently in the lower elevation pits, and the Moran's I value is high at 0.418. Figure 3B shows a segment on Latouche Island that also had high amounts of subsurface oil, but the oiled pits are dispersed, and the Moran's I value is low at 0.058. Figure 3C shows a Knight Island beach segment that had low amounts of LOR but still had a high Moran's I value because it was clustered. In contrast, Figure 3D shows a segment with low amounts of oil, with wide scatter in the location of the three pits with subsurface oil. Thus, the Moran's I value is a useful metric to represent the patchiness of the subsurface oil at the 42 beach segments.

3. Estimating Spatial Distribution of Subsurface Oil by Segment

It is useful to examine not only the distribution of sample pits on beaches but, more generally, what those sample pits indicate about the distribution of subsurface oil in terms of number, shape, and arrangement of patches. As such, we constructed continuous spatial models of subsurface oil. This was performed using indicator kriging of the sample pit data. Indicator kriging is an interpolation procedure that produces a continuous map of the probability of a binary outcome – in this case, the presence of subsurface oil – based upon the statistical properties of the spatial arrangement of known values. All subsurface oiling categories from Table 1 were considered to be a positive value, so the resulting maps depict probabilities of any type of subsurface oiling regardless of the degree of oiling.

We expected the processes that drove oil deposition and persistence to have higher rates of spatial variation in the cross-shore dimension, than the along shore, warranting a model that accounted for this anisotropy. Furthermore, we expected these processes to be similar for all segments. Thus, we computed the geometric mean of all anisotropy ratios and the weighted arithmetic mean of all major axis lengths. This geometric mean of anisotropy ratio weighted by oiling percentage at 90 degrees was 1.97. This indicates that subsurface oiling conditions are about twice as likely to change over a given unit length in the cross-shore dimension as in the alongshore.

Continuous (0.0 to 1.0) kriged subsurface oiling probability surfaces were converted to presence/absence maps by extracting all areas where the probability of subsurface oiling was greater than 0.5. The number of discrete patches present was counted on each of these presence/absence subsurface oiling maps. Patches were designated by grouping contiguous cells with an eight-neighbor cell contiguity rule.

The area of subsurface oiling was then calculated. Note that, as slope of the beach was not accounted for, the area is reported as planimetric area, rather than actual beach surface area. Differences in the two values are minor. The area of subsurface oiling for each segment using this method was compared with the area as estimated by Jeff Short (pers. comm., 2005) using a different method, as shown in Figure 4. The results of each method are very similar, with a correlation coefficient of 0.989.

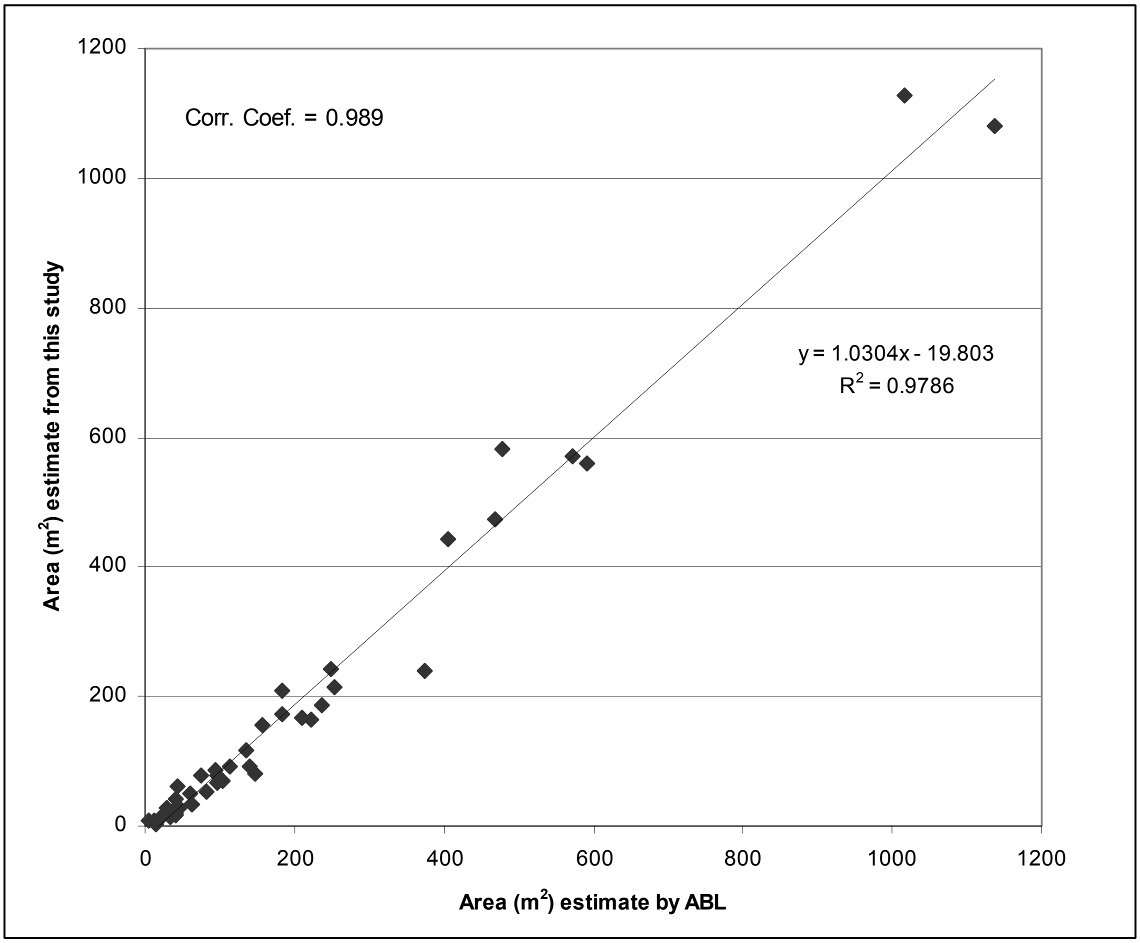
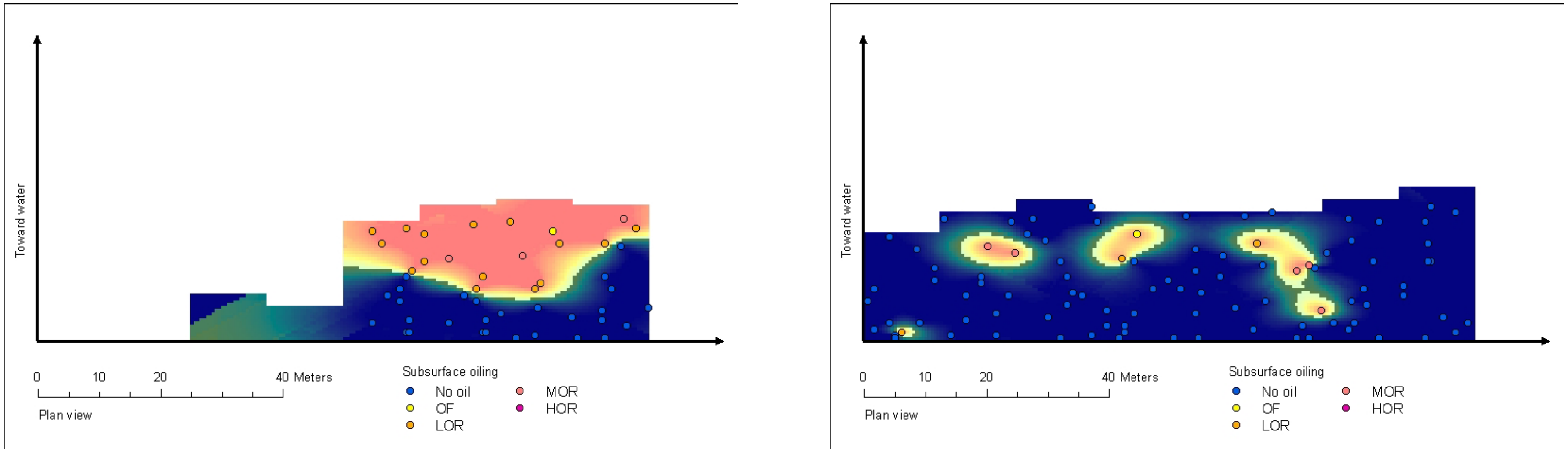
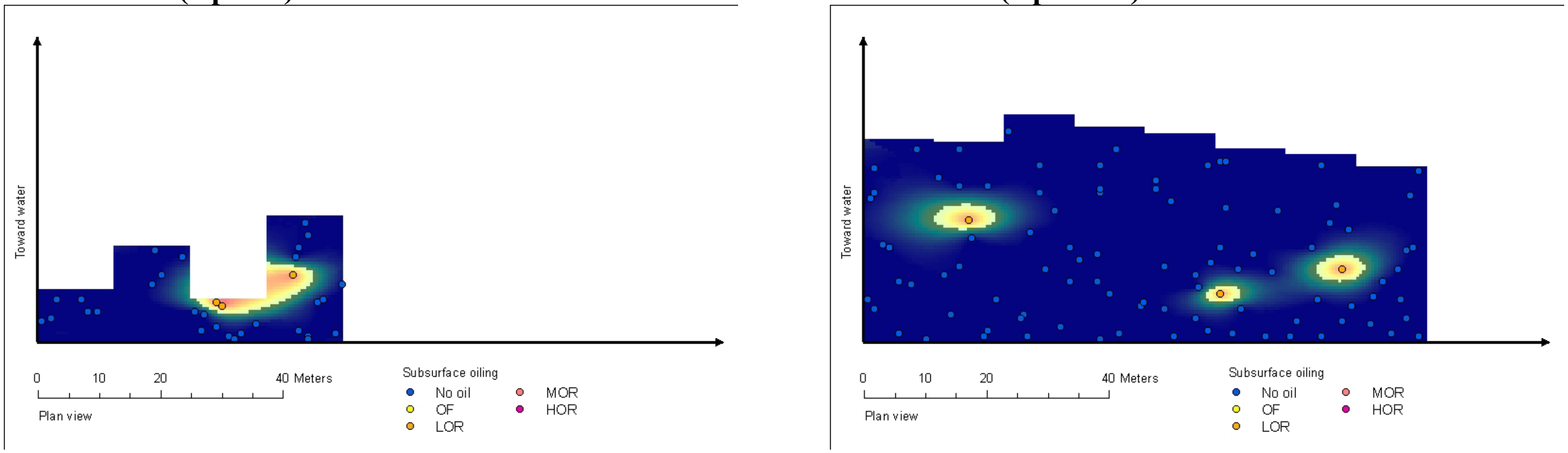


FIGURE 4. Plot of the estimated area of subsurface oiling on the 42 shoreline segments that contained subsurface oil in 2001, as estimated by the methods used in this study versus the areas as estimated by researchers at the NOAA Auke Bay Laboratory (Jeff Short, pers. comm., 2005).

Figure 5 depicts plan-view maps of the same four oiled segments shown in Figure 3, together with pits indicated by circles with colors for subsurface oiling descriptor, with kriged probability surfaces as a color tint over resulting black and white presence/absence oiling maps.



A. KN0109A (1 patch) **B. LA018A1 (5 patches)**



C. KN0506A (1 patch) **D. LA020D (3 patches)**

FIGURE 5. Planimetric maps of kriged probability of subsurface oiling (any descriptor), as color tint, draped over black and white resulting subsurface oiling presence/absence maps, for segments in Figure 3. Blues represent low probability of oiling and oranges and reds represent high probability of oiling. Probability surfaces were converted to discrete maps using a p = 0.5 probability cutoff.

4. Estimating Volume of Oiled Sediment by Oiling Descriptor and Segment

In estimating time and costs of many methods of cleanup, the volume of oiled material, as opposed to the surface area of oiled patches, is an important factor. As such, we used the oiling thickness information recorded in the pit data, in conjunction with area of subsurface oiling as calculated from the kriged probability surfaces, to calculate volume of oiled material by oiling descriptor for each segment. We also calculated the volume of clean overburden in the same manner above that oiled material for each segment.

In some cases, pits with recorded subsurface oiling were lacking thickness information. In these cases, thickness was assumed to be the average thickness of all oiled layers with that oiling descriptor in that segment, or in the dataset as in Table 2 if there were no similar layers in that segment. Where thickness of overburden was unknown, thickness was similarly assumed to be the average thickness of all overburden layers for that segment. It is interesting to note that the oil thickness generally increases with degree of oiling, as would be expected.

TABLE 2. Average thickness of oiled layers by oiling descriptor.

Oiling Descriptor (number of segments)	Avg. Thickness (cm)
OF (n=18)	2.7
OF/LOR (n=1)	10.0
LOR (n=37)	7.7
LOR/MOR (n=1)	8.3
MOR (n=18)	11.8
MOR/HOR (n=1)	8.0
HOR (n=6)	21.5

C. Field Validation Survey

Site visits of beach segments in PWS recommended by Mandy Lindeburg of the NOAA Auke Bay Laboratory were conducted on 23-25 June 2005, in cooperation with NOAA Office of Response and Restoration researchers (John Whitney and Alan Mearns) conducting their own long-term monitoring program. Pits were excavated in specific areas where subsurface oil was observed in either 2001 or 2003. These areas were either delineated on photographs provided by Lindeburg or generally located in the field using the block data for the oiled pits. The objectives of the site visit were to inspect representative segments that might require remediation, confirm the persistence of subsurface oil, and identify possible constraints for promising remediation technologies. Table 3 summarizes the field observations on oiling in 2005, compared to the pit data for either 2001 or 2003. Considering the large differences in number of pits (48-204 pits per segment during the 2001/2003 surveys versus 2-5 pits per segment during the site visits), the observations are consistent temporally. At two of the six segments visited in 2005, no oil was observed in the small number of pits excavated. At the other four segments, the thickness, depth, and type of oiled sediments were similar but lower in 2005 compared to 2001 or 2003. However, the number of pits in 2005 is too few to infer any significant temporal changes.

TABLE 3. Summary of the field observations at selected beach segments in PWS visited in 2005, along with the pit data for either 2001 or 2003. Refer to Table 1 for definition of oiling categories.

