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PROPOSAL SUMMARY PAGE
(To be filled in by proposer)

Project Title:	Factors Responsible for Limiting the Degradation Rate of Exxon Valdez Oil in Prince William Sound Beaches — Submitted under the BAA
Project Period:	April 1, 2007 to September 30, 2009

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Study Location: PWS

Abstract: This proposal will provide important data for explaining the cause of the lingering oil in many of the Prince William Sound beaches affected by the 1989 Exxon Valdez oil spill. Because biodegradation of oil occurs at the oil-water interface, limitations occurring in the vicinity of that interface are hypothesized to be the primary reason for the lingering oil. In this study, we propose to investigate the two major sources of limitation: (1) environmental limitations, which involve nutrient concentrations (nitrogen, phosphorus, and dissolved oxygen) and their transport to the oil-water interface, and (2) the existence of an impenetrable layer or "skin" on the oiled sediment, which inhibits the bioavailability of oil. This often occurs when oil is stranded in the subsurface. The latter will be assessed by use of Scanning Electron Microscopic (SEM) examinations of oiled sediment. The effects of hydrodynamics will be assessed using tracer studies and 2-D or 3-D physics-based modeling of solute (i.e., nutrient) transport through the beach matrix. Hydrodynamics studies are important to understand the delivery (i.e., transport) of limiting nutrients to the oil-water interface. Extensive measurement of nutrient concentrations on PWS beaches will also be conducted to ascertain the extent of nutrient limitations on the biodegradation process. To our knowledge, this is the first rigorous study that addresses how the hydrodynamics of PWS beaches relate to the potential of bioremediation in relieving the aforementioned limitations. The proposed research will provide important inputs to an overall understanding of the transport and fate of oil in the PWS beaches and will provide guidance on how to accelerate the disappearance of the lingering oil present in the subsurface.

Funding: EVOS Funding Requested:

FY07	$ 434.8	(Includes Trustee Agency 9%GA)
FY08	$ 552.5	
FY09	$ 266.6	
TOTAL:	$1,253.9	

Non-EVOS Funds to be Used: $32.8

PROJECT TOTAL W/IN-KIND CONTRIBUTION TOTAL: $1,286.7

(Not to Exceed One Pg)

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1.0 NEED FOR THE PROJECT

This proposal addresses the request by the Exxon Valdez Oil Spill Trustee Council (EVOSTC) for proposals that investigate the physical processes that affect the lingering oil in the subsurface intertidal sediments on some beaches in Prince William Sound. The proposed research will investigate factors that will determine whether in-place treatment of lingering oil by bioremediation is feasible, and if so, determine how to best stimulate this process through engineered manipulation of the physical or chemical environment of contaminated beaches. *In-situ* bioremediation was identified by Michel *et al.* (2006) as one of two feasible alternatives for removing the lingering oil.

2.0 PROBLEM STATEMENT AND HYPOTHESES

Short *et al.* (2004) conducted a comprehensive geospatial survey of lingering oil in Prince William Sound (PWS) and found that about 11 ha of shoreline remain contaminated with nearly 56,000 kg of subsurface oil from the 1989 Exxon Valdez oil spill. Surprisingly, much of the lingering oil was present in subsurface sediments in the middle intertidal zone of the contaminated beaches. Although substantial weathering had occurred, high concentrations of toxic and mutagenic contaminants were present, suggesting that this lingering oil poses an on-going threat to organisms that encounter it. Short *et al.* (2004) classified the residues using the standard descriptive terms adopted in the PWS, which is LOR, MOR, and HOR, representing Low, Moderate, and High Oil Residue, respectively.

The potential for limitation of the oil biodegradation rate by transport of certain critical nutrients, such as nitrogen, phosphorus, and oxygen, has its basis in the stoichiometric requirement for these materials to support biodegradation of petroleum hydrocarbons (Atlas and Bartha, 1972; Atlas, 1981; Wrenn *et al.*, 2006). Therefore, the demand for these nutrients is directly proportional to the concentration of oil in the contaminated sediments. For example, biodegradation of crude oil requires about 0.04 g N/g oil (Atlas and Bartha, 1972) and about 3 g O_2/g oil (Atlas, 1981). Since the initial oil concentrations in beaches with lingering oil appear to have been between 15-45 g oil/kg sediment (unpublished data), approximately 0.6-1.8 g N/kg sediment and 45-135 g O_2/kg sediment would be required to support complete biodegradation of oil. PWS seawater contains only about 0.2 mg N/L (Bragg *et al.*, 1994; Ward, 1997; Eslinger *et al.*, 2001) and about 9 mg O_2/L. Therefore, at least 3,000-15,000 liters of seawater must come into contact with each kilogram of contaminated sediment to provide sufficient nutrients to support complete biodegradation of the initial oil. Since only about 0.20-0.25 L seawater/kg sediment is available in the pore water, biodegradation requires continual exchange of pore water with the surrounding seawater. Incomplete exchange of beach pore water with the surrounding seawater during each tidal cycle would limit the extent of biodegradation. We call this stoichiometric limitation.

Assuming that the mass of nutrients is high enough, there could be also kinetic limitations that are due to low nutrient concentrations. Previous research has shown that nutrient concentrations between about 2 to10 mg N/L are required to support maximum oil biodegradation rates (Boufadel *et al.*, 1999c; Du *et al.*, 1999), and a field study in Delaware Bay showed that nitrogen concentrations of 3 to 6 mg N/L in the interstitial pore water stimulated hydrocarbon biodegradation by 2- to 3-fold over natural attenuation where the average interstitial nutrient concentrations averaged 0.8 mg N/L (Venosa *et al.*, 1996). These reported minimum nutrient concentrations are far higher than the average concentrations of 0.2 mg/L observed in PWS (Bragg *et al.*, 1994; Ward, 1997; Eslinger *et al.*, 2001). Bragg *et al.* (1994) reported an increase in the biodegradation rate of the Exxon Valdez in the PWS beaches when the pore water nitrogen increased from about 0.2 mg N/L to 1 mg N/L.

Temperature and pH could also affect the rapid biodegradation of oil. In particular, the biodegradation of oil is expected to be highest in summer due to the relatively higher temperature of water in the Sound. However, if little mixing occurs between the incoming seawater and the pore water in the vicinity of the oil-water interface, then little or no biodegradation would occur.

Finally, it has been observed during the biodegradation of poorly-soluble hydrocarbons that the microorganisms act at the oil-water interface (Rosenberg and Rosenberg, 1981; Watkinson and Morgan, 1990; Jimenez and Bartha, 1996). Thus, one needs to account for the bioavailability of oil. That is, the biodegradation rate could be limited by the mass-transfer rate of the biodegradable components of oil, such as the PAHs, to the oil-water interface (Rosenberg *et al*., 1992; Nicol, 1994) where the uptake by microorganisms occurs. The bioavailability, and subsequently the biodegradation rate, can be limited by the presence of an interfacial barrier, such as a dense mineral coating on the oil surface or a high-viscosity layer at the oil-water interface (Berger and Mackay, 1994). Therefore, oil biodegradation rate can be affected by three factors: stoichiometric and kinetic limitations by nutrients (namely nitrogen, phosphorus, and oxygen) and the bioavailability of oil, related to the mass transfer of nutrients and biodegradable oil constituents to the oil-water interface. This leads us to pose the following two hypotheses to test:

Hypothesis 1: *The current environmental conditions in the water near the oil might not favor biodegradation either due to nutrient limitations or unfavorable temperature or pH values. We label this hypothesis "environmental limitations".*

Hypothesis 2: *The oil is not bioavailable due to the presence of a "skin" at the interface that prevents the mass transfer of biodegradable components within the oil phase to the oil-water interface We label this hypothesis "bioavailability limitations"..*

In other words, we are looking at limitation on biodegradation from the both sides of the oil-water interface.

Testing Hypothesis 2 relies on taking oil and sediment measurements and analyzing them for chemical indicators of the "skin." Testing Hypothesis 1 is conceptually more complicated and requires much more planning and execution. For this reason, we focus our attention on providing the background for testing Hypothesis 1, namely the hydrodynamics in the beaches of PWS.

3.0 OBJECTIVES

The primary objective of the proposed research is to test the stated Hypotheses. The second objective is to acquire information leading to the best nutrient application strategy if the bioavailability of oil is not limited (i.e., Hypothesis 2 is not true). We will conduct tracer studies during the summer months, monitor selected environmental variables throughout the year, and model the monitored variables and data from the tracer studies. The tracer studies will be conducted on six beaches: three sheltered (lentic) and three subjected to waves (lotic). Tracer studies on one lentic and one lotic beach will be conducted in the summer of 2007, and the remaining tracer studies on the other four beaches (two lentic) and (two lotic) will be conducted in the summer of 2008.

4.0 RELEVANCE TO THE 1994 RESTORATION PLAN GOALS

The proposed research will investigate several mechanisms that may control the persistence of *Exxon Valdez* oil in the subsurface sediments of beaches in PWS. This research will provide information on physical processes that occur in oil-contaminated subsurface sediments and determine whether they differ in important ways from those that occur in adjacent unoiled sediments. The proposed research will characterize the subsurface hydrodynamics in the intertidal zone of contaminated beaches, and relate those processes to their geomorphic characteristics through a mathematical model that is based on the fundamental physical principles of water flow through porous media in the presence of an oscillating driving force (*i.e.*, tidal cycling). The proposed integration of physically-based modeling and experimentation will allow us to interpret the potential constraints on oil biodegradation rates that are imposed by environmental limitations (Hypothesis 1) relative to bioavailability limitations (Hypothesis 2). This information is required to support future remediation efforts because the remediation technology that is selected must address the most important limiting factors.

The results of this investigation will determine whether full-scale bioremediation of PWS beaches is warranted. If the factors that are responsible for the persistence of the subsurface oil can be controlled through engineered manipulation of subsurface conditions, this research will lead to development of a comprehensive bioremediation plan that will restore habitats that are adversely impacted by the lingering oil. The benefits of this research to the evaluation and implementation of bioremediation in PWS is consistent with the EVOSTC's objective of determining whether remediation of specific shorelines would protect or restore injured resources. Bioremediation, if feasible, would be the preferred remediation alternative for contaminated beaches in PWS because it will not result in remobilization of oil. So, the exposure of sensitive species to oil will not increase during remedial operations. The primary beneficiaries of this research will be natural resources in PWS that have not yet recovered from the *Exxon Valdez* oil spill due to exposure to the lingering oil and the human communities that depend on these resources for their livelihood and quality of life.