Beach Segment	2001 Pit Data	2003 Pit Data[1]	2005 Observations
DI067A		80 pits; 12 oiled HOR – 2 pits, 1-2 cm thick, depth 10 cm MOR – 4 pits, 1-5 cm thick, depth 2-5 cm LOR – 4 pits, 1 cm thick, depth 10 cm OF – 3 pits, 0.5-1 cm thick, depth 10 cm	5 oiled pits MOR – 1 pit, 5+ cm thick, depth 25 cm LOR – 3 pits, 20 cm thick, depth 25-30 cm OF – 1 pit, 5+ cm thick, depth 25 cm
KN109A	48 pits; 19 oiled MOR – 3 pits, 10-20 cm thick, depth 10-20 cm LOR – 15 pits, 5-25 cm thick, depth 10-45 cm		No oil found in three pits; 20 cm of clean gravel overlying soft peat layer
KN109A-2		42 pits; 9 oiled MOR – 3 pits, 2-5 cm thick, depth 5 cm LOR – 2 pits, 1 cm thick, depth 5 cm OF – 4 pits, 0.5-1 cm thick, depth 5-10 cm	No oil was found in three pits; 25 cm of clean gravel overlying soft peat layer
KN114A-2		60 pits; 6 oiled HOR – 3 pits, 10-20 cm thick, depth 5 cm MOR – 1 pit, 10 cm thick, depth 5 cm LOR – 2 pits, 1-5 cm thick, depth 5 cm	4 oiled pits MOR/HOR – 2 pits, 10+ cm thick, depth 10 cm LOR – 1 pit, 10+ cm thick; depth 10 cm OF – 1 pit, 10+ cm thick, depth 10 cm
KN115A-2		68 pits; 5 oiled HOR – 1 pit, 40 cm thick, depth 5 cm MOR – 3 pits, 35-40 cm thick, depth 5-15 cm LOR – 1 pit, 1 cm thick, depth 5 cm	2 oiled pits MOR/HOR – 1 pit, 18+ cm thick, depth 7 cm MOR – 1 pit, 10+ cm thick, depth 15 cm
KN117A	204 pits; 54 oiled HOR – 2 pits, 10-40 cm thick, depth 30-50 cm MOR – 14 pits, 5-30 cm thick, depth 10-50 cm LOR – 31 pits, 5-20 cm thick, depth 5-45 cm OF – 9 pits, 1-24 cm thick, depth 5-20 cm		3 oiled pits MOR – 1 pit, 20 cm thick, depth 5 cm LOR – 2 pits, 10+ thick, depth 10 cm

[1] Depth means the distance below the surface to the top of the oiled layer. It represents the thickness of the overlying visually clean sediments.

The characteristics of the shoreline segments with subsurface oil vary widely. Figures 6-9 shows photographs of four of the sites visited in June 2005. The key features to note in these photographs are:

1) Most of the sites are sheltered from significant wave action.
2) Many sites are not true “beaches” defined as sediment accumulations formed by wave action. Instead, we refer to them as rocky rubble shores – steeply sloping shores where the coarse-grained clasts consists of debris that has accumulated on the slope under the influence of gravity. The clasts show no evidence of reworking, such as sorting or rounding, or the formation of depositional berms at the high-tide line.
3) Even the sites that are true beaches in PWS have unique characteristics. They are underlain by gently sloping surfaces of bedrock, probably uplifted, wave-carved platforms, covered by a veneer of gravel. In our studies as part of the long-term monitoring program by NOAA’s Office of Response and Restoration (e.g., Hayes and Michel, 1998), we called beaches such as Smith Island and Point Helen “cobble/boulder platforms with berms” because the only really active part of these beaches are the high-tide and storm berms. The rest of the intertidal zone is composed of very flat platforms with a stable surface armor.
4) Most of the surface sediments are very coarse, dominated by clasts that are cobble (64-256 millimeters [mm]) and boulder (>256 mm) in size. The grain size of the gravel increases seaward.
5) Most beaches with subsurface oil have a stable armor of coarser gravel on the surface, which has played an important role in the long-term persistence of the subsurface oil, as shown in Figure 10.

These characteristics of sites with subsurface oil were considered when evaluating the effectiveness and potential impacts of remediation technologies.

FIGURE 6. Segment DI067A, Disk Island, June 2003. The slope of the intertidal zone is very flat, influenced by the underlying bedrock platform. The surface sediments are mostly cobbles; subsurface sediments also include pebbles and granules. The sediments are sub-angular, indicating low wave energy. Shallow pits (dug by sea otters?) were observed in the lower intertidal area. The subsurface oil occurs in the vicinity where the two people are standing.

FIGURE 7. Segment KN114A, Herring Bay, Knight Island, June 2003. The surface sediments are mostly large boulders that form a stable armor overlying finer gravel sediments. The surface gravel is sub-angular and the clasts have a good cover of algae, indicating low wave energy. Subsurface oil was found adjacent to the large rock outcrop.

FIGURE 8. Segment KN115A-2, Herring Bay, Knight Island, June 2003. This small pocket beach is bordered by rock outcrops. A small stream drains across the middle of the beach. The boulders and cobbles are angular, indicating low wave energy. Subsurface oil (MOR) was found at depths of 7-15 cm where the shovel is located.

FIGURE 9. Segment KN117A, Herring Bay, Knight Island, June 2003. This site consists of a small indentation of the shoreline where bedrock rubble has accumulated in the upper intertidal zone. The lower intertidal zone is a raised bay bottom with fine gravel. Because of the low wave energy and large surface gravel at this site, natural sediment reworking rates are extremely slow. Subsurface oil (LOR) was found under the rubble.

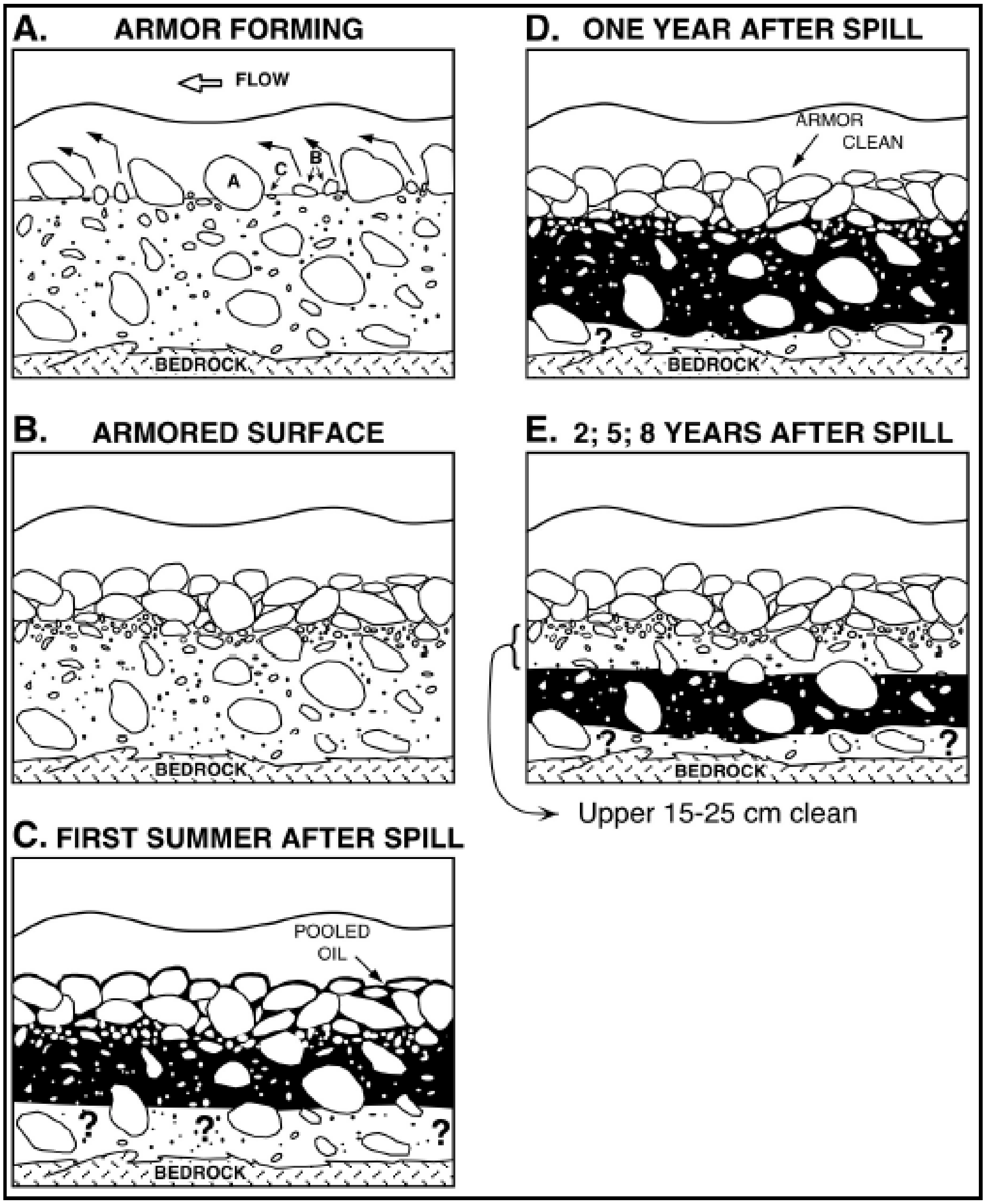


FIGURE 10. Schematic model of effect of well-developed armor on retention of subsurface oil in gravel beaches in PWS. (A) Process involved in the development of an armored surface of coarse material on a gravel beach. The particles of size A are too large to be removed by prevailing currents; those of size B are readily transportable, and some of those of size C are sheltered by the larger particles and are not picked up by the current. (B) Well-developed armor surface. (C) Initial oiling, with some pooled oil between boulders and cobbles. (D) One year later, cleanup efforts and natural processes have removed the oil on the gravel in the armor. (E) After two years, natural processes have cleaned the oiled sediment under the armor to depths of 15-25 cm. Deeper oiled sediments remain relatively unchanged after eight years. From Hayes and Michel (1999).

D. Remediation Technology Assessment

Under this task, promising remediation technologies that may be used for the removal of submerged oil from intertidal gravel beaches, including natural recovery, were reviewed. Literature used in this review included Characteristic Coastal Habitats: Choosing Spill Response Alternatives published by NOAA (2000), Literature Review on the Use of Commercial Bioremediation Agents for Cleanup of Oil-Contaminated Estuarine Environments by Zhu et al. (2004), the U.S. Environmental Protection Agency Assessment and Remediation of Contaminated Sediments (ARCS) Program Remediation Guidance Document (USEPA, 1994), and the U.S. Army Environmental Center Remediation Technologies Screening Matrix and Reference Guide, 4th Edition.

Based on the characteristics of the lingering subsurface oil in gravel beaches in PWS, a list of all promising remediation methods was developed, as shown in Table 4. Each technology is briefly described below.

TABLE 4. Promising oil remediation technologies for the lingering subsurface oil in PWS.

Remediation Technologies Evaluated
Natural Recovery
Sediment Reworking/Tilling
Trenching and Flushing (hot water)
Flushing with Chemical Agents
Bioremediation
Bioaugmentation
Capping with Clean Sediments
Physical Removal - Landfill
Physical Removal - Incineration
Physical Removal - Landfarming
Physical Removal - Sediment Washing

1. Natural Recovery: Oil is left in place to degrade naturally. No action is taken, although monitoring of contaminated areas may be required. Most effective with low residual oil concentrations.

2. Sediment Reworking/Tilling: The oiled sediments are roto-tilled, disked, or otherwise mixed using mechanical equipment or manual tools. The objective is to break up the oiled sediment layers, increasing their surface area and decreasing the oil concentrations, thus enhancing the rate of microbial degradation through aeration. This method also mixes deeper subsurface oil layers into clean surface sediments, where the oil can be physically removed by sediment re-working and/or tidal flushing. Recovery of oil released during tidal inundation is attempted using booms and/or sorbents. Most effective with fresh oils, thin oil layers, low-to-moderate concentrations, and small gravel, but always requires exposure to wave energy to re-

work the surface sediments and return the beach profile and sediment distribution patterns back to normal.

3. <u>Trenching and Flushing (with hot water)</u>: Clean surface sediments are removed and stockpiled, and the oiled layers are excavated and piled in place in trenches. Then the oiled sediments are flushed with hot water to release the oil onto the water table in the beach, where the oil is recovered using skimming systems or sorbents. When no more oil is released, the sediments are spread into the trench and covered by the clean surface sediments. Booms and/or sorbents are used to recover any oil released during tidal inundation of the sediment piles and open trench. Equipment would include barges, tugs, and cranes for transport to the beaches, small bobcats to excavate the sediments, and heaters, pumps, and hoses for applying the hot water wash.

4. <u>Flushing with Chemical Agents</u>: Similar to trenching and flushing (above) but using chemical agents to increase the efficacy of oil release during flushing. Excavation is required because the oiled layers are at depths below which the chemical agent can feasibly be injected from the beach surface.

5. <u>Bioremediation</u>: Natural biodegradation rates in-situ can be enhanced by actions that increase the availability of oxygen and nutrients at the oil:water interface. Nutrients (generally nitrogen and phosphorus) and oxygen can be added to stimulate microbial growth and accelerate the rate of oil hydrocarbon biodegradation due to natural microbial processes. The hydrology of water flow in the oiled substrate and the surrounding clean sediments would need to be understood to insure that nutrients and oxygen can be provided to the oiled sediments at an adequate rate. Because it is not clear what factors are limiting oil degradation in PWS, we refer to adding amendments rather than specifying nutrients, oxygen, surfactants, water, etc. Bioremediation is less effective for weathered oil, high concentrations, and limited oil-water interfacial area (e.g., pooled oil or sediments with oil-filled pores). Specialized methods would be needed to be effective on highly porous gravel beaches due to the potential for the amendments to be washed out of the contaminated area quickly.

6. <u>Bioaugmentation</u>: Formulations containing specific hydrocarbon-degrading microbes are added to the oiled area to increase the rate of oil degradation. Includes only microorganisms that have not been genetically modified. Because microbes require nitrogen and phosphorus to convert hydrocarbons to biomass, formulations containing these oil degraders must also contain adequate nutrients. Generally not effective for open systems such as intertidal habitats where added bacteria compete poorly with indigenous populations. However, it was included because it is often used in terrestrial systems to kick-start the degradation process.

7. <u>Capping with Clean Sediments</u>: Clean sediments are placed over areas of subsurface oil to reduce the rate of oil migration out of the oiled layers and to prevent oil release by bioturbation (such as sea otters digging for shellfish). The placed sediments must be similar in grain size characteristics of the natural beaches. Waste streams would be

generated during the mixing of different grain sizes to create a custom blend for each site.

8. <u>Physical Removal – Landfill</u>: The clean surface sediments are removed and stockpiled, and the oiled sediments are excavated and transported off-site for disposal in a landfill. Because of the characteristics of the gravel beaches that have subsurface oil, only mechanical excavation is feasible. Equipment would include barges, tugs, and cranes for transport to the beaches, small bobcats to excavate the sediments, and containers for storing the oiled sediments. Depending on the volume of sediment removed, it might be necessary to backfill with like materials.

9. <u>Physical Removal – Incineration</u>: Similar to physical removal but with treatment of the waste stream by incineration. Incineration uses high temperatures, 870 to 1,200° C (1,400 to 2,200° F), to volatilize and combust (in the presence of oxygen) organic constituents. The destruction and removal efficiency for properly operated incinerators exceeds the 99.99% requirement for hazardous waste. Distinct incinerator designs are rotary kiln, liquid injection, fluidized bed, and infrared units.

10. <u>Physical Removal – Landfarming</u>: Similar to physical removal but with treatment of the waste stream by landfarming. Landfarming usually incorporates liners and other methods to control leaching of contaminants. Contaminated sediment is applied into lined beds and periodically turned over or tilled to aerate the waste. Moisture, heat, nutrients, oxygen, and pH can be controlled to enhance biodegradation.

11. <u>Physical Removal - Sediment Washing</u>: Similar to physical removal but with treatment of the waste stream by washing of the oiled sediments with biological and/or chemical agents so that the cleaned sediments can be re-used off-site. Equipment requirements for sediment washing include: a truck mounted washing unit, sediment processor, sediment washing unit, hydrocyclones, shaker screens, water treatment equipment, tanks, water blasters, compressors, and earth moving equipment. Treatment and disposal of wash water depends on the agents used.

It should be noted that a combination of methods may be appropriate if effective techniques can be identified and the decision is made to implement them. For example, some mechanical tilling may be necessary to enhance biodegradation. Conditions will differ on nearly every beach and there is a need to remain flexible in our approach if active remediation is the decision.

The next step was to evaluate these methods against factors for effectiveness, implementability, and operations. Each of these main factors was assigned a maximum possible number of points that reflected the relative importance of the factor. The maximum score for all factors was 240 points. Effectiveness was given a total of 130 points, representing more than half the maximum score, because it was considered to be the most important consideration in evaluating promising technologies. Implementability was given a total of 70 points (about 30% of the total points) because these factors have lower overall importance. Operational factors were given a total of 40 points, reflecting their lowest contribution to the evaluation process.

Within each main factor, the sub-factors were also weighted according to their relative importance. For example, of the effectiveness factors, two were given a maximum of 40 points: 1) ability to meet cleanup goals because this was a key consideration; and 2) ability to treat different oil concentrations, which would reduce the complexity of implementation. The other effectiveness factors were given maximum scores of 10 points. This approach is commonly used in treatment technology assessments.

The assignment of points to each factor was based on the author's knowledge of the oil spill cleanup literature and 27 years of experience in actual oil spill response and cleanup (by Michel). It is acknowledged that this process has inherent high uncertainty; based on different experiences, others may come up with different scores. Although this approach is somewhat subjective and relies heavily on best professional judgment, every effort was made to be objective and transparent in the evaluation process.

It is outside the scope of this study to include a comprehensive summary of the literature and case studies on cleanup of oil from gravel beaches. Hayes and Michel (2001) wrote a primer on responding to oil spills in gravel beaches. Owens and Solsberg (1998) prepared response guidelines for spills in Arctic settings that include methods for cleanup of oil gravel beaches. Studies of the rates of natural removal at other spills are not applicable here because our concern is with oil that has resisted natural removal processes for over 16 years. However, the results of studies of the effectiveness and effects of cleanup efforts on gravel beaches have been used throughout the evaluation process. The following scoring system was used.

1. Effectiveness Factors (Maximum Score = 130 points)

Oil recovery: The highest possible score of 10 was assigned to the technology with the highest yield of usable quality oil. If no usable oil is recovered, the score was 0.

Ability to treat different oil concentrations: Technologies that can treat all four different oiled sediment concentration categories (HOR, MOR, LOR, and OF) were given a score of 40. If three concentration categories are handled by technology, the score was 30. If two concentrations categories are handled by technology, the score was 20, and if technology can only be used for one of the categories the score was 10.

Ability to meet cleanup goals: If technology can meet cleanup goals for all four oiling categories, the score was 40. If three concentration categories are handled by technology, the score was 30. Corresponding scores were 20 for two categories and 10 for one.

Number of waste streams generated and requiring treatment or disposal: The lowest score of 0 was given for the highest number of waste streams. If no waste streams are generated, the score was 10.

Relative volume of sidestream solid and liquid waste: If amount of waste generated is more than 10 % of the amount of waste treated, the score was 0. Highest score of 10 points was given for least amount of waste generated.

Number of treatment processes needed to treat byproducts: If total number of processes for treating sidestreams exceeds 3, the score was 0. Maximum score was given to technologies without such treatment requirement.

Relative volume of waste to be disposed: A score of 0 was given for disposal volume of 20 % or more of the total waste volume. Maximum score of 10 was given to technologies with no waste for disposal.

2. Implementability Factors (Maximum Score = 70 points)

Demonstrated effectiveness based on number of full-scale applications completed: Proposed technologies with no full-scale applications on gravel beaches similar to PWS completed were given 0 points. Each completed full-scale application was given 2 points. Maximum score was 20 points.

Mobilization Time: Technologies with the shortest time needed for mobilization and demobilization were assigned the highest score of 10. Other technologies were scored relative to this highest score.

Time to complete: Technologies that require more than one year for completion were given 0 points. Technologies requiring less than less than one year for completion were given the total score of 5 points.

Proven ability to work in sub-Arctic conditions: Documented successful implementation in sub-Arctic climates was given a score of 5 points. Fluctuating performance with weather and temperature changes was assigned a score between 0 and 5 points.

Complexity of equipment: Technologies with the most complex equipment requirements, which will be difficult to effectively operate under the challenging conditions in the intertidal zone on remote beaches in PWS, were given a score of 0. Readily available equipment requirements resulted in a score of 10.

Chemical additives: Full score of 10 points was given if no additives are needed. Potential hazard associated with chemicals was taken into account when assigning lower scores.

Safety of operation: Extensive need for equipment operation and handling of chemicals was assigned a score of 0. Comparison needed for assigning high score of 10.

Safety restrictions: A score of 0 was given if personal protective equipment (PPE) requirements include respirator use. Lower PPE requirements were credited with a higher score (up to 10 points) based on a comparison among technologies.

3. Operational Factors (Maximum Score = 40 points)

Personnel needs: The personnel needs in terms of predicted hours to complete the field project was compared among technologies and each technology was assigned a “high”, “medium”, or “low” classification. Technologies with low personnel needs was given the maximum score of 10, medium needs corresponded to a score of 5, and high needs scored 0 points.

Complexity of operation/training: The amount of training needed to operate equipment was categorized as “high”, “medium”, or “low”. High training needs resulted in a 0 score, medium scored 5, and low scored 10 points.

Complexity of operation/maintenance: Equipment maintenance needs was rated between technologies and classified as above. High level of maintenance was categorized as “high”, “medium”, or “low”. High maintenance needs resulted in a 0 score, medium scored 5, and low scored 10 points.

Energy/power demand: The energy requirement was rated as “high”, “medium”, and “low”. Scores of High resulted in a 0 score, medium scored 5, and low scored 10 points.

Those treatment technologies that meet a minimum score were further evaluated as to more detailed effectiveness factors related to the spatial distribution of the subsurface oil, likely environmental impacts and benefits of remediation, and costs.

III. RESULTS AND DISCUSSION

A. Volume of Oiled Sediments

Final estimates of the volume of oiled sediments are shown in Table 5. In the 42 shoreline segments with subsurface oil, the volume of oiled sediments was estimated to be 732 m^3. Seven segments contained HOR or MOR/HOR totaling 124.4 m^3; 19 segments contained MOR or MOR/LOR totaling 184.1 m^3; 38 beaches contained LOR or LOR/OF totaling 397.9 m^3; and 18 segments contained OF totaling 25.7 m^3 (Table 6). Figure 11 shows the estimated volume of oiled sediments per segment by oiling descriptor, plotted in order of increasing volume. Figure 12 shows that there is a general relationship between the estimated volume and the surface area of oiled sediments. Shoreline segments with the highest amounts of MOR or HOR included Smith Island (3 segments), Herring Bay, Bay of Isles, Northwest Bay, and northeast Latouche Island. These data should be representative of the actual residual oil in PWS because of the random design used by Short et al. (2004) to select segments to survey.

The estimated number of patches of subsurface oil per beach segment ranged from 1 to 7 and averaged 2.5 per segment. The distribution of the number of patches per beach segments was:

7 patches – 3 beach segments
5 patches – 3 beach segments
4 patches – 2 beach segments
3 patches – 8 beach segments
2 patches – 13 beach segments
1 patch – 13 beach segments

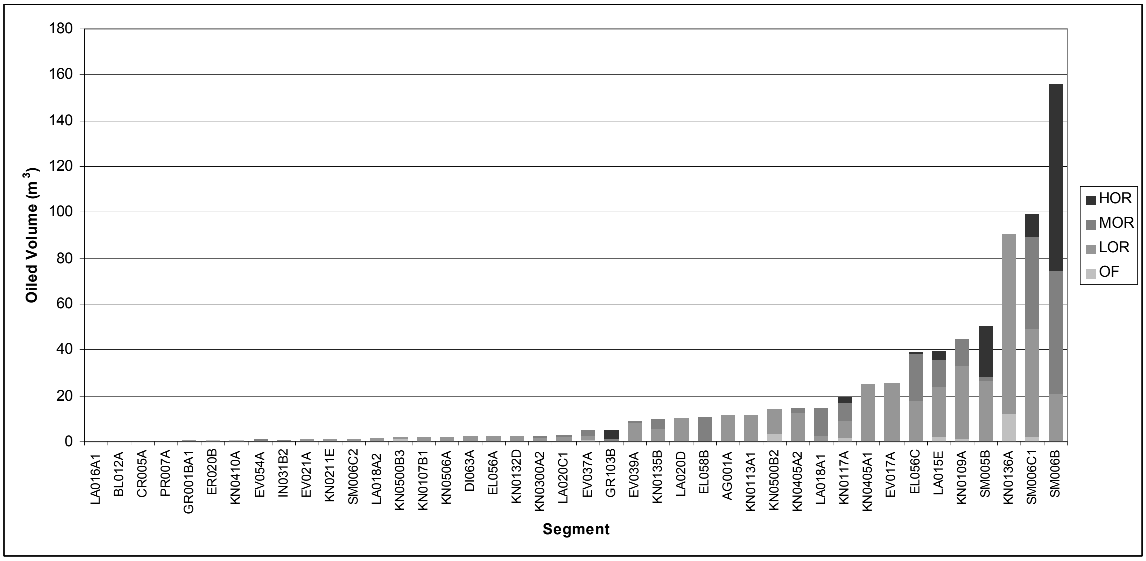


FIGURE 11. Oiled sediment volume by oiling descriptor for all segments where subsurface oil was found in the 2001 surveys.

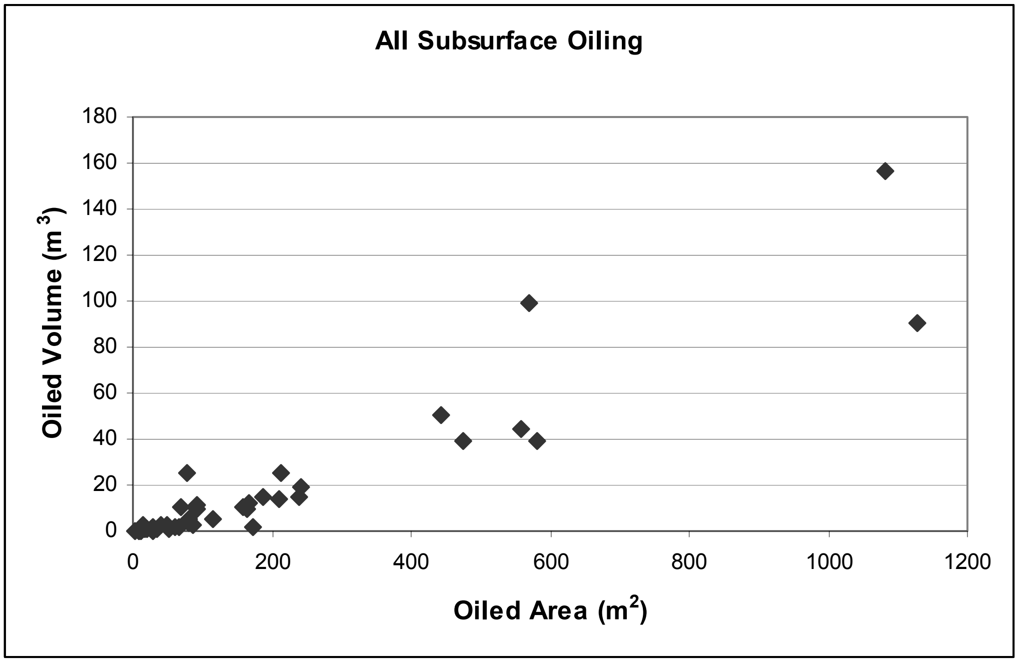


FIGURE 12. Volume of all oiled sediment by planimetric area of subsurface oiling for all segments with subsurface oiling.

The estimated patch size varied by two orders of magnitude (Table 5). Planimetric maps showing the results of the spatial analysis of the pit data for all 42 segments where subsurface oil was found in the 2001 survey are shown in Appendix A. These maps provide a good visual picture of the distribution of the lingering oiled sediments on the 42 segments in 2001. There is a large amount of variability in the location, size, and amount of subsurface oil. Patch size is important in evaluating thresholds for treatment and developing remediation costs. However, the greatest problem in implementation of any kind of remediation activity is locating the subsurface oil prior to treatment. Figure 13 shows the frequency of pits with subsurface oil at 0.25 m intervals above mean lower low water (MLLW), with a breakdown by oiling category, for the 2001 survey data. Vertically, most of the subsurface oil is closer to mean sea level than to mean high water. Short et al. (in press) reported on the 2003 study (a focused study of 10 segments on Knight Island that included pits in the lower intertidal zone) and showed an almost symmetrical distribution of subsurface oil with respect to tidal height that was centered near the mid-intertidal. Nineteen of the 52 pits (36.5 percent) with subsurface oil were located below +1.8 m tide height. Thus, it is clear that most of the lingering oil is centered on the mid-intertidal zone.

With the available data, it is not possible to predict where the subsurface oil occurs along a shoreline segment. The persistence of the lingering oil is a function of the localized geomorphology and sediment distribution patterns in ways that are highly variable. The shorelines in PWS are highly heterogeneous and it would take considerable effort to assess the estimated 100+ km of shoreline with potential subsurface oil.

TABLE 5. Estimated characteristics (surface area, volume by oiling descriptor and total oiled, number of patches, average patch volume) of subsurface oiled sediments for the 42 beach segments sampled in 2001 where subsurface oil was found.