5.0 HYDRODYNAMICS

The existence of significant oil saturation will clog the pores, minimizing permeability to water (Fetter, 1994). However, PWS sediments are coarse with a pore size distribution that is skewed towards larger pore sizes. Thus, even for the HOR, the concentrations of oil per kg of sediment are relatively low. If one assumes a porosity of 30% and the contaminated thickness of HOR sediments to be 0.20 m as reported by Short *et al.* (2004), then one finds the "concentration" of HOR oil to be less than 35 mg/cm^3 of pore water, meaning that most of the pore space is occupied by water. Therefore, with the exception of some locations, it is reasonable to assume that the clogging of pores due to oil has only a small effect on water flow in the beaches.

Water flow through the porous matrix of a beach is driven by a combination of five factors: geomorphology, beach profile, tidal pumping, freshwater-saltwater dynamics, and waves.

5.1 Geomorphology

The beaches impacted by the oil spill in PWS consist of a wide range of sediment sizes in the intertidal zone, both vertically and horizontally. Most of these beaches are underlain by a shallow, convoluted bedrock surface or a peat layer that affects groundwater flow patterns. Many of them are "armored" because of the 1964 earthquake, with larger clasts on the surface that slow natural sediment reworking processes, particularly in the middle and lower intertidal zone. Bedrock outcrops commonly occur in combination with gravel beaches. The highly variable sediment grain size and bedrock distributions have resulted in complex patterns of permeability and groundwater flow that may have contributed to the persistence of subsurface oil.

It is unlikely that small-scale heterogeneity (i.e., at the centimeter scale) caused the persistence of oil in PWS. One reason is that substantial heterogeneity in the beach matrix would create a high contrast in oil concentration (per total volume). However, the areas of HOR had the highest thickness in the beach (~21 cm), indicating a gradual variation in beach properties. In other words, centimeter-scale heterogeneity has a tendency to create many small lenses of oil trapped in the sediment rather than fewer large ones. Thus, it is more likely that large-scale heterogeneity (say over meters) exists in the beach (i.e., geomorphology). For more discussion on small-scale heterogeneity, the reader is urged to consult the works by Boufadel *et al*. (2000) and Tennekoon *et al*. (2003).

5.2 Beach Profile.

When a porous medium (e.g., a beach) is in contact with an open water body (sea, lake, river), the velocity vectors of water leaving or entering the submerged surface are perpendicular to that surface (Figure 1). This fact, observed in many systems where groundwater is connected to an open water body, has been used widely by geotechnical engineers to construct flow nets in earth dams (Cedergren, 1967). However, most studies of groundwater flow have focused on large-scale transport (i.e., km or miles), and concluded that water flow and solute transport occur predominantly in the horizontal direction, which is correct far landward of the beach. The transport at the beach-scale is essentially two-dimensional with a considerable vertical component, as demonstrated by Boufadel (2000), Naba *et al*. (2002), and Boufadel *et al*. (2006).

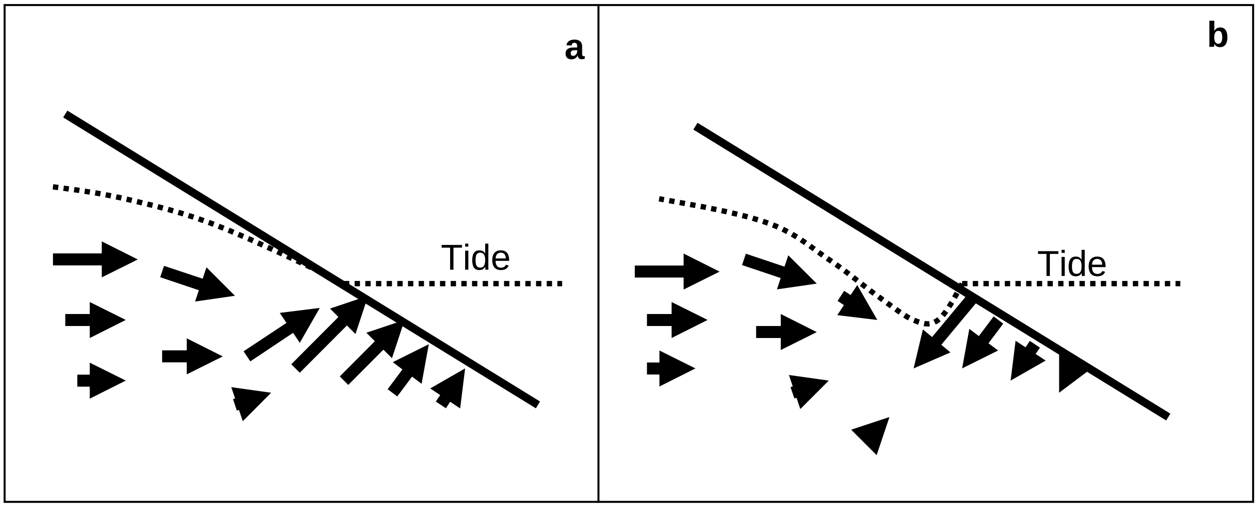


Figure 1: Illustration of velocity vectors in the beach matrix during (a) falling or slowly rising tides and (b) fast rising tides. The dashed line represents the water table in the beach and the tide level at sea. The velocity vectors are perpendicular to the submerged beach surface, and their magnitude decreases seaward, whether water is draining from or entering the beach.

It has also been observed that, on the submerged face of the beach, water velocity decreases seaward whether water is leaving or entering the beach (Figure 1). Hence, not much convective exchange occurs between the beach and the open water seaward of the tide line. If the buoyancy forces on the oil are not dominant, oil trapped in the submerged beach near the low tide would not move deeper in the sediments or out to sea, which explains the persistence of oil in the lower intertidal and subtidal zones of beaches (Short *et al*., 2004). In addition, nutrients (potentially) present in seawater would not likely convect into the beach seaward of the tide line. To exacerbate this situation, it has been observed that on some beaches in PWS, a break in the beach slope occurs near the mid-tide line, where the slope becomes sharply milder on the seaward side. Such a sharp break has the unfortunate effect of reducing further the convective exchange seaward of the tide line.

5.3 Tidal Pumping

It has long been understood that beaches fill faster than they drain (Philip, 1973; Nielsen 1990; Boufadel *et al*., 1998), and this is due to the fact that the water table responds rapidly to the tidal level near the high tide (where the beach fills from the sea) but lags behind it during a falling tide. This indicates that the predominant hydraulic gradient in beaches (i.e., at the beach-scale) is seaward and that solutes applied onto the beach would be washed out to sea. This indeed was observed in tracer studies on tidally influenced beaches by Wrenn *et al*. (1997a,b).

A mechanistic investigation reveals that if the tide rises slowly while being below the landward water table, beach water would continue to drain to sea (i.e., the flow is seaward), as shown in Figure 1a. This drainage at the exit point to sea is similar to the one that exists during falling tides. However, if the tide rises fast, seawater would enter the beach, as illustrated in Figure 1b. The classifications "fast or slow" for the speed of tide movement depends on a comparison between the actual speed of the tide and beach properties. In a series of papers, Boufadel and coworkers (Boufadel *et al.* 1998; Boufadel 2000; Boufadel and Peridier 2002; Naba *et al.* 2002) developed dimensionless formulations that take into account such a comparison. The formulation is too detailed to present herein, but it can be used to provide an order of magnitude analysis as follows: One needs to compare the seaward pore water velocity at the intersection of the water table and the beach surface $V_s = \dfrac{K\sin(\alpha)}{n}$ to the local landward velocity during to a rising tide $V_L = \dfrac{V_r}{\sin(\alpha)}$, where K is the hydraulic conductivity of the beach, α is the angle of the local beach surface with the horizontal, "n" is the porosity of the beach, and V_r is the rise speed of tide.

Thus, if: $V_s > V_L$ which is equivalent to $K > \dfrac{n\,V_r}{(\sin(\alpha))^2}$, water will exit the beach to sea during rising tides (Figure 1a), and freshwater will be above high salinity water. In the converse case, seawater will enter the beach and overtop the lower salinity water (Figure 1b). In one of the few works investigating hydraulics in PWS, Carls *et al.* (2003) took measurements on two beaches and found that low salinity water was above the high salinity water at one beach (Sleepy Bay), while high salinity water was above low salinity water at another (Junction Creek). They did not provide an explanation for their observations, but the conceptual mathematical models that they used do not account for vertical flow and thus cannot explain the salinity stratification they observed. Using the arguments above, one concludes that, all factors being the same, the lower hydraulic conductivity beach would more likely result in high salinity water overtopping the low salinity water. This was indeed the case at Junction Creek, whose hydraulic conductivity was 0.2 cm/s while that of Sleepy Bay beach was 1.1 cm/s (Carls *et al*., 2003). Thus, there could be many situations, especially for lentic beaches, where seawater (containing nutrients and dissolved oxygen) does not enter the beach during rising tides.

5.4 Freshwater-saltwater interactions.

Freshwater is lighter than saltwater (about 2% difference in density). Thus, freshwater propagating seaward in the beach tends to float above a saltwater wedge before exiting the beach (Henry, 1964). However, as discussed above, freshwater could be entrapped by saltwater if the tide rises fast. Typically, this causes the freshwater to "pinch out" of the beach somewhere near the low tide line (Boufadel, 2000).

5.5 Wave Action.

Studies based on water measurements (Nielsen, 1989; Hegge and Masselink, 1991; Aseervathan *et al*., 1997) have shown that wave run-up results in two zones in the beach that have different hydraulic gradients: a zone landward of the swash zone with a mild seaward hydraulic gradient and the swash zone itself with a much steeper seaward gradient. Wrenn *et al*.,(1997b) conducted tracer studies on two adjacent beaches in Maine, an exposed beach and a protected embayment. Both beaches were subjected to the same tidal amplitudes, but the exposed beach was also inundated by moderately energetic wave action. The study revealed that the presence of waves greatly accelerated the washout of the applied tracer solution (simulating nutrient addition). Our mechanistic investigation using a 6-m laboratory beach in a wave tank (Boufadel *et al*., 2007) confirmed the observations of the aforementioned studies.

The waves on most PWS beaches where oil is lingering are relatively small. Hence, it is expected that the effect of wave action does not extend too deeply into the beaches. The armoring of beaches further minimizes the effects of waves on oil entrapment and subsequently the washout of oil to sea. Hayes and Michel (1997) and Short *et al*. (2004) report data and present explanations supporting the sheltering of oil due to armoring. This implies that even if a seaward hydraulic gradient due to tide favors the washout of oil to sea, the armoring would entrap some of the oil behind boulders of pocket beaches, near boulder or bedrock outcrops.

6.0 OVERALL APPROACH

6.1 Modeling

A numerical model will be calibrated to measurements of water level, salinity, and tracer (or temperature), and this model will be used to help interpret the results. Our inclination is to use the MARUN model (Boufadel *et al*., 1999a), which is vertical across shore and is capable of simulating the five hydrodynamic factors stated above. However, if subsurface flow includes a significant along shore component, a three-dimensional model would be required, and we would use the SUTRA model, developed by the U. S. Geological Survey (USGS, 2003). Modeling will be used also to plan the study (*e.g.*, placement of sample wells in the transects).

6.2 Tracer Study Experimental Design

The two main response variables in this tracer study will be the time-varying water level at several locations along two landward-seaward transects on each of the six shorelines, and the concentrations of a conservative tracer as a function of time at multiple depths at each of several locations along each transect. These measurements, along with water salinity and temperature, will be made throughout several tidal cycles to characterize groundwater flow in the beaches. The geomorphology (namely the bedrock) will be characterized during the excavation of pits to place the wells along each transect. Although less frequent, measurements of nutrient concentrations (e.g., nitrate, ammonium, and phosphate), and dissolved oxygen, will be made to characterize conditions that could affect microbial activity.

6.2.1 Plot Setup

Six shorelines will be investigated in this study. They will be selected based on the presence of lingering subsurface oil and the geomorphological characteristics based on the recommendations of Drs. Jacqueline Michel and Jeff Short, who will be conducting field work to locate the areas of lingering oil in PWS in 2007. The results of field work conducted by Short in 2001 and 2004 will also be used to select the six study sites. The study will be conducted on two different types of shorelines: exposed beaches that are subject to relatively high-energy waves and sheltered, low-energy beaches. Examples of two beaches that meet our selection criteria are Smith Island (high energy; 60.527962115 N, 147.3855754280 W) and Northwest Bay on Eleanor Island (low energy; 60.550952593 N, 147.5788009370 W). Shorelines on these islands were heavily oiled following the *Exxon Valdez* oil spill and relatively large patches of lingering oil remain in the subsurface sediments at moderate to high concentrations (Michel *et al*., 2006).

6.2.2 Transects.

Two transects will be established perpendicular to the shoreline at each site. One transect will intercept a patch of subsurface oil, and the other will be established in a clean segment of the shoreline (Figure 2). Before installing the transects, the shorelines will be surveyed to determine the profile, establish benchmarks, and estimate the approximate locations of the mean high and low water levels relative to the benchmarks and the oil patch.

Each transect will include six piezometer wells and six multiport sampling wells. At each location a pit will be excavated, similar to the approach of Carls *et al*. (2003) at Sleepy Bay, followed by placement of a multiport sampling well and a slotted PVC pipe in the pit, which will be refilled with gravel (average size, 5 cm). This will allow water that reaches the vicinity of the wells to pass freely. The piezometers (Leveloggers, Solinst) will also be equipped with temperature sensors to record temperature readings. The sensors are cylindrical, ¾ inch in diameter and about 2 inches long. Each will be tied to a string and suspended in a slotted PVC pipe, which will facilitate removal of the sensors from the beach. The exact location of the wells will be selected based on preliminary modeling of the shoreline using the 2-D beach hydraulics model MARUN (Boufadel *et al*., 1999a), but a general representation of the locations is provided in Figure 3. One piezometer will be placed below the lowest low tide, and another above the highest high tide to establish the boundary conditions of the beach. The duration between piezometer readings will be 5 minutes. One data logger will be able to record the data from all of the sensors on one shoreline.

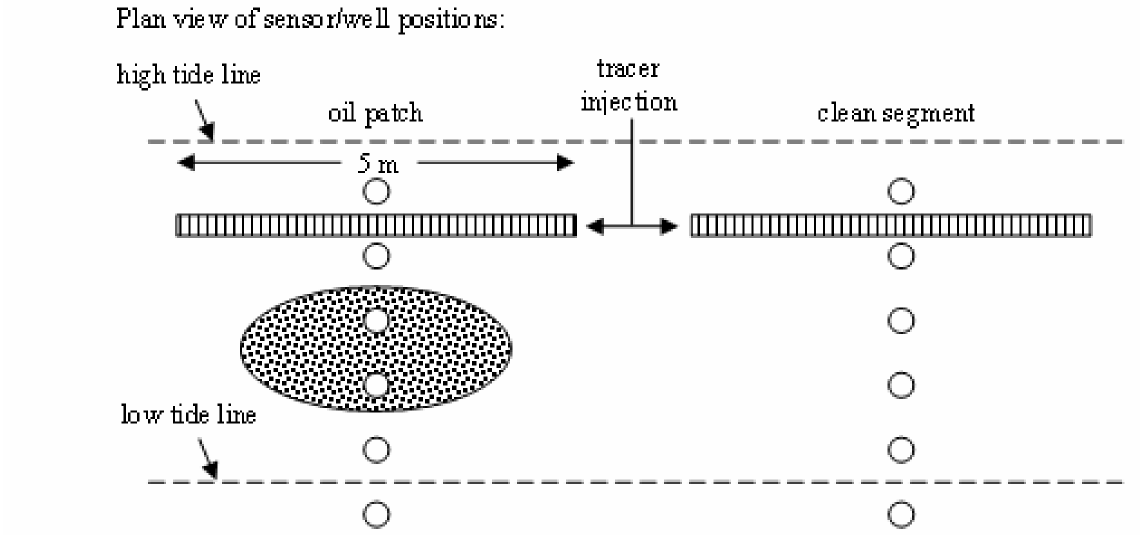
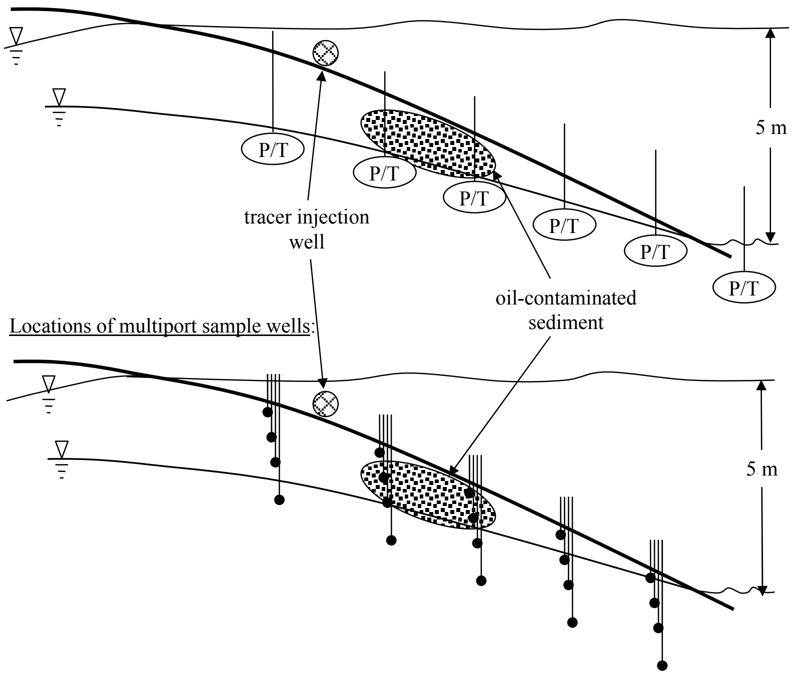


Figure 2: Plan view of sensor and multiport well positions for tracer study. Tracer studies will be conducted along two transects on the selected beaches: one transect will intercept a patch of oil-contaminated sediments, whereas the other will be installed on a clean segment of the shoreline. The injection wells, sensors, and multiport sample wells will be installed at similar vertical elevations in both transects

Locations of pressure/temperature/salinity sensors:



Locations of multiport sample wells:

Figure 3: Schematic diagram of sensor and multiport well layout for tracer tests. Sensors will measure pressure (P) and temperature (T) semicontinuously with the data recorded by a datalogger. The multiport wells will allow water samples to be collected from four depths to about 1 m. The conservative tracer will be injected through a horizontal well installed landward of the oil patch (and at a similar location in the clean beach segment).

The measurement of wave parameters (height prior to breaking, runup, rundown, etc..) will be obtained based on pictures taken of the waves while having a known scale (3-ft Philadelphia Rod) in the picture. Simple geometric calculations (while accounting for the shooting angle) would provide sufficient information to estimate wave parameters. Water samples will be collected through well points that will be installed at similar locations in each transect, except wells will not be installed in the open water (Figure 2). Well points will be installed at four depths, spaced about 25 cm apart, at each location. Samples will be collected by withdrawing the desired volume through tubing connected to the screened sample inlet using a syringe. The volume of the tubing will be calculated and each port will be purged with at least 3-times the tubing volume to ensure that water is collected from the formation.

The tracer will be applied to the beach surface through a horizontal manifold constructed from 1-inch slotted PVC pipe that is about 5 m long. The manifolds will be screened over the entire length and wrapped with a porous fabric to ensure uniform distribution of tracer over the length of the well. Since most of the lingering oil exists in the mid-intertidal zone, the tracer will be applied slightly landward of the mid-intertidal zone at a location that would allow treatment of the lingering oil without requiring information on the exact location of oil on any particular shoreline. For example, the distribution of subsurface oil in PWS shorelines suggests that application of nutrients 3.8 m above mean low water would allow us to treat about 95% of the oil patches (Short *et al*., in press). The exact location of tracer application will be determined based on preliminary data on beach profiles, water level, and salinity collected prior to the experiments. These data will be interpreted using the numerical model.

6.2.3 Tracer Study

After the piezometers are installed, the hydraulic characteristics of the beach will be monitored for several days to establish background conditions and to calibrate the sensor measurements with independent observations of the same quantities. For example, the open water level at high and low tide will be measured relative to the benchmark for each shoreline and compared to the levels estimated by the piezometers. The piezometers will measure water level and temperature at each position along the transect at 5-minute intervals. In addition, salinity, dissolved oxygen, and nutrient concentrations will be measured in water samples collected offshore and from the well points on at least two falling tides. These measurements will establish the background hydraulic and biogeochemical characteristics of the shoreline sediments and will be used in the numerical model to select the application location.

The tracer study will be started by pumping 400 gallons of a 5 g/L solution of the conservative tracer lithium nitrate ($LiNO_3$) onto the shoreline surface at low tide. If freshwater is available at the study site and is observed in the groundwater, the tracer solution will be made using freshwater; otherwise seawater will be used to prepare the solution. Considering the high hydraulic conductivity of the beach sediments (more than 1 cm/s), it is likely that a high discharge rate of the tracer solution could be adopted without ponding, but a lower application rate will reduce the impact of tracer addition on the hydraulic gradient in the shoreline sediment. Therefore, the tracer will be applied over a three-hour period (about 130 gal/hr), such that the tide will have reached the mid-intertidal zone when the application is complete. The second tracer study (*e.g.*, the low-energy beach) will begin after the first tracer study ends because the field crew cannot collect samples at both beaches simultaneously.