Segment	Segment Length (m)	Area (m^2)			# Patches	Moran's I	Volume (m^3)					
		Surface Area	Subsurf. Oiling Area	Avg. Patch Area			Clean Overbur.	OF	LOR	MOR	HOR	Total Oiled
AG001A	71	1133.5	91.5	45.8	2	0.57	14.4	0.0	11.5	0.0	0.0	11.5
BL012A	37	176.0	7.3	7.3	1	-0.02	1.1	0.1	0.0	0.0	0.0	0.1
CR005A	88	868.8	10.3	10.3	1	0.00	2.4	0.0	0.1	0.0	0.0	0.1
DI063A	55	627.0	49.3	24.6	2	-0.03	6.8	0.0	2.5	0.0	0.0	2.5
EL056A	18	198.0	15.5	7.8	2	-0.54	1.2	0.0	2.5	0.0	0.0	2.5
EL056C	89	975.0	473.8	118.4	4	0.29	71.2	0.1	17.7	20.3	1.1	39.2
EL058B	53	929.5	157.3	157.3	1	0.27	23.6	0.0	0.0	10.5	0.0	10.5
ER020B	100	2350.0	52.3	26.1	2	0.01	2.6	0.5	0.0	0.0	0.0	0.5
EV017A	74	1743.8	78.0	78.0	1	0.01	9.8	0.0	25.4	0.0	0.0	25.4
EV021A	37	918.8	16.5	16.5	1	-0.01	3.3	0.0	0.8	0.0	0.0	0.8
EV037A	100	2568.8	115.8	38.6	3	0.02	7.2	0.9	1.4	2.9	0.0	5.2
EV039A	110	3212.3	164.8	54.9	3	0.05	14.1	0.0	8.2	1.2	0.0	9.4
EV054A	100	1512.5	14.5	7.3	2	-0.01	0.7	0.0	0.4	0.4	0.0	0.7
GR001BA1	100	2518.8	28.8	28.8	1	0.01	2.9	0.0	0.3	0.0	0.0	0.3
GR103B	100	2212.5	80.3	40.1	2	0.05	3.8	0.0	0.4	0.4	4.4	5.2
IN031B2	83	996.0	20.0	10.0	2	0.00	2.1	0.0	0.1	0.6	0.0	0.7
KN0107B1	100	2575.0	66.5	16.6	4	0.01	5.8	0.3	1.5	0.0	0.0	1.8
KN0109A	100	1243.8	559.5	559.5	1	0.42	96.1	0.8	32.1	11.8	0.0	44.7
KN0113A1	100	1687.5	166.0	83.0	2	0.22	28.2	0.2	11.6	0.0	0.0	11.8
KN0117A	80	741.3	242.8	34.7	7	0.32	40.5	1.5	7.7	7.8	2.2	19.1
KN0132D	90	1817.0	41.0	20.5	2	0.00	9.6	0.2	2.3	0.0	0.0	2.5
KN0135B	67	1639.0	93.3	31.1	3	-0.01	37.3	0.0	5.6	4.1	0.0	9.7
KN0136A	79	2618.0	1127.5	375.8	3	0.30	133.0	12.1	78.5	0.0	0.0	90.6
KN0211E	100	2493.8	15.3	15.3	1	0.00	1.5	0.0	0.8	0.0	0.0	0.8
KN0300A2	52	1306.5	86.3	86.3	1	0.29	5.8	0.0	1.7	0.9	0.0	2.6
KN0405A1	100	1937.5	213.3	42.7	5	0.53	43.7	0.0	25.0	0.0	0.0	25.0
KN0405A2	100	2031.3	239.8	34.3	7	0.24	75.1	0.0	12.9	1.6	0.0	14.5
KN0410A	100	1612.5	34.5	11.5	3	0.00	14.1	0.3	0.2	0.0	0.0	0.6
KN0500B2	106	4825.0	209.5	209.5	1	0.05	69.8	3.5	10.5	0.0	0.0	14.0
KN0500B3	100	1631.3	174.0	87.0	2	0.01	34.8	0.9	0.9	0.0	0.0	1.7
KN0506A	100	643.8	60.8	60.8	1	0.52	8.1	0.0	2.0	0.0	0.0	2.0
LA015E	100	3312.5	581.3	193.8	3	0.25	58.1	1.9	22.1	11.6	3.9	39.5
LA016A1	108	1106.3	2.8	2.8	1	-0.04	0.4	0.0	0.0	0.0	0.0	0.0
LA018A1	100	2156.3	187.0	37.4	5	0.06	13.9	0.2	2.3	12.3	0.0	14.8
LA018A2	100	1525.0	28.8	14.4	2	0.00	4.3	0.0	1.4	0.0	0.0	1.4
LA020C1	100	2825.0	79.3	39.6	2	0.03	13.2	0.0	1.8	1.3	0.0	3.2
LA020D	93	3013.0	69.5	23.2	3	-0.01	2.3	0.0	10.4	0.0	0.0	10.4
PR007A	100	1250.0	7.5	7.5	1	0.00	0.8	0.1	0.0	0.0	0.0	0.1
SM005B	80	1714.5	442.5	147.5	3	0.31	92.2	0.0	26.6	1.8	22.1	50.5
SM006B	100	2662.5	1081.5	216.3	5	0.37	208.3	0.0	20.9	54.1	81.3	156.3
SM006C1	100	2362.5	570.5	81.5	7	0.39	55.6	2.0	47.1	40.5	9.4	99.0
SM006C2	100	1243.8	27.0	13.5	2	0.00	9.2	0.1	0.7	0.0	0.0	0.8

TABLE 6. Estimated area and volume of oiled sediments in the 42 beach segments surveyed in 2001 by oiling category.

Oiling Category	Number of Beach Segments	Surface Area of Oiled Sediments (m^2)	Volume of Oiled Sediments (m^3)
OF	18	859	25.7
LOR	38	4,858	397.7
MOR	19	1,540	184.1
HOR	7	7,838	124.4

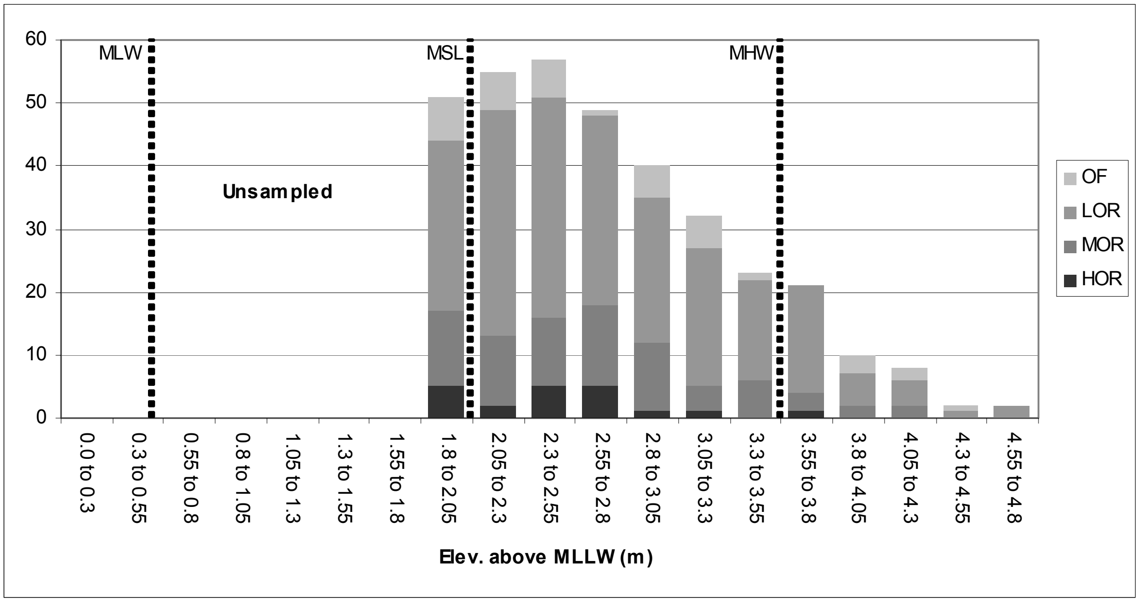


FIGURE 13. Histogram (0.25 m intervals) of pit locations by elevation above MLLW in meters and oiling descriptor for all pits with subsurface oiling in 2001. Mean high water (MHW), mean sea level (MSL), and mean low water (MLW) are based upon NOS Cordova, AK reference station.

B. Evaluation of Promising Technologies for Remediation of Subsurface Oil

The promising remediation technologies were evaluated using the screening factors for effectiveness, implementability, and operational considerations considering the conditions of subsurface oil in gravel beaches in PWS. A key factor was the ability to meet cleanup goals, which have not been determined. The setting of cleanup goals is a very important component of the risk assessment process and should include a methodology that uses quantitative criteria to support decision making. In the absence of a cleanup goal, a surrogate goal had to be used. The treatment goal used during evaluation was the reduction of oil to levels that no longer pose ecological threats to intertidal and nearshore aquatic resources. Because there are limited data what oiling levels or amounts of oil that do cause ecological threats, the highest surrogate measure of effectiveness is removal of subsurface oil to background levels. An alternative, more reasonable cleanup goal is remediation of the oil residues so that they are no longer bioavailable to intertidal and aquatic resources. The technologies were scored using this alternative cleanup goal. The results are summarized in Tables 7, 8, and 9. The sums of all scores are shown in Table 10.

It is not appropriate to discuss the basis for each individual score; the guidelines for scoring are outlined in the methods section, and scoring involves much professional judgment and experience. However, some of the key considerations are discussed below.

1. Natural Recovery was scored low for ability to treat different oil concentrations and to meet cleanup goals because it was assumed that the rates of natural removal have significantly slowed now, more than fifteen years after the spill. Hayes and Michel (1998) reported little change between 1994 and 1997 in the subsurface oil in gravel beaches. For example, Figure 14 shows the changes over time in subsurface oil along a transect on Smith Island (Hayes and Michel, 1998). The oil in the upper intertidal zone (high-tide berms) was removed by both berm relocation and natural sediment reworking. On the upper platform (about mid-tide), however, only the top 10-15 cm of oil was removed naturally, and there was little change in the degree of oiling (HOR) between 1994 and 1997. Smith Island was one of the segments surveyed in 2001 by Short et al. (2004) and, of the 30 pits with oil, 10 contained HOR and 11 contained MOR. Therefore, there has been essentially no change in the subsurface oiling on this relatively high-energy beach since 1994.

The residual oil is mostly located in sheltered areas where physical reworking of the sediments below the surface armor will only occur during very rare events. However, it should be noted that lingering oil occurs on exposed shorelines as well, with the largest amount of residual oil on any segment occurring on two beaches on Smith Island (SM006B and SM006C1; Table 5). The coarse armor on these exposed beaches is also very stable and only mobilized during very high-energy events. Removal by physical flushing has also slowed, with reports of sheens being released from shorelines during falling tides decreasing over time. According to Alan Mearns of NOAA (pers. comm., 2006) the number of the NOAA monitoring sites exhibiting sheen, both natural and undisturbed, has definitely decreased from the late 1990s to 2005. Microbial degradation will likely continue, although the waters of PWS are nutrient limited (Zhu et al., 2004) and rates are likely to be very slow. It was assumed that only the lightest oiling category (oil film, OF) would be effectively remediated during natural recovery over the next couple of years, so a score of 10 (out of 40) was given.

2. Bioremediation was scored for its ability to treat different oil concentrations based on analysis of chemical data provided by Jeff Short (Auke Bay Laboratory, pers. comm.) for samples collected in 2001. Several indices were used to evaluate the degradability of the residual oil. Of the 38 sediment samples, about half had nC17/pristane ratios greater than 0.6 (compared to 1.13 in the fresh oil) and nC18/phytane ratios greater than 0.8 (compared to 1.61 in the fresh oil). The ratio of total normal alkanes to total PAH in the fresh oil was 3.33, whereas 65 percent of the samples had a ratio less than 0.5, indicating considerable degradation of the alkanes (greater than 85 percent) relative to the PAH. Short (2002) developed an index, w, of PAH weathering losses for Exxon Valdez oil, This index was calculated for the 38 samples of oiled

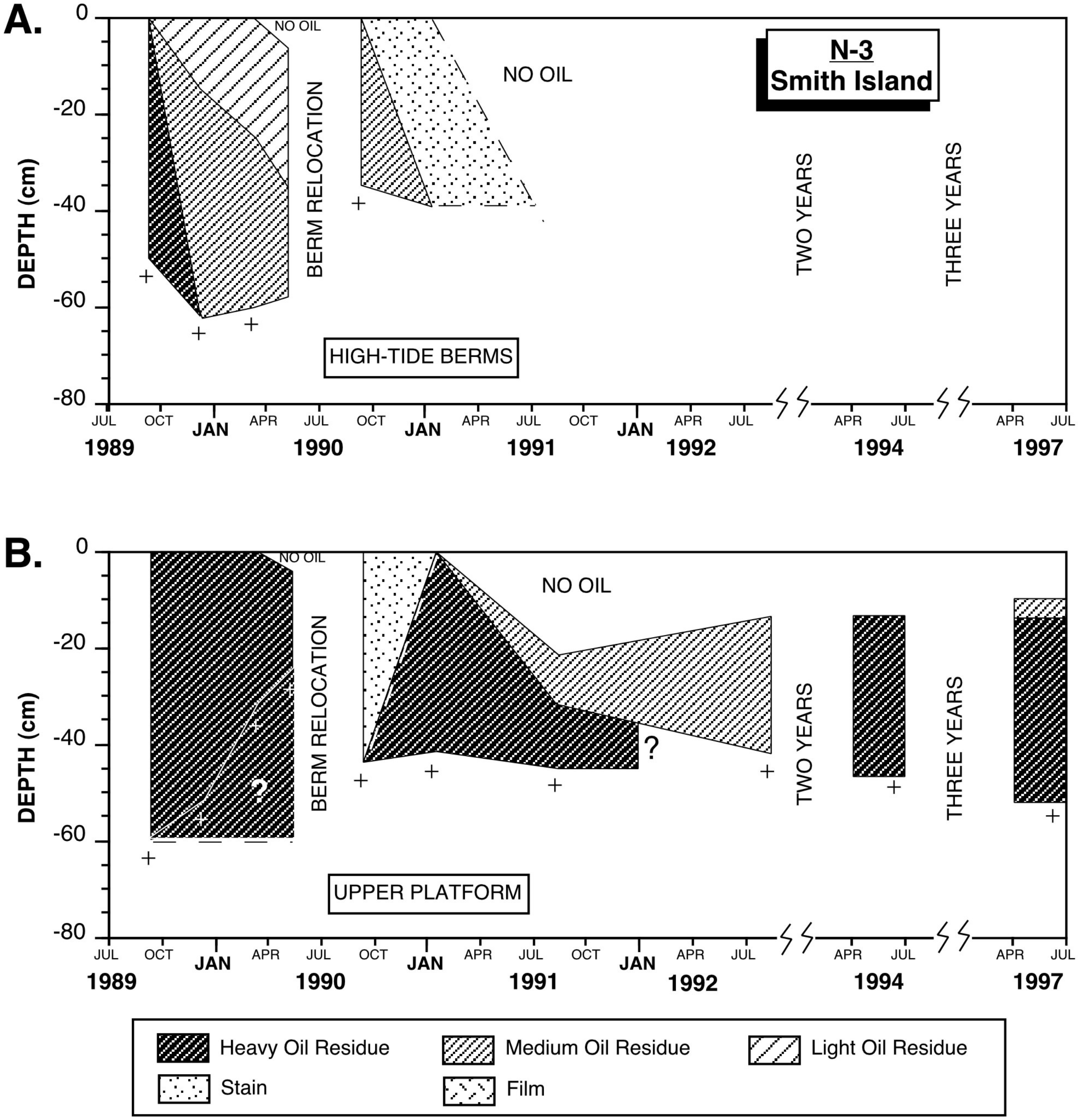


FIGURE 14. Time-series plot of the interval and degree of subsurface oil at station N-3 (Smith Island), based on trench descriptions and chemical analyses, for the (A) high-tide berms and (B) upper platform (Hayes and Michel, 1998). Note that there was little change in the degree of subsurface oiling in the upper platform (about mid-tide) since 1994. This segment contained large amount of HOR and MOR in 2001.