Collection of water samples from the multi-port wells will begin immediately after injection of the tracer. Water samples will be collected on every falling tide until the tracer concentration in the experimental domain is decreased by a factor of 100. Each tracer study is expected to last about one week.

6.2.4 Seasonal Variability

The tracer studies will be conducted in the summer. In the remainder of the year, water level, water temperature, and salinity will be measured only at the most landward well on the beaches using sensors made by Solinst (Levelogger Gold 3001). These sensors are designed to function in temperatures of -20°C, and they will be in wells below ground where the temperature is expected to be higher than 0°C. Each sensor can store up to 40,000 sampling events for the three variables. Thus, if samples are taken every 15 minutes, the sensor can store data for up to 13 months, allowing us to download the data in the summer.

6.2.5 Analytical Chemistry

6.2.5.1 Lithium Tracer.

The concentration of lithium in water samples collected from the well points during the conservative tracer study will be measured by atomic absorption spectroscopy (AAS). Samples will be preserved by acidification ($pH < 2$) with sulfuric acid and stored in clean polyethylene bottles until the field work is completed. The samples will be shipped to the Temple University lab for analysis. The initial tracer concentration (5 g $LiNO_3$/L) corresponds to a lithium concentration of about 500 mg/L. The detection limit for lithium using AAS is less than 1 mg/L, which is less than the final concentration of 5 mg/L that would result from a 100-fold reduction in the lithium concentration during the tracer study.

6.2.5.2 Nitrate Concentration.

The tracer concentration must be monitored in the field to determine when sample collection can be stopped. This will be accomplished by measuring nitrate concentration using test strips or a similar field test (*e.g.*, Hach Company, Loveland, CO). Detection limits for these methods are on the order of 1 mg N/L, which corresponds to about 0.5 mg Li/L. These methods are generally only semi-quantitative, but they are sufficiently accurate for the intended use.

6.2.5.3 Nitrogen and phosphorus measurements.

The concentrations of ammonia, nitrate, and phosphate in water samples collected before beginning the tracer study will be measured using the automated indophenol-blue, cadmium-reduction, and antimony-phosphomolybdate methods (U.S. EPA, 1997), respectively. The water samples will be filtered through 0.45-μm membrane filters, stored frozen in clean high-density polyethylene bottles, and shipped to the Temple University lab for analysis after the field work has been completed. The detection limits for these methods are 20 μg N/L for ammonia by the automated indophenol-blue method, 0.1 μg N/L for nitrate by the automated cadmium-reduction method, and 0.7 μg P/L for phosphate by the automated antimony-phosphomolybdate method.

6.2.5.4 Dissolved Oxygen (DO).

DO will be measured in the field using the Winkler titration (APHA, 1999). These samples will be collected in completely filled glass bottles sealed with ground-glass stoppers (*e.g.*, BOD bottles), and the DO will be measured immediately after the samples are returned to the ship. The detection limit of this method is <1 mg O_2/L, and the surface seawater is expected to be saturated with dissolved oxygen (9-10 mg O_2/L, depending on the temperature and salinity).

6.2.5.5 Salinity.

Salinity will be determined by measuring the conductivity of water samples collected from the well points. Conductivity will be measured using a commercial meter (*e.g.*, the Hach SensIon 5 conductivity meter).

7.0 Hypothesis Testing

If Hypothesis 1 (environmental limitations) is the cause of lingering oil, then the applied tracer will not pass through the oil patch. Rather, it will pass through the corresponding location on the control transect of the same beach. Temperature will be used as a surrogate tracer. Its use would help to identify additional sources of water input to the shoreline and to characterize the conditions to which oil-degrading microorganisms are exposed. Salinity will assist in identification of additional water sources, especially input of freshwater from the terrestrial sources. Thus, different variables will be used to characterize water motion and solute transport in the beaches.

Dissolved oxygen and nutrient concentration measurements will be made before beginning the tracer study, but pore-water samples will be collected using the multi-port sampling wells that will be installed for use in the tracer study. Low oxygen and nutrient concentrations are considered to be the factors that ultimately limit the rate of oil biodegradation and thus cause the oil to persist. Therefore, the concentrations of oxygen and nutrients (especially, nitrate, ammonium, and phosphate) will be measured in sediment pore water and the local seawater. Since the conservative tracer contains nitrate at a concentration that will overwhelm the background concentration, the nutrient measurements must be made before beginning the tracer study. Water samples will be collected from the multi-port sampling wells at all locations in both transects on falling tides for two days after installation of the wells and before beginning the tracer study. Nutrient samples will be preserved and shipped to an analytical laboratory for analysis. Oxygen will be measured immediately on board the support ship using the Winkler titration, which enables rapid processing of a large number of samples. We will look for evidence of nutrient and oxygen depletion in the oil-contaminated sediments relative to the overlying water and sediments in the clean shoreline segment.

To test Hypothesis 2, oil-contaminated sediment samples will be collected during excavation of the pits from the top using small coring devices to obtain relatively undisturbed samples. These will be frozen and transported to a laboratory for examination by scanning electron microscopy (Lavoie *et al*., 1994; Ray *et al*., 1997). Since a large accumulation of minerals would be required to exert a significant limitation on the long-term biodegradation rate, the sensitivity of this method should be adequate. In addition, scanning electron microscopy (SEM) will be used to assess the presence of asphaltene and resins at the oil-water interface. If these are predominant and/or minerals are present, then it will be concluded that Hypothesis 2 is true regardless of Hypothesis 1. In terms of biodegradation, the presence of the skin indicates that one would need to disturb the oil to cause breakage of the skin and increase the bioavailability of the oil.

8.0 SCHEDULE

8.1 Project Milestones

The objective is to conduct a tracer study to evaluate whether environmental limitations negatively affect biodegradation in PWS shoreline sediments.

- Preliminary modeling of shorelines completed by April 30, 2007
- Field work to be completed by August 15, 2007.
- Sample analysis to be completed by November 15, 2007.
- Hydrodynamics and solute transport modeling to be completed by June 15, 2008.

8.2 Measurable Project Tasks

FY 07, Third Quarter (April 1, 2007 – June 30, 2007)

- April 1: Notification of funding by Trustee Council.
- May 31: All equipment and supplies ordered, support boat and captain identified and contracted.
- June 15: Preliminary modeling of study sites complete.

FY 07, Fourth Quarter (July 1, 2007 – September 30, 2007)

- June 20: Staging area in Whittier identified and leased. Equipment and supplies shipped to staging area.
- June30: Arrive in Whittier, inspect and test equipment, load supplies onto boat, prepare for travel to site.
- July 3-July 20: Conduct field tracer studies at two selected sites
- July 20: Remove all equipment from 2 sites and head back to staging area.
- July 21: Arrive in Whittier, unload boat, store equipment, send all preserved samples to Temple University for analysis. Return home.
- July 31, all sample analyses completed.

FY 08, First Quarter (October 1, 2007 – December 31,2007)

- November 30: Arrive in Whittier, inspect and test equipment and supplies, load boat.
- December 2-10: Conduct winter field sampling at 2 sites.
- December 10: Head back to Whittier, offload equipment and supplies, store equipment, send preserved samples to Temple University for analysis.
- December 11: Fly home.

FY 08, Third Quarter (April 1, 2008– June 30, 2008)

- May 25: Travel to Whittier
- May 26: Load boat with supplies and equipment
- May 27: Sail to next sites to begin tracer studies (4 sites altogether).
- May 28-June 30: conduct tracer studies on 4 sites

FY 08, Fourth Quarter (July 1-September 30, 2008)

- June 30-July 15: Complete all tracer studies at 4 sites.
- July 16: Remove equipment from sites, load all samples and supplies onto boat.
- July 17: Return to Whittier.
- July 18: Send preserved samples to Temple University for analysis
- July 31: Analyses completed.

FY 09, First Quarter (October 1, 2008 – December 31, 2008)

- November 30: Arrive in Whittier, inspect and test equipment and supplies, load boat.
- December 2-10: Conduct winter field sampling at 4 sites.
- December 10: Head back to Whittier, offload equipment and supplies, store equipment, send preserved samples to Temple University for analysis.
- December 11: Fly home.
- December 31: Sample analyses completed.

FY 09, Second Quarter (January 1-March 31, 2009)

- Attend annual Marine Science Symposium
- March 31: Beach hydrodynamics and solute transport modeling completed.

FY 09, Third Quarter (April 1-June 30, 2009)

- Circulate draft final report for comments.

- June 30: Submit final report to Trustee Council.

9.0 RESPONSIVENESS TO KEY TRUSTEE COUNCIL STRATEGIES

9.1 Community Involvement

How will affected communities be informed about the project and be given an opportunity to provide their input? Discussions have already taken place with Ms. Katherine McLaughlin, Environmental Program Technician for the Chenega Bay Environmental Office, a subsidiary of the Chenega Indian Reclamation Act (IRA) Council. She indicated willingness to notify not only the Chenega native villagers of the project but also inform all other villages in the region through newsletters that we will be conducting this project and looking for a field crew to assist with sampling and logistics.

How will research findings and other project information be communicated to local communities? We plan to write fact sheets and other summary materials and make them available to local communities and environmental coordinators. We will travel to PWS and meet with the native communities at an agreed location, presenting summaries of progress. We will rely on guidance from the EVOSTC on how to distribute summary documents and fact sheets, as part of its overall outreach program on lingering oil and associated impacts.

To what extent will local hire be used for the acquisition of such things as vessels, technicians, and equipment? Our needs include a boat, captain, and crew plus at least two field technicians to help with setting up, sampling, and disassembly at the completion of the project. We plan to hire local people to supply these needs.

To what extent will traditional and local knowledge be incorporated into the project? We are relying not only on collaboration with another research team (J. Michel and J. Short) involving finding the lingering oil but also on the knowledge of the local people who have their own unique experience with the location of the oil and the layout of the area. We will solicit this knowledge through the EVOSTC outreach program.

9.2 Resource Management Applications

If we are successful in demonstrating that environmental limitations have played a major role in explaining why oil has lingered in PWS beaches for 17 years, it will lead to an important strategy for removing the oil cost-effectively and eventually restoring the affected areas for a full recovery of the biological resources that have been negatively impacted by the spill. Before implementing any restoration/remediation effort, it is critical to understand what is causing the oil to remain behind. If we can show that nutrient and oxygen limitation are the main factors, then it will strongly suggest a way to finally stimulate the natural populations to degrade the oil rapidly. This will be an important outcome for all area resource managers and communities, who want the lingering oil removed. We can claim this because we already know how to implement nutrient application methodology on exposed and sheltered marine shorelines, having done extensive research in the past in the field and the laboratory (wave tanks) and through hydrodynamic modeling. In Venosa *et al*. (1996), we investigated the biodegradation of an experimental oil spill on a beach in Delaware. In Wrenn *et al*. (1997a,b), we conducted tracer studies similar to the ones that we proposing on beaches in Delaware and Maine. In Boufadel (1998) and Boufadel *et al*. (2006, 2007), we ran extensive laboratory experiments in a 6-m mesocosm mimicking nutrient application on a sandy beach and developed and published a 2-D model (MARUN) that has been used is subsequent research. More recently, we have developed a model with design nomographs that describe how much and how often nutrients need to be applied (and the method of applying them) to maintain a level that would result in maximum biostimulation. Journal articles are currently in review on this subject. The methodology requires knowledge of the hydrodynamics of groundwater and tidal flow on shorelines, and we have a unique knowledge of these important factors and interactions. Drs. Jacqui Michel and Jeff Short have conducted extensive research in PWS in regards to geomorphology and levels of contamination lingering in PWS beaches, and we will be relying on their expertise to guide us in finding the best locations to conduct our research. Thus, due to our combined expertise and experience, we are confident that the proposed investigation will answer the important question as to why oil has lingered for so long in PWS. After completing the proposed tracer studies, we should be able to propose methods to accelerate the ultimate disappearance of the lingering oil.

10.0 PUBLICATIONS AND REPORTS

The annual report for FY07 will be submitted on September 30, 2007. The draft final report will be submitted to the Trustee Council by March 31, 2009. The revised final report will be submitted by June 30, 2009. At least, six journal publications are expected from this study. These will address the hydrodynamics of PWS beaches (not thoroughly addressed in previous studies) and the limitations affecting oil biodegradation.

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12.0 DATA MANAGEMENT AND QA/QC STATMENT

12.1 Study Design

The objective of this research is to describe groundwater transport in intertidal beaches in Prince William Sound (PWS) that remain contaminated with oil from the Exxon Valdez oil spill. This will involve combining experimental measurements of hydraulic gradients and transport of a conservative tracer (lithium) on six beaches, 3 lotic and 3 lentic, with fundamental pore-scale transport modeling that can be generalized to predict solute transport in a variety of shoreline types. The tracer studies will be conducted on two beaches that are known from a previous survey to contain relatively large patches of lingering oil. Low- and high-energy beaches were selected for this study because tides and waves can affect solute transport in intertidal shorelines, and these beaches are good examples of each shoreline type.

The data collected in support of this objective will include measurement of water levels in the beach at six locations along two transects perpendicular to the shoreline on all beaches. One transect will intersect an oil patch, and the other will be installed in an oil-free control section. Water levels will be measured at 5-minute intervals using vibrating-wire piezometers. The locations of the piezometers will be determined based on preliminary modeling of the shoreline using beach slope and tidal range as inputs. A range of hydraulic conductivities will be tested to evaluate the sensitivity of the optimum locations to the assumptions. After the field crew arrives on site and completes the beach surveys, the model will be re-run using the actual beach slopes and information on the boundary conditions (e.g., depth to impermeable layers) to confirm that the best locations were selected.

In addition to measurement of water levels, water samples will be collected from four depths below the beach surface at five locations along the same transects. The concentrations of nutrients (ammonia, nitrate, and phosphate), dissolved oxygen, the conservative tracer (lithium), and salt will be measured in the water samples (not all measurements will be made on every water sample). Like the piezometer locations, the well points will be installed at locations that are identified as being optimal by the solute-transport model. Optimal in this case is defined to be locations that give thorough coverage of the experimental domain and allow the model parameters to be determined with reasonable accuracy. Nutrient and oxygen concentrations will be measured in samples that will be collected over several tidal cycles before the conservative tracer is introduced into the beach, whereas lithium will be measured after the tracer is introduced. Salinity will be measured before and during the conservative tracer study.

12.2 Data Quality Acceptability

Because the tidal range in PWS is about 5 m, and the elevation difference between adjacent piezometer wells will be about 1 m, the water-level measurements must be accurate to within about 10 cm. This level of accuracy will allow adequate specification of the driving forces for water movement in the beach subsurface.

Since the concentration of the conservative tracer over the course of a tracer study will decrease by at least 95% (e.g., from about 500 mg/L to < 5 mg/L), and the background lithium concentrations are expected to be below the method detection limit, measured lithium concentrations should be accurate to within about 20% of the true concentration. Accuracy at this level will be sufficient to determine the flow rate of water through the beach subsurface in the experimental domain.

Nutrient concentrations in the beach subsurface will be compared to either (1) the concentrations that are expected to limit the growth rate of hydrocarbon-degrading bacteria or (2) the nutrient concentrations in the open water offshore of the beach. The first comparison will evaluate whether the kinetics of nutrient consumption can be responsible for the slow rate of oil biodegradation in these shorelines. The second will evaluate whether nutrients in the surrounding seawater are consumed by microorganisms fast relative to the flux rate of nutrients through the contaminated sediments. Because the nutrient concentrations that limit the rate of microbial growth are known only to about one order of magnitude (e.g., the limiting nitrogen concentration appears to be between about 0.5-5 mg N/L), and the concentration of nutrients in the shoreline sediments would have to decrease by about 90% to consider nutrient flux to be a limiting factor, nutrient concentration measurements that are accurate within about 20% of the true value will be adequate.

Dissolved oxygen (DO) concentrations in beach pore water will be compared to the concentrations in the surrounding seawater, which are expected to be near saturation. Since DO concentrations must be less than about 2 mg/L to limit the rate of aerobic microbial growth and the saturation concentrations are on the order of 8-10 mg/L (depending on temperature and salinity), the accuracy of DO concentration measurements should be within about 20% of the true value.

12.3 Sensor Algorithms

The Solinst Levelogger Gold piezometers measure pressure. Pressure (P, psi) can be converted to water depth (Z, m) using the following equation:

$$Z = \frac{P}{\rho}\left(0.705\ \mathrm{g \cdot m/cm^3 \cdot psi}\right)$$

where ρ (g/mL) is the water density:

$$\rho = \rho_o\left(1 + \varepsilon C\right)$$

where C (g/L) is the salinity and ρ_o is the density of deionized water at the given temperature. The conversion factor, ε, is approximately 7.4×10^{-4} L/g. By calibrating the electrical conductivity to salinity, one would be able to predict the density based on electrical conductivity measurements.

12.4 Sample Handling, Preservation, and Storage

Conservative tracer and nutrient samples will be preserved and stored after collection. At the end of the field study, the samples will be shipped from Whittier, AK to the Temple University analytical laboratory. Nutrient samples will be filtered through 0.45 μm syringe filters immediately after collection (during transfer of the sample to the storage bottle). Filtration is not necessary for lithium samples. All tracer and nutrient samples will be stored in acid-washed, rinsed, high-density polyethylene bottles. Nutrient samples will be stored frozen and shipped by air packed in dry ice. Lithium samples will be acidified by addition of 0.2 mL of concentrated sulfuric acid per 100 mL. Lithium samples can be stored and shipped at room temperature.

Salinity and dissolved oxygen will be analyzed on board the support vessel. No preservation is required, and samples will be analyzed within 6 hours of collection. Dissolved oxygen will be measured by the Winkler titration, and the reagents (manganous sulfate and alkali-iodide-azide solutions) will be added immediately upon arrival on board the ship. Once the dissolved oxygen has reacted with Mn(II) to form manganese dioxide, the samples will be stable and can be processed at a more leisurely pace, but they must be sealed without headspace to prevent contamination of the solution with atmospheric oxygen. Samples collected for measurement of salinity are stable and require no special handling.

12.5 Calibration Procedures

All piezometers will be calibrated after they arrive in Valdez and after completion of the field study. Pressure measurements will be calibrated by measuring the response of each sensor upon immersion at the bottom of a 2-m column of fresh water. The temperature response of the piezometers will also be calibrated by measuring the water temperature with an NIST-traceable calibrated digital thermometer. The 2-m water column will be contained in a PVC pipe that is sealed at one end and held vertical in a stable frame.

The dissolved oxygen measurements involve titration with sodium thiosulfate. The thiosulfate concentration will be determined by standardization using potassium biiodate as the primary standard (APHA, 1997). The thiosulfate solution will be standardized every day that it is used.

The conductivity meter will be calibrated daily using a commercially available certified standard solution. A five-point calibration curve will be prepared by analyzing standard solutions prepared by dilution of the commercial standard solution with reagent-grade deionized water. A check standard and reagent blank will be analyzed at least once per 20 samples.

Lithium will be measured by atomic absorption spectrometry, and the method will be calibrated by generating an external five-point calibration curve. The standards will be prepared using a commercially available certified standard solution containing lithium carbonate. Check standards will be measured at least once per 20 samples, and one sample will be analyzed in duplicate at least once per 20 samples. Matrix interferences will be evaluated by spiking at least one sample out of every 20 with a known concentration of lithium in the mid range of the calibration curve. Synthetic seawater will be used for all sample dilutions. One reagent blank will be analyzed per 20 samples.

Nutrient analyses will be performed by autoanalyzer (gas-segmented continuous-flow colorimetric analysis). The measurements will be calibrated as described in Methods 349.0, 353.4, and 365.5 for ammonia, nitrate, and phosphate, respectively (EPA, 1997). Check standards, duplicate samples, matrix spikes, and reagent blanks will be analyzed as described for lithium, above.

12.6 Data Reduction and Reporting

Water level and tracer concentration data will be analyzed using MARUN, a 2D model for groundwater transport in intertidal shorelines. This analysis will identify patterns of groundwater flow in the beach subsurface and estimate the residence times for water at different locations in the subsurface. The data and the model will be able to identify, for example, whether groundwater flow bypasses the oil-contaminated zone.

Pore-water nutrient and dissolved oxygen concentrations will be compared to surface-water concentrations to determine whether nutrients are being consumed in the subsurface, especially in the oil-contaminated zones. Nutrient concentrations will be measured in pore water and surface water during three different tidal cycles on all beaches and the differences will be analyzed using a repeated measures ANOVA.

13.0 BUDGET JUSTIFICATION = Total Project Cost = $1,253.9

13.1 Personnel: Total = $494.7 (FY 07/$105.4)(FY 08/$213.8)(FY 09/$175.5)

Salary support is included for eight key members of the research team: Albert Venosa (Senior Research Microbiologist and co-PI), Michel Boufadel (hydrologist/environmental engineer and co-PI), Brian Wrenn (environmental scientist and co-PI), Jacqui Michel (coastal geologist), Jeff Short (senior scientist), three environmental engineering graduate students at Temple University for the duration of the project, a post-doctoral hydrologist at Temple University for modeling for 1 year, and the field crew for the duration of the tracer studies.

Dr. Boufadel will devote a total of 6 months to the project: 2 months during FY07 for planning, coordination of logistics (*e.g.*, ordering equipment and supplies), supervision of mobilization, setup, and hydraulic modeling of the shoreline, and 2 months during FY08 for planning, data analyses, additional hydraulic and solute transport modeling, report and articles preparation, and 2 months during FY09 for writing publications.