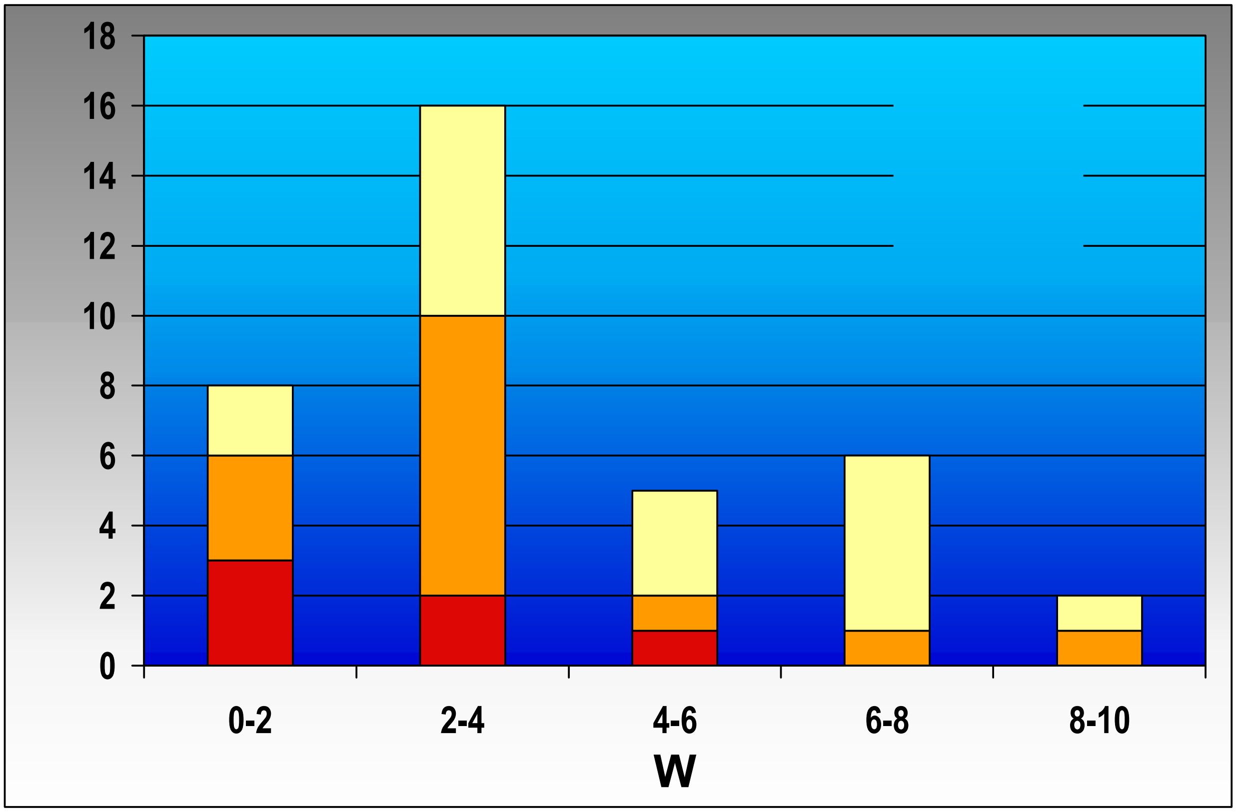


FIGURE 15. Plot of a PAH weathering index, w, for the 38 oiled sediment samples collected in 2001. Note that 24 of the 38 samples indicate only slight or moderate weathering and few samples are heavily weathered.

sediments from PWS in 2001. Figure 15 shows a histogram plot of the index values. The PAHs in only a very few samples are heavily weathered, and nearly two-thirds show slight to moderate PAH weathering. Figures 16-18 show representative plots of the PAH distribution in these samples from 2001, for sediments described as LOR, MOR, and HOR with both low and high PAH weathering indices.. There are abundant PAHs in the oil remaining on the beaches of PWS, including the 2- and 3-ringed PAH that are most degradable and bioavailable. In evaluating the studies of bioremediation through nutrient addition to the surface of two test beaches with subsurface oil, Bragg and Owens (1995) reported that, where the oil was not already extensively degraded, fertilizer addition increased biodegradation rates, with 40-65% removal of the 2- and 3-ringed PAHs.

We also asked Al Venosa of the U.S. Environmental Protection Agency, a noted expert in biodegradation of oil, to review the chemical data and provide an assessment of the potential effectiveness of bioremediation. He concluded that "…the data seem to justify trying to bioremediate those areas."

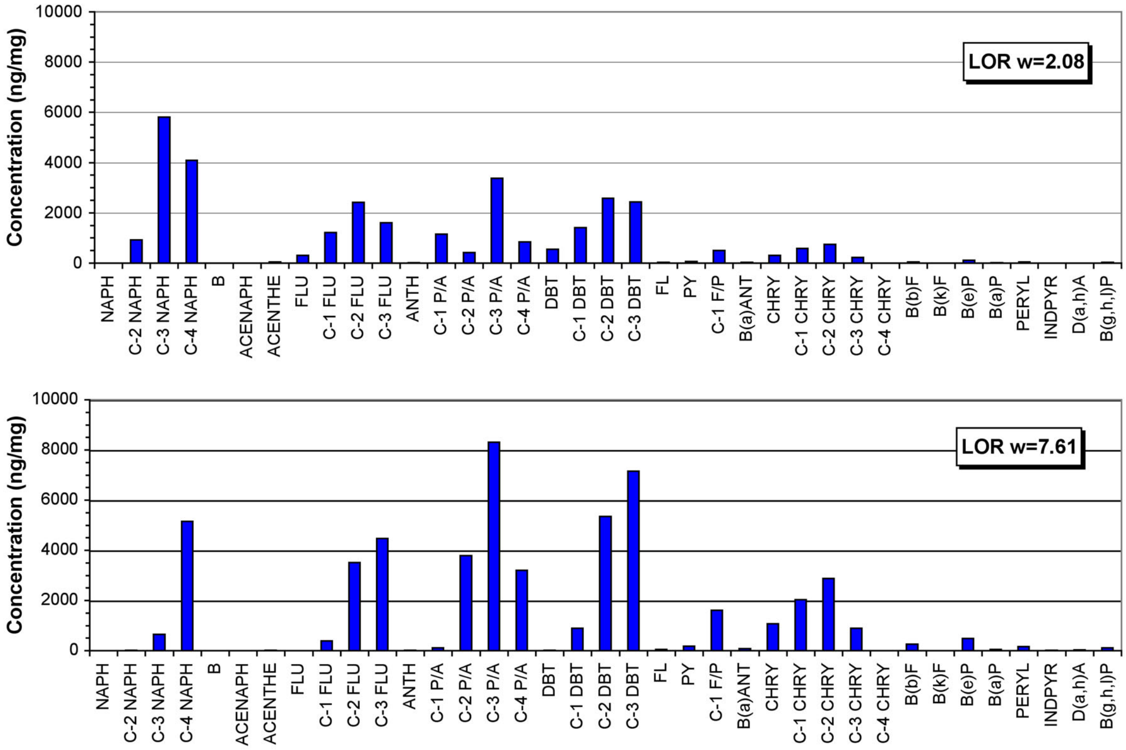


FIGURE 16. PAHs in sediment samples described as LOR collected in 2001for slightly weathered (top) and moderately to heavily weathered oil (bottom).

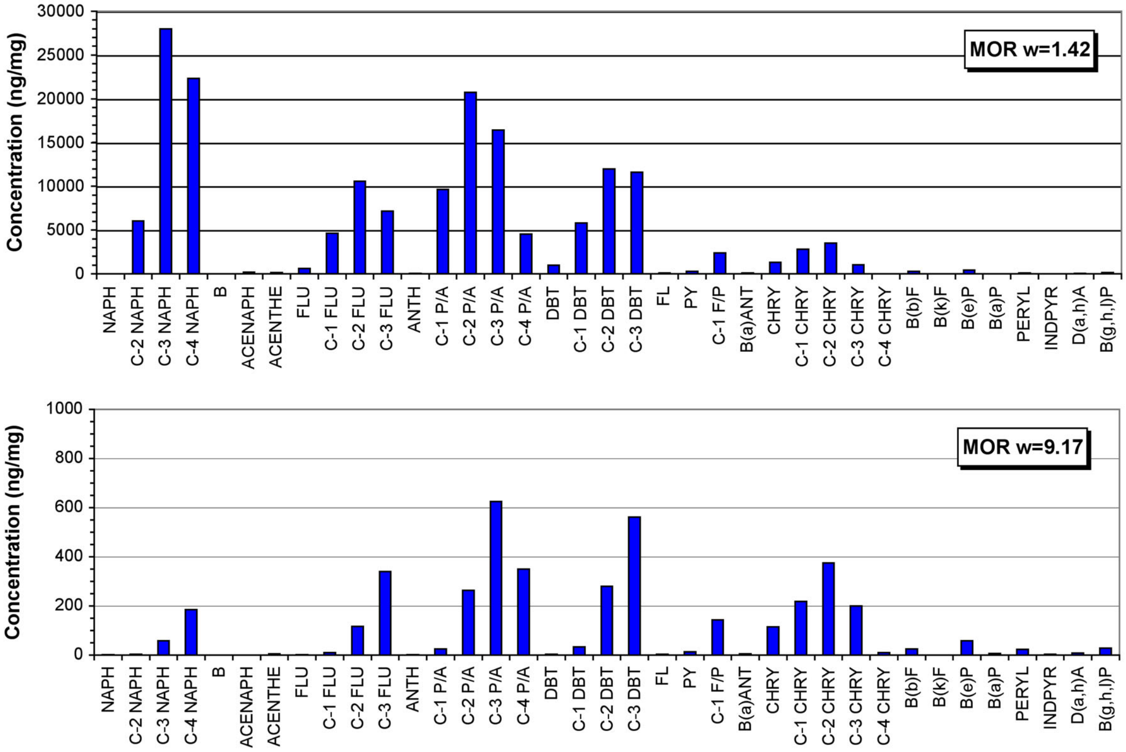


FIGURE 17. PAHs in sediment samples described as MOR collected in 2001for slightly weathered (top) and heavily weathered oil (bottom).

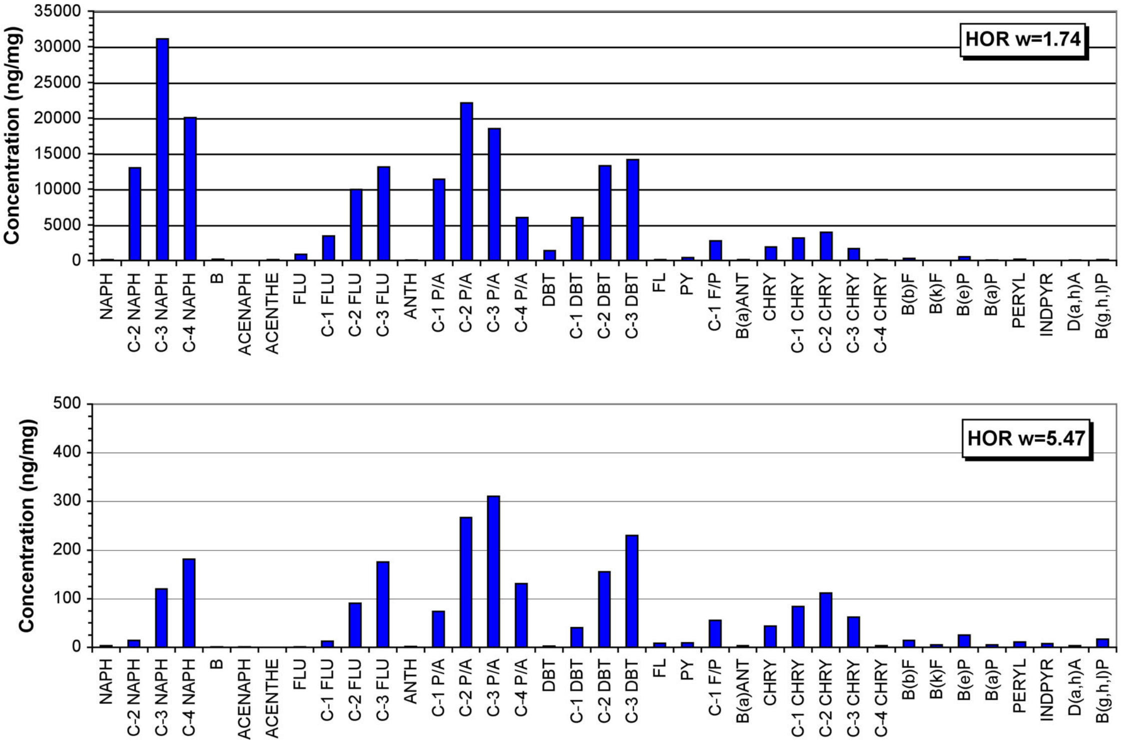


FIGURE 18. PAHs in sediment samples described as HOR collected in 2001for slightly weathered (top) and moderately to heavily weathered oil (bottom).

Based on these results, we gave bioremediation a score of 20 (out of 40) for ability to treat different concentrations because of the uncertainty in its effectiveness on HOR and MOR. Similarly, bioremediation was given a score of 20 for meeting cleanup goals, assuming that OF and LOR would be completely degraded within one year.

3. Bioaugmentation was given low effectiveness scores, based on the recent synthesis report on bioremediation of marine shorelines by Zhu et al. (2001). In this report, they say:

> "Actually, most field studies indicated that bioaugmentation is not effective in enhancing oil biodegradation in marine shorelines, and nutrient addition or biostimulation alone had a greater effect on oil biodegradation than the microbial seeding (Jobson *et al*., 1974; Lee and Levy, 1987; Lee *et al*., 1997b, Venosa *et al*., 1996). The failure of bioaugmentation in the field may be attributed to the fact that the carrying capacity of most environments is likely determined by factors that are not affected by an exogenous source of microorganisms (such as predation by protozoans, the oil surface area, or scouring of attached biomass by wave activity), and that added bacteria seem to compete poorly with the indigenous population. Therefore, it is unlikely that externally added microorganisms will persist in a contaminated beach even when they are added in high numbers. In short, those criteria mentioned above for a successful colonization are very difficult to be met in the field.

> It seems that in most environments, indigenous oil-degrading microorganisms are more than sufficient to carry out oil biodegradation if nutrient levels and other adverse environmental conditions do not limit them. Future research on oil bioaugmentation should focus on investigating which ecosystems may be deficient in oil degrading microorganisms and what types of oils or important oil components indigenous bacteria may be incapable of degrading."

Based on these conclusions by Zhu et al. (2001), no further research or evaluation of bioaugmentation technologies was conducted.

4. It was assumed that locating the subsurface oil was feasible, even though the subsurface oil occurs in patches that will be difficult to locate without extensive digging to delineate the boundaries of the patches.

5. *In-situ* technologies, such as tilling and bioremediation, were considered to be effective on OF and LOR oiling categories but not on MOR and HOR because the higher oil loadings would still persist at levels of concern at the termination of remediation efforts. It should be remembered that about half of the lingering oil is LOR, so merely reducing the oil concentration, such as by tilling and mixing, will not guarantee higher rates of natural removal after treatment.

Four technologies scored the highest: Natural recovery (score of 161); Physical removal with landfill disposal (score of 142); Physical removal with landfarming (score of 140), and bioremediation (score of 145). These technologies will be further evaluated as to more detailed effectiveness factors related to the spatial distribution of the subsurface oil, likely environmental impacts, and benefits of remediation.

TABLE 7. Scoring matrix for promising treatment technologies – effectiveness factors.

Remediation Technology	Effectiveness Factors							
	Oil Recovery	Treat Different Oil Concentra-tions	Meet Cleanup Goal	Number of Waste Streams	Volume of Solid/ Liquid Wastes	Number of By-product Treatment Processes	Volume of Wastes for Disposal	Sum of Scores
Natural Recovery	0	10	10	10	10	10	10	60
Sediment Reworking/Tilling	0	20	10	5	5	6	6	52
Trenching and Flushing (hot water)	5	40	20	0	0	3	3	71
Flushing with Chemical Agents	5	40	30	0	0	3	3	81
Bioremediation	0	20	20	10	10	10	10	80
Bioaugmentation	0	0	0	10	10	10	10	40
Capping with Clean Sediments	0	40	0	10	10	6	10	76
Physical Removal - Landfill	0	40	40	5	0	6	0	91
Physical Removal - Incineration	0	40	40	0	0	3	0	83
Physical Removal - Landfarming	0	40	40	5	0	6	10	101
Physical Removal - Sediment Washing	0	40	40	0	0	0	0	80
Maximum Possible Score per Factor	10	40	40	10	10	10	10	130

TABLE 8. Scoring matrix for promising treatment technologies – implementability factors.