Dr. Venosa will devote a total of 2.5 months to the study: 0.5 month during FY07 for project management, planning, and reporting to the Trustee Council and 1.5 months during FY08 for project management, planning, and report preparation, and 0.5 month during FY09 for report and preparation of journal articles. Compensation for Dr. Venosa's effort will be contributed to the project as in-kind support by the U.S. EPA.

Dr. Wrenn will devote 3.5 months to the project: 1.5 months during FY07 for planning and supervision of the field study setup, 1 month during each of FY08 and FY09 for analysis of the results and report and journal article writing, and water chemistry and conservative tracer data (including QA/QC) and report preparation.

Drs. Short (0.5 months) and Michel (0.5 months) per year for FY07 and FY08 will contribute their expertise and knowledge of PWS beaches to identify appropriate study sites and provide information regarding beach profiles, oil location, and beach geomorphology to assist project PI's with preliminary modeling of the shorelines. All salary rates shown are fully loaded.

The tracer studies will generate a large amount of data (water level, lithium tracer, temperature, salinity, nutrients, and DO) for six beaches, each having two transects. Reducing these data in accordance with a rigorous Quality Assurance Plan will require two students per year. An additional graduate student and post-doc will work on the modeling. Thus, three graduate students per year for two years and a post-doc for one year are needed.

13.2 Travel: Total = $41.6

Per diem during travel via public transportation is $200/day, which will include hotels, meals, and ground transportation.

FY 07: **$14K**

Dr. Venosa will travel to Anchorage to present plan to Trustee Council and to Whittier and to help set up field study. $1.8K for ticket and $0.8K for 4 days at 0.2K/day. $2.6K.

Dr. Boufadel and four workers (the crew) will travel from Philadelphia to Whittier, AK where they will meet the support boat for the field study (5 x $1.8K = 9K). Each will have 2.5 days of per diem. At 0.2K per day, this gives 2.5 x 0.2 x 5 = 2.5K. Total is 11.6K.

Dr. Wrenn will travel from St. Louis to Whittier, AK for the field study. ($1.8K for airfare and 2.5 days x 0.2 K perdiem = $0.5 K per diem) = $2.3K.

FY 08: **$21.0K**

Dr. Venosa and Dr. Boufadel will travel to Anchorage AK to report findings of this research at the Marine Sciences Symposium in Anchorage, AK ($2K). Five days per diem for each person, totaling $4K.

Dr. Boufadel and six people (the crew) will travel from Philadelphia to Whittier, AK where they will meet the support boat for the field study. (6 x $1.8K = $10.8K). Per diem = 6 x 2.5 days x $0.2K/day or 3.6K. Total = $14.4K.

Dr. Wrenn will travel from St. Louis to Whittier, AK for the field study. ($1.8 K airfare + $0.8K per diem for four days = $2.6K)

FY 09: **$6.6K**.

Drs. Venosa and Boufadel will travel to Anchorage AK to report findings of this research at the Marine Sciences Symposium in Anchorage, AK ($2K for airfare and $2K for per diem, 5 days per person at $0.2K/day). Total = $4.0K.

Dr. Wrenn will fly to Whittier to remove the field equipment ($2.6K).

13.3 Contractual Costs: Total = $251.5 (FY 07/$72.0)(FY 08/$167.5)(FY 09/$12.0)

Funds are requested to charter a support vessel for the field study. The study is estimated to last 18 days in the summer 2007, 50 days in the summer 2008, and 4 days in the winter of 2009. The charter for a boat that can accommodate six scientists is estimated to cost $3000/day.
Dr. Jacqui Michel, President of Research Planning Inc., will assist us with the logistics into and out of Prince William Sound, and for obtaining the permits to conduct the studies in the summers of 2007 and 2008. These costs are estimated at $17.5 K per year for two years.

13.4 Commodities Costs: Total $70.5 (FY 07 Only)

Funds ($30K) are requested for supplies, which consist of bottles for nutrient and conservative tracer samples ($6 K), nitrate test strips for real-time monitoring of tracer washout ($3 K), reagents, chemicals, and supplies for shipboard analysis ($5.0 K), lithium nitrate ($3 K), a 3 kW electrical generator ($0.5 K), three electrical water pumps ($1.0 K), three pressure valves to control flow ($1.0 K), two 50-m hoses, PVC piping used for addition of the tracer to the beaches ($5 K), and shipping costs ($5.5 K).

Funds ($27.5K) are also requested for analytical costs for measuring concentrations of lithium and nutrients at Temple University.

Funds ($10K) are needed to conduct the SEM analyses on 200 samples.

13.5 New Equipment Purchases: Total $54.7 (FY 07 Only)

The conductivity meter ($2K) will be used for shipboard analysis of salinity of pore-water samples.

The four Solinst Levelogger Gold piezometers provide measurements of water pressure, temperature, and electrical conductivity during winter. They withstand temperatures of -20°C, and each can store up to 40,000 samples of the three variables. Thus, if samples are taken every 15 minutes, the sensors will accumulate data for 415 days (13.5 months), and we will be able to download the data during the following summer. Two of them will be used during the winter of 2007-2008. Four will be used the following winter (2008-2009).

Fifteen LevelLoggers to measure pressure (water level), temperature, and salinity will be used for the summer tracer studies. Twelve will be used on a beach, and the remaining three are spare.

The Solinst Barologgers, which cost $0.7K each, are needed to measure atmospheric pressure, which will provide correction for the other LevelLoggers. The Solinst LevelLoggers-Gold are equipped with automatic barometric pressure correction.

The Solinst multiport sampling wells each cost $0.8K. At times, 24 of them will be in use. We plan to order an additional 12 for spare replacement of damaged or clogged screens. We have successfully used these multiport sampling wells in previous research (Wrenn *et al*., 1997a,b).

13.6 Indirect Costs:

The indirect cost rate is 26%, which is the minimum rate that Temple University would charge for projects that require tuition remission for graduate students (i.e., the grant will not pay for students' tuition).

13.7 Trustee Agency G&A: Total = $103.5 (FY 07/$35.9)(FY 08/$45.6)(FY 09/$22.0)

Budget Category:		Authorized FY 2006	Proposed FY 2007	Proposed FY 2008	Proposed FY 2009	Proposed Total			
Personnel			$105.4	$213.8	$175.5	$494.7			
Travel			$14.0	$21.0	$6.6	$41.6			
Contractual			$72.0	$167.5	$12.0	$251.5			
Commodities			$70.5	$0.0	$0.0	$70.5			
Equipment			$54.7	$0.0	$0.0	$54.7			
Sub-Total		$0.0	$316.6	$402.3	$194.1	$913.0			
Indirect	26.0%		$82.3	$104.6	$50.5	$237.4			
Contract Total		$0.0	$398.9	$506.9	$244.6	$1,150.4			
Trustee Agency G&A	9.00%		$35.9	$45.6	$22.0	$103.5			
PJ 070836 Total			$434.8	$552.5	$266.6	$1,253.9			
Full-time Equivalents (FTE)			1.2	4.6	4.3	0.0			
		Dollar amounts are shown in thousands of dollars.							
Other Resources			$6.4	$19.8	$6.6	$32.8			

Comments:
Albert Venosa's Personnel Costs for FY 07 - FY 09 in the amount of $32.8 are provided as in-kind support by EPA, detailed above under "Other resources."

FY07-09

Prepared: Revised 2/22/07

Project Number: 070836
Project Title: Factors Responsible for Limiting the Degradation Rate of Exxon Valdez Oil in Prince William Sound Beaches
Name: Albert Venosa

FORM 4A
Non-Trustee
SUMMARY

Personnel Costs:		Months	Monthly	EPA	Proposed
Name	Position Description	Budgeted	Costs	In-Kind	FY 2007
Albert Venosa (EPA)	Senior Research Microbiologist	0.5	12.8	6.4	0.0
Michel Boufadel (Temple	Associate Professor of Environmental	2.0	16.0		32.0
	Env. Engg. Graduate Student	3.0	2.0		6.0
	Env. Engg. Graduate Student	3.0	2.0		6.0
Brian Wrenn	Environmental Engineer	1.5	16.0		24.0
	Field Crew member	0.8	4.5		3.6
	Field Crew member	0.8	4.5		3.6
	Field Crew member	0.8	4.5		3.6
	Field Crew member	0.8	4.5		3.6
Jacqui Michel (RPI)	Coastal Geologist	0.5	30.0		15.0
Jeff Short (NOAA)	Senior Scientist	0.5	16.0		8.0
					0.0
					0.0
					0.0
					0.0
	Subtotal	14.2	112.8	6.4	
				Personnel Total	$105.4

Travel Costs:	Ticket	Round	Total	Daily	Proposed
Description	Price	Trips	Days	Per Diem	FY 2007
Cincinnati-Anchorage-Whittier	1.8	1	4	0.2	2.6
Venosa to help set up field plan					
Philadelphia-Anchorage-Whittier	1.8	5	13	0.2	11.6
Travel for five people (Boufadel and four students to Whittier)					0.0
St. Louis - Whittier (RT)					0.0
Wrenn to set up tracer study	1.8	1	3	0.2	2.4
					0.0
					0.0
					0.0
					0.0
				Travel Total	$14.0

FY07

Prepared: Revised 2/22/07

Project Number: 070836
Project Title: Factors Responsible for Limiting the Degradation Rate of Exxon Valdez Oil in Prince William Sound Beaches
Name: Albert Venosa

FORM 4B
Personnel
& Travel
DETAIL

Contractual Costs:					Proposed
Description					FY 2007
Vessel Charter	18	days @	3	per day	54.0
Logistics and permits					17.5
Truck rental, Anchorage to Whitter, to load boat in Whittier					0.5
				Contractual Total	$72.0

Commodities Costs:					Proposed
Description					FY 2007
Polystyrene or fiberglass tanks	4	each @	0.5	per each	2.0
Tools for excavation	1				1.0
Supplies (chemicals, reagents, sample bottles)					30.0
Analysis of tracer (Li^+) concentration	1500	analyses @	0.01	analysis	15.0
Analysis of nutrient concentration	250	analyses @	0.05	analysis	12.5
SEM Analyses	200	analyses @	0.05	analysis	10.0
				Commodities Total	$70.5

FY07

Prepared: Revised 2/22/07

Project Number: 070836
Project Title: Factors Responsible for Limiting the Degradation Rate of Exxon Valdez Oil in Prince William Sound Beaches
Name: Albert Venosa