Remediation Technology	Implementability Factors								
	Demonstrated Effectiveness	Mobilization Time	Time to Complete	Proven Effective in Sub-Arctic Conditions	Complexity of Equipment	Use of Chemical Additives	Safety of Operations	Safety Restrictions	Sum of Scores
Natural Recovery	10	10	0	1	10	10	10	10	61
Sediment Reworking/Tilling	10	6	5	5	6	10	6	8	56
Trenching and Flushing	2	4	5	5	4	10	5	7	42
Flushing with Chemical Agents	2	4	5	5	3	0	3	0	22
Bioremediation	2	8	0	1	8	5	8	8	40
Bioaugmentation	0	8	0	0	7	5	7	5	32
Capping with Clean Sediments	0	0	0	3	0	10	4	6	23
Physical Removal - Landfill	10	0	0	5	2	10	6	8	41
Physical Removal - Incineration	10	0	0	5	0	10	4	8	37
Physical Removal - Landfarming	10	0	0	5	2	8	6	8	39
Physical Removal - Sediment Washing	4	0	0	5	0	0	4	6	19
Maximum Possible Score per Factor	10	10	5	5	10	10	10	10	70

TABLE 9. Scoring matrix for promising treatment technologies – operational factors.

Remediation Technology	Operational Factors				
	Personnel Needs	Complexity of Operation/ Training	Complexity of Operation/ Maintenance	Energy/ Power Demand	Sum of Scores
Natural Recovery	10	10	10	10	40
Sediment Reworking/Tilling	5	5	0	5	15
Trenching and Flushing	5	5	0	5	15
Flushing with Chemical Agents	5	0	0	5	10
Bioremediation	5	5	5	10	25
Bioaugmentation	5	0	0	10	15
Capping with Clean Sediments	0	0	0	0	0
Physical Removal - Landfill	0	5	0	5	10
Physical Removal - Incineration	0	0	0	0	0
Physical Removal - Landfarming	0	0	0	0	0
Physical Removal - Sediment Washing	0	0	0	0	0
Maximum Possible Score per Factor	10	10	10	10	40

TABLE 10. Sum of all evaluation scores.

Remediation Technology	Effectiveness Score	Implementa - bility Score	Operational Score	Sum of Scores
Natural Recovery	60	61	40	161
Sediment Reworking/Tilling	52	56	15	123
Trenching and Flushing	71	42	15	128
Flushing with Chemical Agents	81	22	10	113
Bioremediation	80	40	25	145
Bioaugmentation	40	32	15	87
Capping with Clean Sediments	76	23	0	99
Physical Removal - Landfill	91	41	10	142
Physical Removal - Incineration	83	37	0	120
Physical Removal - Landfarming	101	39	0	140
Physical Removal - Sediment Washing	80	19	0	99
Maximum Possible Score per Factor	130	70	40	240

C. Evaluation of the Environmental Impacts of Selected Technologies

The likely environmental impacts of the four technologies were evaluated using five factors with a total possible score of 100, weighted and scored as described below:

Length of time needed for disturbed sediments to return to normal distribution: The highest possible score of 20 was given to the technology that caused no sediment disturbance; a score of 10 was given if sediments would likely return within two years; and a score of 0 was given for a ten-year or greater period of disturbance.

Length of time for intertidal communities to return to pre-cleanup health: The highest possible score of 30 was given to the technology that caused no disturbance to intertidal communities; a score of 20 was given if intertidal communities would return within two years; a score of 10 was given if intertidal communities would return within five years and a score of 0 was given when the intertidal communities would take ten or more years to recover.

Potential for acute and chronic toxicity off-site during implementation: The highest possible score of 10 was given for those technologies that caused no acute or chronic toxicity associated with the release of oil or oiled sediments during implementation. Technologies that released a minor amount of oil or oiled sediments were given a score of 5; those that were likely to release more than minor amounts of oil or oiled sediments were given a score of 0.

Degree of fish and wildlife disturbance during implementation: The highest possible score of 10 was given for those technologies that caused no disturbance of fish and wildlife during implementation. Technologies that caused a minor amount of disturbance were given a score of 5; those that were likely to cause more than minor disturbances were given a score of 0.

Amount of bioavailable oil remaining after termination of cleanup activities: The highest possible score of 30 was given for those technologies that would remove all bioavailable oil with a two-year period. Other technologies were scored relative to this highest score based on the likely percent removal of bioavailable oil within two years. Two years was selected as an appropriate time period because the active removal technologies could be completed in this period. The results of the scoring are shown in Table 11 and discussed below.

Natural recovery would have no environmental impacts associated with implementation, thus it was given the full score for those factors. However, it was assumed that natural removal rates have leveled off and would have no significant reductions in the amount of bioavailable oil over a two-year period. Thus, it was given no points for the last factor. Total score was 70 out of 100.

Bioremediation was given a sediment recovery score of 15 (out of 20) because it would require some physical disturbance to the intertidal sediments and communities in that trenches or pits

TABLE 11. Evaluation scores for environmental impact factors that total 100.

Remediation Technology	Sediment Recovery	Intertidal Community Recovery	Acute/ Chronic Toxicity	Fish and Wildlife Disturb.	Remove Bioavail-able Oil	Sum of Scores
Natural Recovery	20	30	10	10	0	70
Bioremediation	15	20	5	5	15	60
Physical Removal - Landfill	5	10	0	0	30	45
Physical Removal - Landfarm	5	10	0	0	30	45
Max. Score/Factor	20	30	10	10	30	100

will have to be dug for the amendment to be placed in close proximity to the oiled sediments and to minimize dilution by surface water. Microbial degradation of oil in sediments takes place largely at the interface between the oil and the interstitial pore water (Zhu et al., 2004); therefore, in order to be effective, the amendment concentration in the pore water needs to be kept at some minimum levels to support bacterial growth. Amendments would have to be added in sufficient amounts spatially and temporally. However, the surface area of trenches or pits would be a fraction of the surface area covered by the subsurface oil, and a very small percentage of the entire intertidal zone. The subsurface oil in the 42 known segments averages 1 percent of the total intertidal area in the segment, with high values of 4 and 6 percent of the intertidal area for the largest area of subsurface oil on Smith Island. Therefore, the surface area of trenches or pits for placement of amendments adjacent to oiled subsurface sediments would cause small but intensive direct disturbance to the sediments and intertidal biota. Small trenches would be dug using small-scaled equipment; the sediments are too large for manual excavation on any significant scale.

According to Zhu et al. (2001):

> “the major challenge for this technology is control of the release rates so that optimal nutrient concentrations can be maintained in the pore water over long time periods. For example, if the nutrients are released too quickly, they will be subject to rapid washout and will not act as a long-term source. On the other hand, if they are released too slowly, the concentration will never build up to a level that is sufficient to support rapid biodegradation rates, and the resulting stimulation will be less effective than it could be.”

With some creative research, it is likely that a system could be developed to facilitate the necessary repeated application of amendments to speed the oil’s degradation over time without additional sediment/habitat disturbance.

Bioremediation was given a score of 20 (out of 30) for intertidal community recovery because of the physical damage during sediment excavation as well as some potential toxic impacts associated with excessive concentrations of added amendments. The habitat disturbances and amendment addition would occur mostly in the mid-intertidal zone where the intertidal communities are quite rich and diverse, and where many aquatic animals forage.

Bioremediation would also have some potential toxicity during implementation, associated with oil released during sediment excavation and any added amendments. These activities would also have some effect on fish and wildlife. Therefore, it was given a score of 5 out of 10 for both of these factors.

The final environmental factor was the effectiveness of bioremediation on removal of the bioavailable oil after two years. Based on the 2001 chemical results for 38 subsurface oiled sediment samples (Figs. 15-18), roughly half of the residual oil would be amenable to further biodegradation. However, the effectiveness of bioremediation 15 years after the spill is unknown. It is assumed that the least weathered oil poses the highest risk of negative effects to biota. It is also assumed that bioremediation would be 50 percent effective on the oil within two years after initial application. Field studies of the nutrient addition in PWS showed that oil degradation could be stimulated shortly after nutrient addition and was effective within one season (Bragg et al., 1994). As a result, a score of 15 out of 30 was given.

Physical removal, with either landfill or landfarming as the disposal method, would have the same environmental impacts at the treatment sites, so they were given the same scores. This method was given the lowest sediment disruption score, 5 out of 20, because of the extensive disruption associated with removal/stockpiling of the clean surface sediments and excavation of the oiled subsurface layers. The studies by Hayes and Michel (1998) as part of the monitoring program conducted by NOAA Office of Response and Restoration showed that it took up to several years for exposed beaches to return to their normal sediment distribution patterns after berm relocation. On the mostly sheltered beaches with subsurface oil, the rate at which the sediments would be reworked into their normal distribution would likely be on the order of decades.

Physical removal would impact intertidal communities by their complete removal in the excavation areas and crushing in work and stockpiling areas. Recovery could start shortly after completion of the work, since the replaced sediments would be clean and all residual oil removed. Recovery trajectories would be a function of the life histories of the different species and would be aided by very close recruitment sources. A score of 10 out of 30 was given for impacts to intertidal communities because of the relatively small areas to be treated and the proximity of sources of recruitment.

In summary, after evaluation of the environmental impacts of the four most promising technologies, natural recovery and bioremediation had the highest scores, and thus are carried to the next step of cost analysis. Physical removal has significant environmental impacts that make it inappropriate as a treatment technology.

D. Costs of Natural Recovery and Bioremediation

1. Natural Recovery Costs

The only costs for natural recovery would potentially include some sort of monitoring program to document the actual rates of natural removal processes. Costs were estimated for a monitoring program that would be conducted every other year for 10 years, using the following inputs (based on 2004 costs in previous proposals submitted by the NOAA Auke Bay Laboratory):

Two cruises at 10 days each	
Vessel cost - \$1,500/day x 20 days =	\$30,000
Field party chief – 1 person month: \$6,000	6,000
Field assistant – 1 person month: \$5,000	5,000
Report Preparation	12,000
Villager field technicians – 4 per day @ \$200/each	16,000
Field gear - \$5,000	5,000
Sample chemistry costs – 100 samples @ \$500/each	50,000
Airfare	6,000
Subtotal	130,000
Overhead (9%)	11,700
Total Per Survey (2004 costs)	141,700

Assuming that the monitoring program would start in 2007 and a 3% annual increase in costs, the monitoring program costs are shown in Table 12.

TABLE 12. Estimated costs for monitoring of natural recovery.

Year	Costs
2007	\$155,000
2009	\$164,000
2011	\$174,000
2013	\$185,000
2015	\$196,000
Total	\$874,000

2. Bioremediation Costs

Our approach to cost estimation for bioremediation was to estimate the costs for remediation of the known areas of subsurface oil (based on the 2001 survey data), then extrapolate these costs to the estimated areas of subsurface oil as calculated by Short et al. (2004). With this approach, the range of subsurface oiling conditions can be included. With the strong statistical basis for the estimates by Short et al. (2004), it is appropriate to assume that the 2001 segment data are representative of all the subsurface oil of concern. However, it is important to remember that the exact location of all the subsurface oil to be treated in PWS is not known. The costs discussed below do not include *finding* the oil to be treated.

To be most effective, bioremediation would require a system for repeated application of amendment to the subsurface oil directly rather than on the sediment surface. Thus, the work would include design, construction, and installation of such a system, plus repeated site visits to monitor pore water and add amendment as needed. The design for optimal delivery of amendment to the residual oil would have to be customized to the conditions in PWS and pilot tested prior to full-scale implementation. We have roughly estimated this design and pilot test phase to cost about $500,000.

We assumed that amendment would be applied to shoreline segments where the subsurface oil consisted of any combination of LOR, MOR, or HOR in area greater than 100 m^2. These criteria accounted for 646 m^3 of the total estimated 732 m^3 of subsurface oil on the 42 segments. It included all HOR segments with the exception of an estimated 4.4 m^3 on Green Island. It included 12 of the 18 segments that had MOR and 176.4m^3 of the 184.1 m^3 estimated amount of MOR on all segments. Using these criteria, we felt that all of the potentially significant occurrences of subsurface oil would be treated. The result was that 17 of the 42 segments were selected for bioremediation, as shown in Table 13.

TABLE 13. Data on the 17 segments that were selected for bioremediation, listed in order of increasing surface area.

Segment	Length (m)	Subsurface Oil Area (m^2)	Number of Patches	Average Hours Exposed per Day	Installation Days
EV037A	100	115.8	3	7.5	5
EL058B	53	157.3	1	5.0	4
EV039A	110	164.8	3	7.8	5
KN0113A1	100	166	2	4.6	5
KN0500B3	100	174	2	4.4	5
LA018A1	100	187	5	6.1	6
KN0500B2	106	209.5	1	4.9	5
KN0405A1	100	213.3	5	5.3	6
KN0405A2	100	239.8	7	6.2	7
KN0117A	80	242.8	7	7.7	7
SM005B	80	442.5	3	5.0	8
EL056C	89	473.8	4	7.4	8
KN0109A	100	559.5	1	5.6	6
SM006C1	100	570.5	7	5.6	8
LA015E	100	581.3	3	6.1	6
SM006B	100	1081.5	5	6.1	9
KN0136A	79	1127.5	3	7.6	9
Total		6706.9			109

Estimating the time available for cleanup at different locations in the intertidal zone is an important factor in cleanup logistics. Hourly tidal predictions for NOS Cordova, AK reference station for June-August 2006 were used to calculate the average daily work hours for tidal elevations from 0.0 to 5.0 meters above mean lower low water (MLLW) as the number of hours in the summer that that elevation was exposed between 0800 and 2000 hours each day, as in Figure 19. These predictions were intended to be generic and loosely applicable to all Prince William Sound. No correction was made for tidal differences between beach segment locations and the Cordova, AK reference station. For each segment selected for treatment, average daily work hours were calculated for all oiled areas, by unit area (Table 12). The average for all 17 segments was 6.1 hours.

Next, we estimated the number of days needed for installation of the amendment application system and the first amendment application, as follows:

1) 1 day mobilization to the segment, *plus*
2) If the area of subsurface oil was less than 500 m^2, installation to treat 100 m^2 per day (with average exposure of the work area of 6 hour per low tide); If the area of subsurface oil was greater than 500 m^2, installation to treat 200 m^2 per day, *plus*
3) Number of patches divided by 3, *plus*
4) 1 day de-mobilization

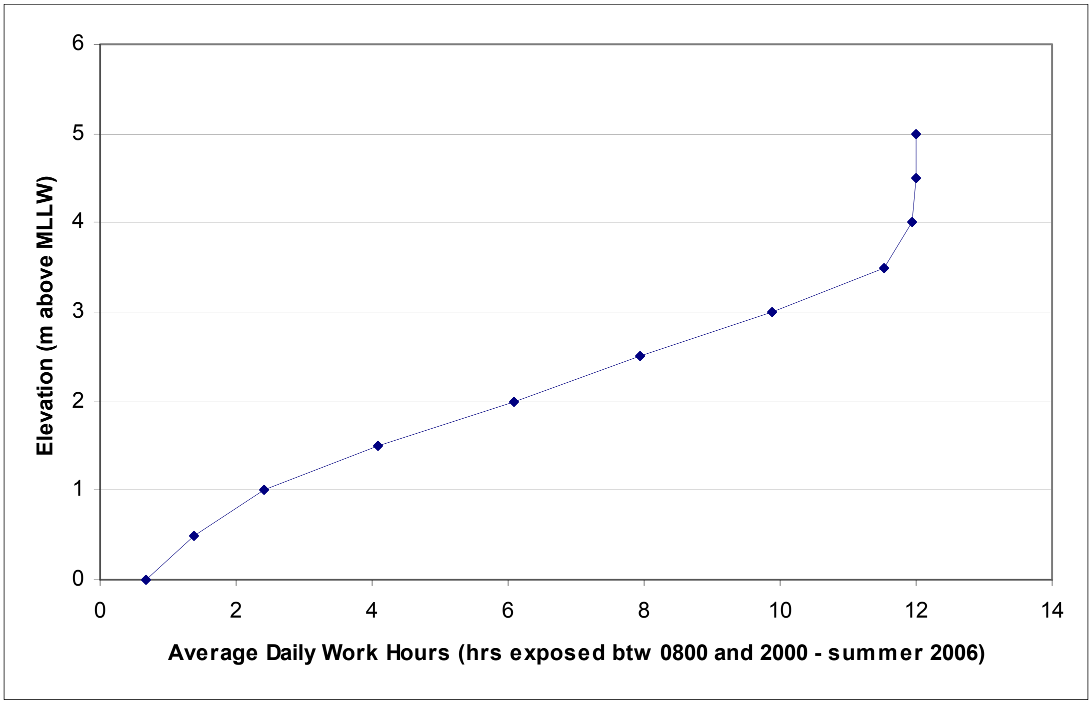


FIGURE 19. Average daily exposed work hours by tidal elevation in meters above MLLW for Prince William Sound, AK.

Therefore, as an example, for segment SM006C1 with 570.5 m^2 of subsurface oil in 7 patches, the calculation would be:

$$1 + 570/200 + 7/3 + 1 \quad = \quad 7.18 \text{ days, rounded up to 8 days}$$

The estimated number of days for the 17 segments is shown in Table 13 and totals 109 days. Adding in an additional 33% of time for weather delays, the total number of days for installation of the bioremediation systems at the 17 segments is estimated to be 145 days. Four teams would complete the installations within 36 days, starting in early May and ending in mid June.

The daily costs for installation and the first amendment addition were based on the costs in Table 14. Materials costs for the 17 segments are roughly estimated to be $100 per m^2 of subsurface oil, equaling $670,700. Multiplying the daily costs by 145 days and adding in the fixed costs, the initial installation and nutrient addition would cost $4,697,150.

For costing, it is assumed that amendment addition/maintenance would be conducted twice, in early July and early August, to maximize degradation rates during the warmer months. It is assumed that a team could collect and test pore water, add amendments, and

TABLE 14. Daily and total costs for installation of bioremediation system and first round of amendment application.

Cost Category	Daily Rate	Total Costs (145 days)
Project Mobilization: $20,000 (each of 4 teams)		80,000
Project De-Mobilization: $20,000 (each of 4 teams)		80,000
120 ft vessel with 4-person crew and berthing capacity for 12	8,500	1,232,500
22 ft landing craft	425	61,625
20 ft skiff for beach transit	350	50,750
Honda ATV with trailer (2)	200	29,000
Tracked bobcat with hoe and bucket attachments (2)	600	87,000
160 ft barge with tug	4,500	652,500
50 ton hydraulic crane	450	65,250
Oil, fuel, lube, food, travel, shipping materials, consumables, etc. (20% of above costs)	3,005	435,725
8 Person Team (1 foreman; 2 equip. operators; 3 technicians, 2 specialists)	8,640	1,252,800
Materials ($100 per m^2 of subsurface oil)		670,000
Total		$4,697,150

make minor repairs to three segments per day, including transit time between segments, plus two days each for mob-demob. Therefore, each field trip for re-application would require 10 days of time, for a total of 20 days. Adding 33% for weather days, the final total is 27 days. Daily rates for this effort are shown in Table 15. Total costs for installation and three amendment applications are shown in Table 16.

TABLE 15. Daily and total costs for two repeat applications of amendment in PWS.

Cost Category	Daily Costs	Costs for 2 Trips (27 days)
Vessel Charter	$2,500	$67,500
Team Leader	$1,000	27,000
Field Technician	$750	20,250
Field Assistant	$600	16,200
Supplies	$1,000	27,000
Total		$157,950

TABLE 16. Total estimated costs for bioremediation at the 17 selected segments.

Cost Category	Costs
Installation and initial amendment addition	$4,697,150
Two amendment additions/maintenance	$157,950
Total	$4,855,100

The 42 segments surveyed in 2001 were estimated to contain 6,640 kilograms (kg) of oil (Jeff Short, pers. comm., 2005), which represents 12 percent of the 55,600 kg estimated to be present in western PWS (Short et al., 2004). The 2003 survey data indicate that there is perhaps 30 percent more oil in the lower intertidal zone (Short et al., in press); we added this 30 percent to the 2001 estimate to total 71,500 kg. Using this higher estimate, the 42 segments surveyed in 2001 represent 9.3 percent of the amount of subsurface oil in PWS. Roughly estimating that the costs in Table 15 would treat 10 percent of the subsurface oil that met the criteria of a minimum area of 100 m^2, total costs for field application for treating the total subsurface oil in PWS (as calculated by Short et al., 2004) are estimated to be $48,551,000 (Table 17).

Costs for monitoring program would be similar to the costs for monitoring natural recovery (Table 11). Thus, the total costs for treating subsurface oil in PWS is $49,925,000 (Table 17). These costs do not include *finding* the subsurface oil prior to remediation. They also do not include project management and oversight by government agencies.

TABLE 17. Total estimated costs for bioremediation of all the subsurface oil that met the selection criteria.

Cost Category	Costs
Design Phase	$500,000
Bioremediation	$48,551,000
Monitoring	$874,000
Total	$49,925,000

IV. SUMMARY

The objective of this study was to identify and evaluate technologies for remediating the lingering oil in Prince William Sound. The 2001 survey data were processed geospatially to produce maps and statistics on the estimated area and volume of subsurface oil, by degree of oiling. Several sites were visited in the field. Eleven promising technologies were identified and evaluated using a scoring matrix for factors of effectiveness, implementability, and operations. Four technologies scored the highest out of maximum score of 240: Natural recovery (score of 161); Physical removal with landfill disposal (score of 142); Physical removal with landfarming (score of 140), and bioremediation (score of 145). These technologies were evaluated further using a scoring matrix for environmental factors considering: sediment recovery; intertidal community recovery; acute and chronic impacts during implementation; fish and wildlife disturbance during implementation; and amount of bioavailable oil remaining after termination of cleanup activities. Two technologies scored the highest out of maximum score of 100: Natural recovery (score of 70) and bioremediation (score of 60). It should be noted that natural recovery scores were very high for many factors because no cleanup activities are undertaken (e.g., no personnel, no energy demand, no training). Costs for these two technologies were developed. Natural recovery costs included only bi-annual monitoring for 10 years, at a cost of \$875,000. Bioremediation costs were estimated based on implementation on shoreline segments where the subsurface oil met the following criteria: any combination of LOR, MOR, or HOR in area greater than 100 m2. We used the geospatial data for the 42 segments with known subsurface oil to calculate the costs for treating the 17 segments that met the oiling criteria, then extrapolated these costs for treating the volume of oiled sediments as calculated by Short et al. (2004). The total costs for bioremediation were estimated to be \$49,925,000. These costs do not include: 1) finding the rest of the subsurface oil to be treated; 2) government project management and oversight; and 3) multi-year application.

It is important to note that this analysis of promising technologies for the lingering oil in PWS is only an initial, scoping effort to determine if there were possibly any feasible methods. Much additional work is needed to determine the factors that are limiting natural recovery of the lingering oil and then develop field pilot test specific remediation technologies that may overcome these limiting factors. The field tests need to be well designed so they provide objective and statistically meaningful results. If the field tests show that bioremediation is effective, and the risk assessment process shows benefits to natural resources, then the decision has to be made on implementation.

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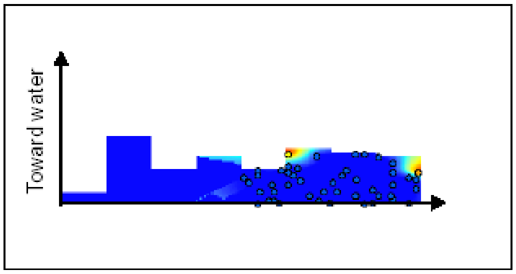
APPENDIX A

Planimetric Maps of the Estimated Distribution of Subsurface Oil for the 42 Segments with Subsurface Oil in 2001



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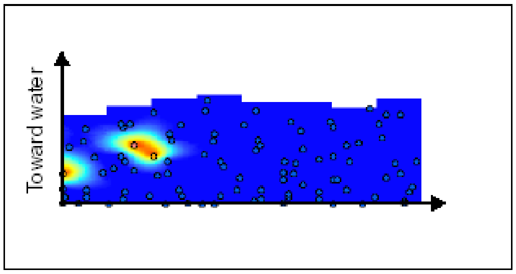

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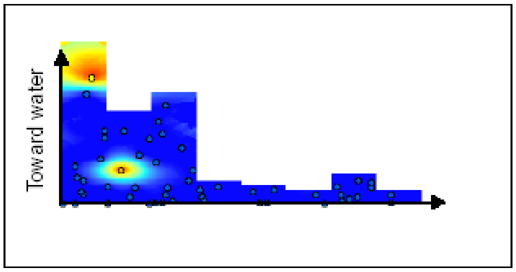

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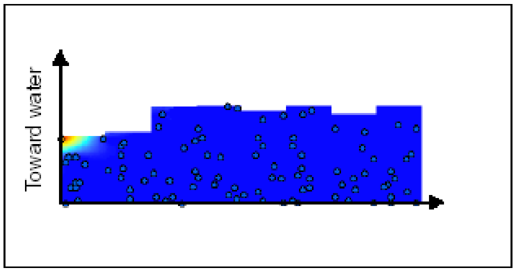

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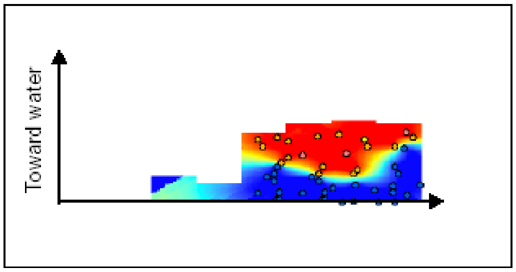

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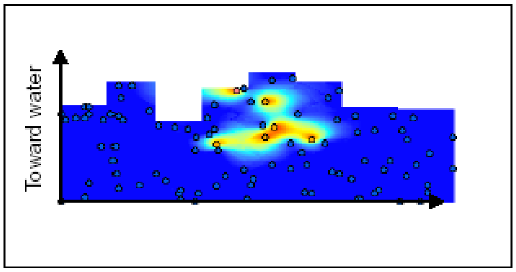

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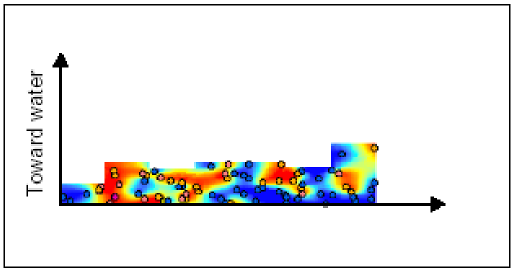

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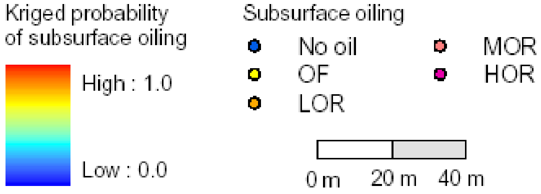
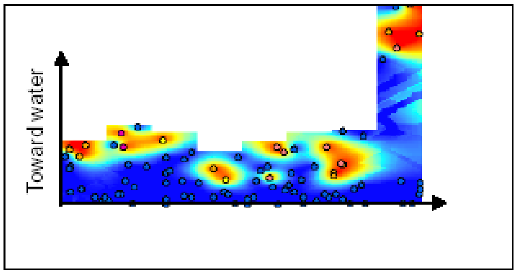
Planimetric (overhead) view of segments with subsurface oiling, pit locations and descriptors, and kriged subsurface oiling probability surface





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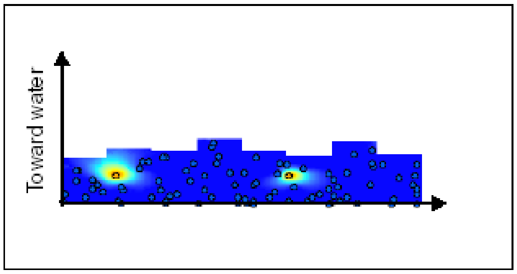

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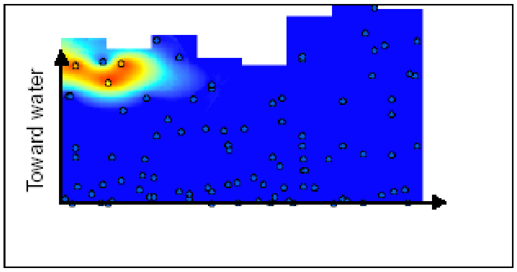

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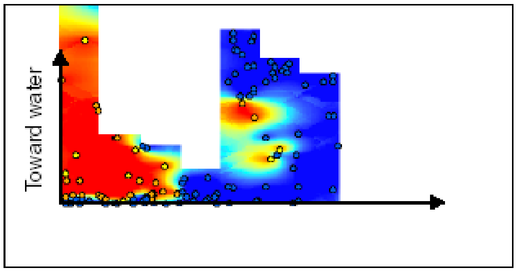

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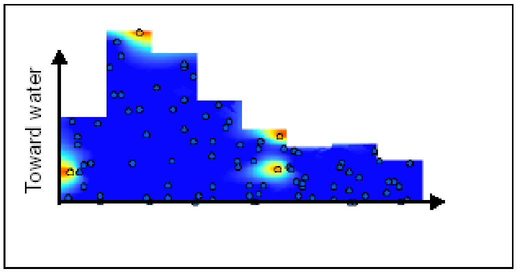

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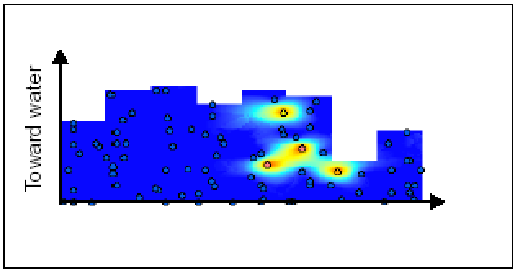

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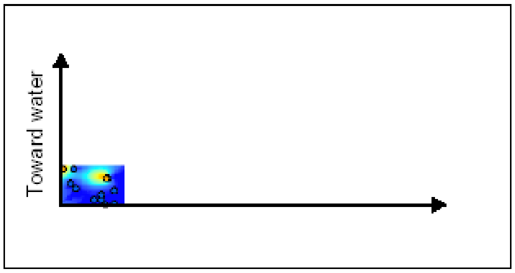