FORM 4B
Contractual &
Commodities
DETAIL

New Equipment Purchases: Description		Number of Units	Unit Price	Proposed FY 2007
				0.0
	Conductivity meter	1	2	2.0
	Level Logger Gold (Level, Temperature, Conductivity)	4	3.0	12.0
	Level Loggers (Level, Temperature)	15	0.7	10.5
	Barometric Pressure Logger	2	0.7	1.4
	Multiport sampling wells	36	0.8	28.8
				0.0
				0.0
				0.0
				0.0
				0.0
				0.0
				0.0
Those purchases associated with replacement equipment should be indicated by placement of an R.			**New Equipment Total**	$54.7

Existing Equipment Usage: Description	Number of Units	

FY07

Prepared: Revised 2/22/07

Project Number: 070836
Project Title: Factors Responsible for Limiting the Degradation Rate of Exxon Valdez Oil in Prince William Sound Beaches
Name: Albert Venosa

FORM 4B
Equipment
DETAIL

Personnel Costs:				Months Budgeted	Monthly Costs	EPA In-Kind	Proposed FY 2008
	Name	Position Description					
	Albert Venosa (EPA)	Senior Research Microbiologist		1.5	13.2	19.8	0.0
	Michel Boufadel (Temple	Associate Professor of Envl. Eng		2.0	16.5		33.0
		Env. Enggr. Graduate Student		12.0	2.0		24.0
		Env. Enggr. Graduate Student		12.0	2.0		24.0
		Env. Enggr. Graduate Student		12.0	2.0		24.0
	Brian Wrenn	Environmental Engineer		1.0	16.5		16.5
		Chief of field crew		2.2	9.0		19.8
		Field crew member		2.2	4.5		9.9
		Field crew member		2.2	4.5		9.9
		Field crew member		2.2	4.5		9.9
		Field crew member		2.2	4.5		9.9
		Field crew member		2.2	4.5		9.9
	Jacqui Michel (RPI)	Coastal Geologist		0.5	30.0		15.0
	Jeff Short (NOAA)	Senior Scientist		0.5	16.0		8.0
							0.0
		Subtotal		54.7	129.7	19.8	
						Personnel Total	$213.8

Travel Costs:		Ticket Price	Round Trips	Total Days	Daily Per Diem	Proposed FY 2008
	Description					
	Drs. Venosa and Boufadel to travel from Cincinnati and Philadelphia to Anchorage to present at the Marine Science Symposium	1	2	10	0.2	4.0
	Philadelphia-Anchorage-Whittier Boufadel, chief of field crew, and 5 graduate studer	1.8	6	18	0.2	14.4
	St. Louis - Anchorage-Whittier (Dr. Wrenn)	1.8	1	4	0.2	2.6
						0.0
						0.0
					Travel Total	$21.0

FY08

Prepared: Revised 2/22/07

Project Number: 070836
Project Title: Factors Responsible for Limiting the Degradation Rate of Exxon Valdez Oil in Prince William Sound Beaches
Name: Albert Venosa

FORM 4B
Personnel
& Travel
DETAIL

Contractual Costs:			Proposed
Description			FY 2008
			0.0
Charter Boat	50 days	3 per day	150.0
Logistic and Permits			17.5
		Contractual Total	$167.5

Commodities Costs:	Proposed
Description	FY 2008
	0.0
	0.0
	0.0
	0.0
Commodities Total	$0.0

FY08

Prepared: Revised 2/22/07

Project Number: 070836
Project Title: Factors Responsible for Limiting the Degradation Rate of Exxon Valdez Oil in Prince William Sound Beaches
Name: Albert Venosa

FORM 4B
Contractual &
Commodities
DETAIL

New Equipment Purchases: Description		Number of Units	Unit Price	Proposed FY 2008
				0.0
				0.0
				0.0
				0.0
				0.0
				0.0
				0.0
				0.0
				0.0
				0.0
				0.0
				0.0
Those purchases associated with replacement equipment should be indicated by placement of an R.			**New Equipment Total**	$0.0

Existing Equipment Usage: Description	Number of Units	

FY08

Prepared: Revised 2/22/07

Project Number: 070836
Project Title: Factors Responsible for Limiting the Degradation Rate of Exxon Valdez Oil in Prince William Sound Beaches
Name: Albert Venosa

FORM 4B
Equipment
DETAIL

Personnel Costs:				Months	Monthly	EPA	Proposed
	Name	Position Description		Budgeted	Costs	In-Kind	FY 2008
	Albert Venosa (EPA)	Senior Research Microbiologist		0.5	13.2	6.6	0.0
	Michel Boufadel (Temple	Associate Professor of Envl Eng		2.0	16.5		33.0
		Env. Enggr. Graduate Student		12.0	2.0		24.0
		Env. Enggr. Graduate Student		12.0	2.0		24.0
		Env. Enggr. Graduate Student		12.0	2.0		24.0
		Postdoc		12.0	4.5		54.0
	Brian Wrenn	Environmental Engineer		1.0	16.5		16.5
							0.0
							0.0
							0.0
							0.0
							0.0
							0.0
							0.0
		Subtotal		51.5	56.7	6.6	
						Personnel Total	$175.5

Travel Costs:		Ticket	Round	Total	Daily	Proposed
	Description	Price	Trips	Days	Per Diem	FY 2008
	Cincinnati -Philadelphia- Anchorage (RT)	1.0	2	10	0.2	4.0
	Venosa and Boufadel to present at Marine Science					0.0
	Symposium					0.0
						0.0
	St. Louis-Anchorage-Whittier	1.8	1	4	0.2	2.6
	Wrenn to remove equipment from beaches					0.0
						0.0
					Travel Total	$6.6

FY09

Prepared: Revised 2/22/07

Project Number: 070836
Project Title: Factors Responsible for Limiting the Degradation Rate of Exxon Valdez Oil in Prince William Sound Beaches
Name: Albert Venosa

FORM 4B
Personnel
& Travel
DETAIL

Contractual Costs:			Proposed
Description			FY 2008
			0.0
Charter boat for removal of equipment	4 days	3	12.0
		Contractual Total	$12.0

Commodities Costs:	Proposed
Description	FY 2008
	0.0
	0.0
	0.0
	0.0
Commodities Total	$0.0

FY09

Prepared: Revised 2/22/07

Project Number: 070836
Project Title: Factors Responsible for Limiting the Degradation Rate of Exxon Valdez Oil in Prince William Sound Beaches
Name: Albert Venosa

FORM 4B
Contractual &
Commodities
DETAIL

New Equipment Purchases:		Number of Units	Unit Price	Proposed FY 2008
Description				
				0.0
				0.0
				0.0
				0.0
				0.0
				0.0
				0.0
				0.0
				0.0
				0.0
				0.0
				0.0
				0.0
Those purchases associated with replacement equipment should be indicated by placement of an R.			**New Equipment Total**	$0.0

Existing Equipment Usage:	Number of Units	
Description		

FY09

Prepared: Revised 2/22/07

Project Number: 070836
Project Title: Factors Responsible for Limiting the Degradation Rate of Exxon Valdez Oil in Prince William Sound Beaches
Name: Albert Venosa

FORM 4B
Equipment
DETAIL

ABBREVIATED RESUMES OF PI's

Michel C. Boufadel, PhD., PE
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Philadelphia, Pennsylvania 19122
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Education:	1998, Ph.D., Environmental Engineering, University of Cincinnati 1992, M.S., Environmental Engineering, University of Cincinnati 1988, B.S., Hydraulic Engineering, Jesuit University at Beirut, Lebanon.
Current Position:	Chair and Associate Professor of Environmental Engineering
Research Interests:	Environmental Hydrology and Hydraulics, Remediation of oil spills, Solute transport in multimedia.

Professional Affiliations: American Society of Civil Engineers, American Geophysical Union.

Reviewer for: Environmental Science and Technol., ASCE J. Env. Engrg.,. NOAA's Coastal Resource Research Center, National Science Foundation.

INVITED TALKS

"Nutrients transport during bioremediation of oil spills on beaches", "Solute transport in multifractal porous media", or "The use of dispersants on oil spills"
•Department of Civil and Environmental Engineering, Villanova University, 2006.
•Department of Civil and Environmental Engineering, Georgia Tech, 2002.
•Department of Civil, Env., and Coastal Engineering, Univ. of Delaware, 2002.
•Department of Civil and Environmental Engineering, Lehigh University, 2001.
•Department of Civil and Environmental Engineering, Auburn University, 2001.
•Department of Civil and Environmental Engineering, Temple University, 1999.
•Department of Civil and Environmental Engineering, Virginia Tech, 1999.
•Department of Civil and Environmental Engineering, University of South Carolina, 1999.
•Environmental Engineering and Science Department, Clemson University, 1998.
•Department of Civil and Environmental Engineering, University of Cincinnati, 1998.

"Stationary versus nonstationary stochastic models of subsurface heterogeneity", Hydrology Symposium I, Modeling Aquifer Heterogeneity, University of South Carolina, January 2000.

"Multifractal anisotropic scaling of the hydraulic conductivity: Effects of method of analysis and data limitation" In Hydrofractals, European Geophysical Society, Nice, France, March 2001.

FIVE RECENT PUBLICAITONS

1) Boufadel, M.C., H. Li, M.T. Suidan, and A.D. Venosa. "Tracer studies in a laboratory beach subjected to waves". J. Environmental Engineering, ASCE, in press, 2007.

2) Boufadel, M.C., M.T. Suidan, and A.D. Venosa. "Tracer studies in a laboratory beach simulating tidal influences". J. Environmental Engineering, ASCE, 132(6):616-623, 2006.

3) Naba, B. (Graduate student), M. C. Boufadel, and J. Weaver, The role of capillary forces in steady-state and transient seepage flows, Ground Water, 40 (4), 407-415, 2002.

4) Boufadel, M. C. and V. Peridier, Exact analytical expressions for the piezometeric profile and water exchange between streamwater and groundwater during and after a uniform rise of the stream level, Water Resources Research, 7, 2002.

5) Boufadel, M. C. "A mechanistic study of nonlinear solute transport in a groundwater-surface water system under steady-state and transient hydraulic conditions", Water Resources Research, Vol. 36, p 2549-2566, 2000.

OTHER SIGNIFICANT PUBLICATIONS

1) Li, H., L. Li, D. Lockington, M. C. Boufadel, and G. Li, Modelling tidal signals enhanced by a submarine spring in a coastal confined aquifer extending under the sea, Advances in Water Resources, in press 2007.

2) Boufadel, M.C., Ryan Daniel Bechtel, and J. Weaver, The movement of oil under non breaking waves, Marine Pollution Bulletin, (52) 1056-1065, 2006.

3) Ryan, R. J., and M. C. Boufadel, The role of subsurface heterogeneity in controlling hyporheic exchange in streams, Environmental Geology, August, 2006.