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Planimetric (overhead) view of segments with subsurface oiling, pit locations and descriptors, and kriged subsurface oiling probability surface

Kriged probability of subsurface oiling

High : 1.0

Low : 0.0

Subsurface oiling

● No oil

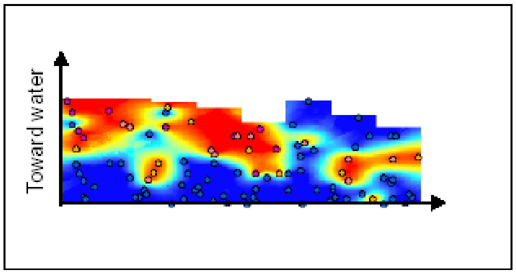
● OF

● LOR

● MOR

● HOR

0 m 20 m 40 m



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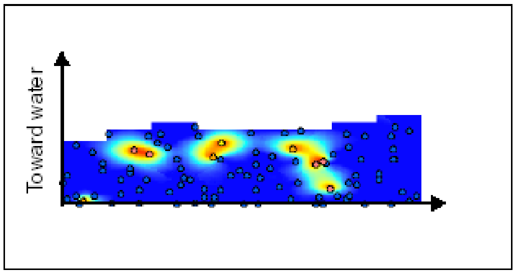

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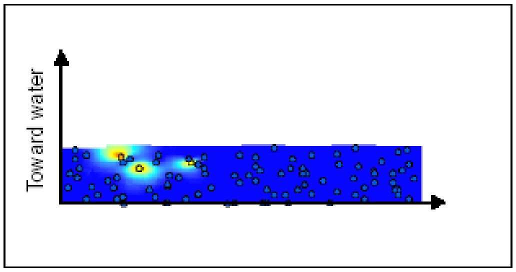

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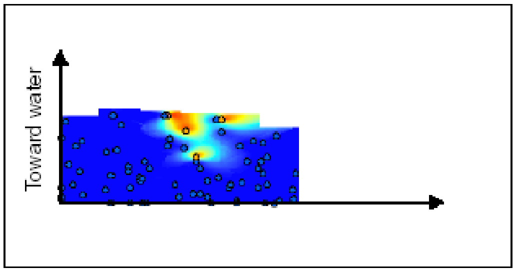

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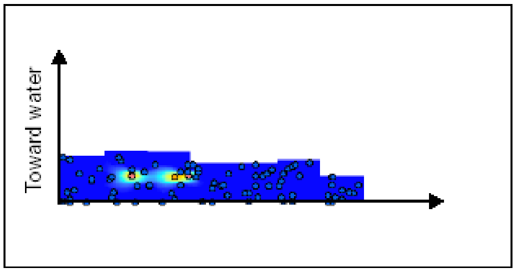

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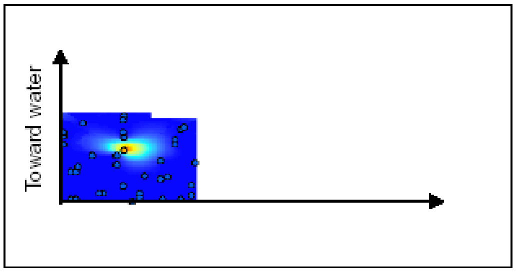

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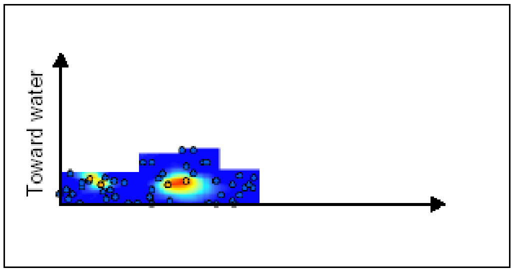

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Planimetric (overhead) view of segments with subsurface oiling, pit locations and descriptors, and kriged subsurface oiling probability surface

Kriged probability
of subsurface oiling

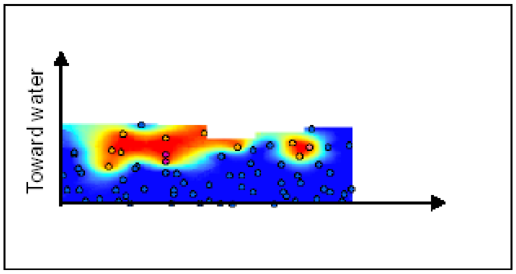
High : 1.0

Low : 0.0

Subsurface oiling

● No oil
● OF
● LOR
● MOR
● HOR

0 m 20 m 40 m



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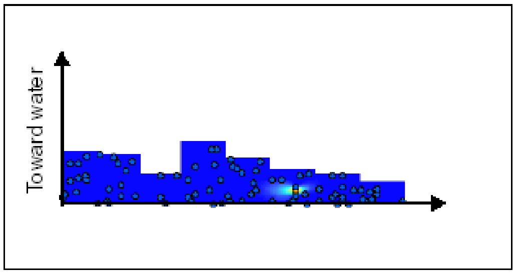

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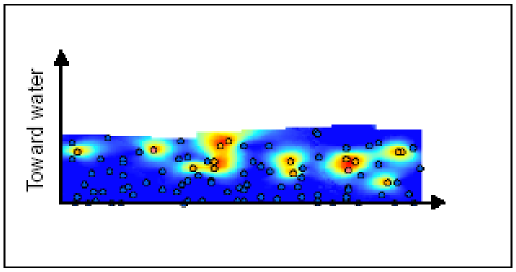

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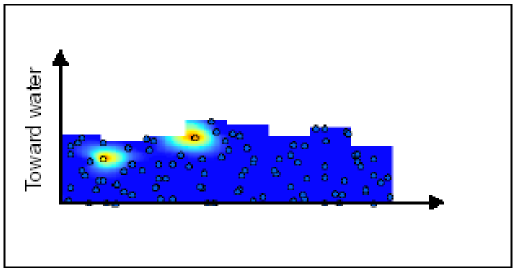

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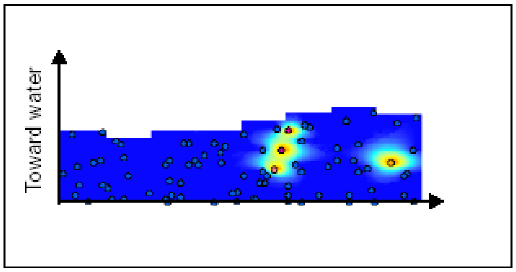

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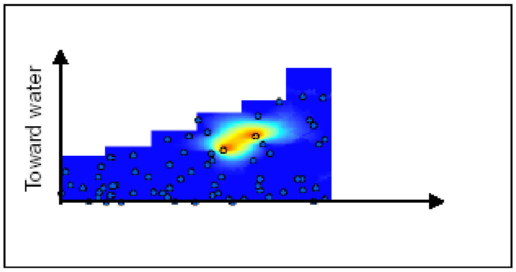

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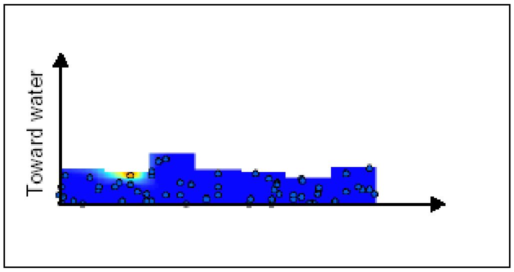

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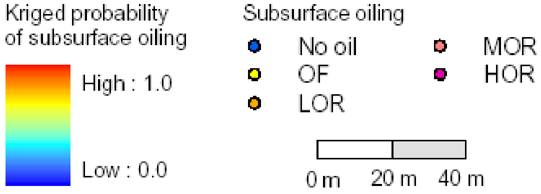
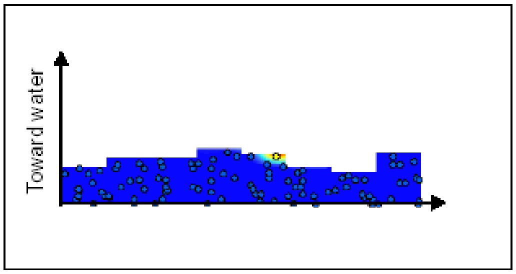
Planimetric (overhead) view of segments with subsurface oiling, pit locations and descriptors, and kriged subsurface oiling probability surface





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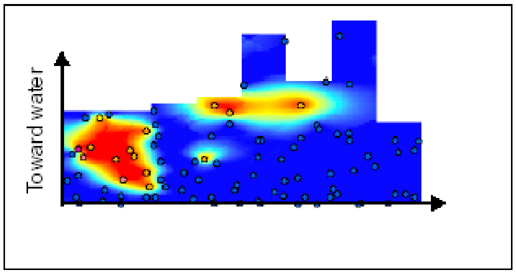

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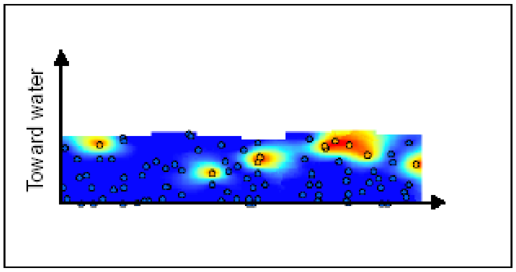

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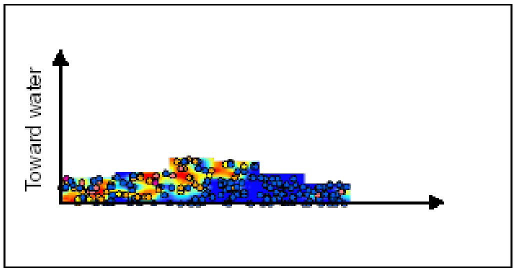

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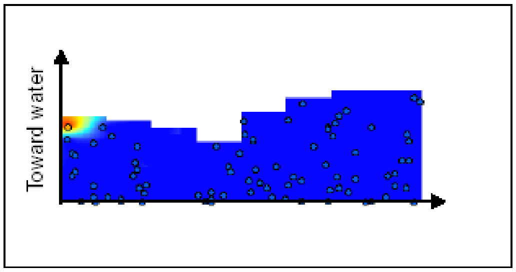

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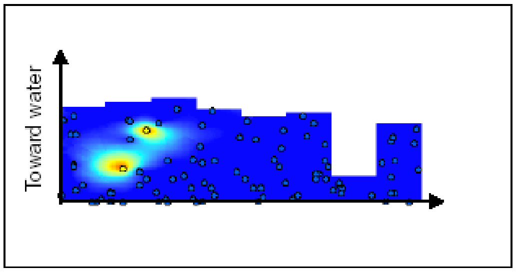

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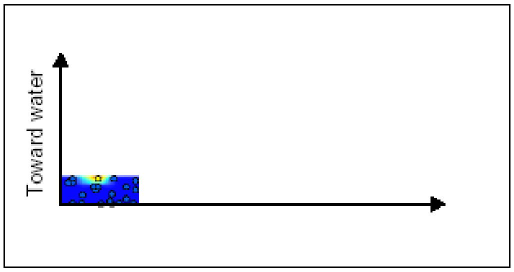

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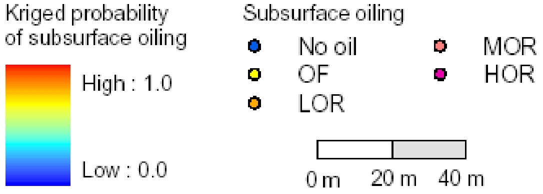
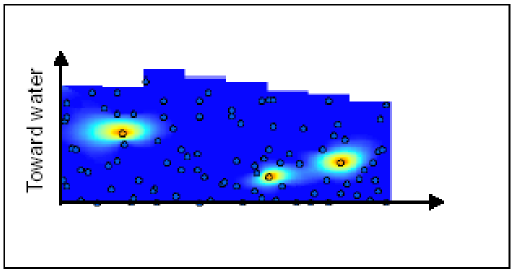
Planimetric (overhead) view of segments with subsurface oiling, pit locations and descriptors, and kriged subsurface oiling probability surface





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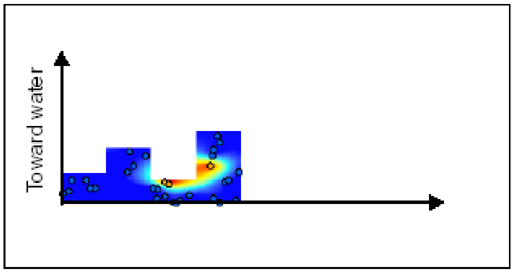

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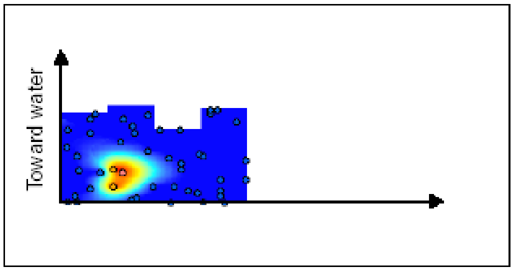

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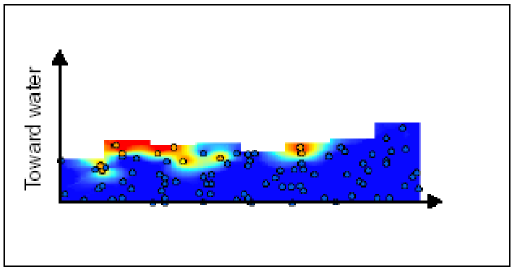

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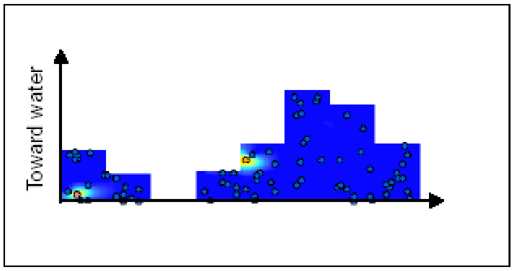

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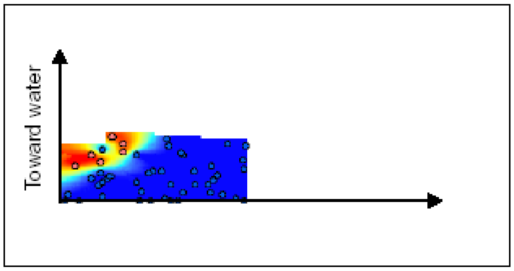

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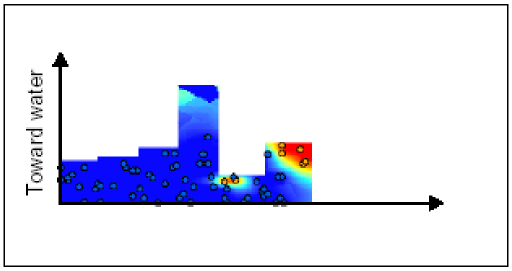

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Planimetric (overhead) view of segments with subsurface oiling, pit locations and descriptors, and kriged subsurface oiling probability surface

Kriged probability of subsurface oiling

High : 1.0

Low : 0.0

Subsurface oiling

● No oil

● OF

● LOR

● MOR

● HOR

0 m 20 m 40 m