4) Ge. Y. (Graduate Student) and M. C. Boufadel, Solute transport in multiple-reach experiments: Evaluation of parameters and reliability of predictions, J. of Hydrology, 323, 106-119, 2006.

5) Tennekon, L. (Graduate student), M. C. Boufadel, J. Weaver, and D. Lavallee, Multifractal anisotropic scaling of the hydraulic conductivity, Water Resources Research, 39(7), 2003.

LIST OF COLLABORATORS OVER PAST 48 MONTHS

Lavallee, D. (UC Santa Barbara), Lee, K. (Fisheries & Oceans, Canada), Michel, J. (RPI), Short, J. (NOAA), Suidan, M. (University of Cincinnati), Venosa, A. (USEPA), Weaver, J. (USEPA), Wrenn, B. (U. of Washington, St. Louis).

ALBERT D. VENOSA

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EDUCATION

1980	Ph.D., Environmental Science, University of Cincinnati
1968	M.S., Environmental Engineering, University of Cincinnati
1967	B.S., Microbiology, University of Cincinnati

PROFESSIONAL EXPERIENCE

Program Manager, Oil Spill Research Program, 1990 to present, U.S. EPA, Remediation and Restoration Branch, Land Remediation and Pollution Control Division, NRMRL, Cincinnati

Team leader, 1989 and 1990. Alaska Oil Spill Bioremediation Project involved with assessing effectiveness of nutrient formulations in the field and in 1990 led an independent analysis of commercial inocula in multiple field plots

Program Co-manager, Biosystems Technology Development Steering Committee, 1988 to 1996, U.S. EPA, Treatment and Destruction Branch, Land Remediation and Pollution Research Division, NRMRL, Cincinnati

Program Manager, Sludge Pathogen Program, 1986 to 1990, U.S. EPA, Sludge Technology Section, Municipal Wastewater Branch, Water and Hazardous Waste Treatment Research Division, Risk Reduction Engineering Laboratory, Cincinnati

Program Manager, Municipal Wastewater Disinfection Program, 1975 to 1986, U.S. EPA, Wastewater Treatment Division, Water Engineering Research Laboratory, Cincinnati

PROFESSIONAL SOCIETIES & PUBLICATION BOARDS

Society of the Sigma Xi
American Society for Microbiology
Society for Industrial Microbiology
Water Environment Federation

REVIEWER FOR:

Environmental Science & Technol., Bioremediation Journal, Biodegradation, Chemosphere, Pedosphere, J. Ind. Microbiol. Biotechnol., Canadian J. Microbiol., ASCE J. Env. Engrg., J. Env. Qual., numerous other journals. NOAA's Coastal Resource Research Center, State of Louisiana's Oil Spill Research and Development Program, Integrated Petroleum Env. Consortium.

RECENT PUBLICATIONS

Venosa, A.D. and E.L. Holder. 2007. “Biodegradability of dispersed oil at two different temperatures. Marine Pollution Bulletin, in press.

Venosa, A.D. and X. Zhu. 2005. “Guidance for the Bioremediation of Oil-Contaminated Wetlands, Marshes, and Marine Shorelines” In: S. Fingerman, Ed. Bioremediation of aquatic and terrestrial ecosystems. Science Publishers, Inc. Enfield, New Hampshire, in press.

Venosa, A.D. and X. Zhu. 2003. “Biodegradation of crude oil contaminating marine shorelines and freshwater wetlands.” Spill Sci. & Technol. Bulletin 8(2):163-178.

Venosa, A.D., K. Lee, M.T . Suidan, S. Garcia-Blanco, S. Cobanli, M. Moteleb, J.R. Haines, G. Tremblay, and M. Hazelwood. 2002. “Bioremediation and Biorestoration of a Crude Oil-Contaminated Freshwater Wetland on the St. Lawrence River,” Bioremediation Journal, 6(3):261-281.

Venosa, A.D., K. Lee, M.T. Suidan, S. Garcia-Blanco, S. Cobanli, M. Moteleb, J.R. Haines, G. Tremblay, and M. Hazelwood. 2002. Bioremediation J. 6(3):261-281.

Venosa, A.D., King, D.W., and Sorial, G.A. 2002. “The Baffled Flask Test for Dispersant Effectiveness: A Round Robin Evaluation of Reproducibility and Repeatability,” Spill Science & Technology Bulletin, 7(5-6), 299-308.

LIST OF COLLABORATORS OVER LAST 48 MONTHS

K. Lee (Fisheries and Oceans Canada), Z. Li (Fisheries and Oceans Canada), P. Kepkay (Fisheries and Oceans Canada), M. Boufadel (Temple University), B. Wrenn (Washington University St. Louis), M. Suidan (University of Cincinnati), J. Michel (Research Planning, Inc.), J. Short (NOAA), J. Weaver (U.S. EPA, Athens, GA)

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EDUCATION

1980	B.S.	Biochemistry/Chemistry	University of Illinois, Urbana-Champaign
1984	M.S.	Biological Oceanography	University of Miami (FL)
1992	Ph.D.	Environmental Science	University of Illinois, Urbana-Champaign
1992-1995		Postdoctoral Associate	University of Cincinnati (OH)

PROFESSIONAL EXPERIENCE

1998 – present	Assistant Professor, Civil Engineering Department, Washington University, St. Louis, MO
1995 – 1998	Vice-President, Environmental Technologies & Solutions, Inc., Rochester, NY
1992 – 1995	Post-Doctoral Research Associate, Dept. of Civil and Environmental Engineering, University of Cincinnati, Cincinnati, OH
1986 – 1991	Graduate Research Assistant, Dept. of Civil Engineering, University of Illinois, Urbana-Champaign, Urbana, IL
1984 – 1986	Scientist, Central Research and Development Department, DuPont, Inc., Wilmington, DE
1980 – 1984	Technician, Ocean Chemistry and Biology Laboratory, NOAA, Miami, FL

TEACHING AND RESEARCH INTERESTS

bioremediation, biological treatment of industrial and hazardous wastes**,** water and wastewater treatment**,** environmental microbiology and biodegradation**,** environmental and analytical chemistry**,** biodegradation kinetics

FIVE PUBLICATIONS MOST CLOSELY RELATED TO PROPOSED RESEARCH

Wrenn, B.A., M.T. Suidan, K.L. Strohmeier, B.L. Eberhart, G.J. Wilson, and A.D. Venosa. 1998. Influence of tide and waves on washout of dissolved nutrients from the bioremediation zone of a coarse-sand beach: application in oil-spill bioremediation. Spill Science & Technology Bulletin 4: 99-106.

Wrenn, B.A., M.T. Suidan, K.L. Strohmeier, B.L. Eberhart, G.J. Wilson, and A.D. Venosa. 1997. Nutrient transport during bioremediation of contaminated beaches: evaluation with lithium as a conservative tracer. Water Research 31: 515-524.

Wrenn, B.A., K.L. Sarnecki, E.S. Kohar, K. Lee, and A.D. Venosa. 2006. Effects of nutrient source and supply on crude oil biodegradation in continuous-flow beach microcosms. J. Environ. Engin. (ASCE) 132: 75-84.

Boufadel, MC., P. Reeser, M.T. Suidan, B.A. Wrenn, J. Cheng, X. Du, T.L. Huang, and A.D. Venosa. 1999. Optimal nitrate concentration for the biodegradation of n-heptadecane in a variably saturated sand column. Environ. Technol. 20: 191-199.

Venosa, A.D., M.T. Suidan, B.A. Wrenn, K.L. Strohmeier, J.R. Haines, B.L. Eberhart, D. King, and E. Holder. 1996. Bioremediation of an experimental oil spill on the shoreline of Delaware Bay. Environ. Sci. Technol. 30: 1764-1775.

Wrenn, B.A., J.R. Haines, A.D. Venosa, M. Kadkhodayan, and M.T. Suidan. 1994. Effects of nitrogen source on crude oil biodegradation. J. Ind. Microbiol. 13: 279-286.

OTHER SIGNIFICANT PUBLICATIONS

Li, Z., B.A. Wrenn, and A.D. Venosa. 2005. Effect of iron on the sensitivity of hydrogen, acetate, and butyrate metabolism to inhibition by long-chain fatty acids in vegetable-oil-enriched freshwater sediments. Water Res. 39: 3109-3119.

Li, Z., B.A. Wrenn, and A.D. Venosa. 2005. Anaerobic biodegradation of vegetable oil and its metabolic intermediates in oil-enriched freshwater sediments. Biodegradation 16: 341-352

Li, Z. and B.A. Wrenn. 2004. Effects of ferric hydroxide on the anaerobic biodegradation kinetics and toxicity of vegetable oil in freshwater sediments. Water Res. 38: 3859-3868.

Wincele, D.E., B.A. Wrenn, and A.D. Venosa. 2004. Sedimentation of oil-mineral aggregates for remediation of vegetable oil spills. J Environ. Engin. (ASCE) 130: 50-58.

Angenent, L.T., K. Karim, M.H. Al-Dahhan, B.A. Wrenn, and R.Domiguez-Espinosa. 2004. Production of bioenergy and biochemicals from industrial and agricultural wastewater. Trends Biotechnol. 22: 477-485.

SYNERGISTIC ACTIVITIES

- Member of NRC Committee on Understanding Oil Spill Dispersants: Efficacy and Effects (2004-2005)
- Member of ASCE Natural Attenuation Task Committee (1999-2000) and contributing author to *Natural Attenuation of Hazardous Wastes* (2004, ASCE Press)
- Mentor for Lemelson-MIT InvenTeams project at Nerinx Hall High School (Webster Groves, MO) – Invention of an integrated water treatment and transport apparatus for use by women in rural villages in developing nations (2005-2006)
- Conducted demonstrations of environmental engineering for middle and high school students as part of "Women in Engineering Day" (1999-2003)
- PI for REU Program in Environmental Engineering Science (2002-present); lead workshops on experimental design and data analysis, tours of environmental engineering facilities, organize seminar series and Undergraduate Research Symposium

LIST OF COLLABORATORS OVER PAST 48 MONTHS

M. Boufadel (Temple University), K. Lee (Fisheries & Oceans, Canada), A. Venosa (U.S. EPA), J. Short (NOAA), J. Michel (RPI), D. Walker (National Research Council), E. Adams (MIT), Y. Addassi (CA Dept. Fish & Game), T. Copeland, M. Greeley (ORNL), B. James (Shell), B. McGee (Chesapeake Bay Foundation), C. Mitchelmore (U. Maryland), Y. Onishi (PNNL), J. Payne (PECI), D. Salt (OSRL), D. Giammar (Wash U), P. Biswas (Wash U), L. Angenent (Wash U), Z. Li (Fisheries & Oceans Canada), D. Wincele (ERM, Inc.), K. Karim, M.H. Al-Dahhan (Wash U), R.Domiguez-Espinosa.