Evaluation of Oil Removal from Beaches 8 Years after the Exxon Valdez Oil Spill

Christine Brodersen, Jeffrey Short, Larry Holland, Mark Carls, Jerome Pella,
Marie Larsen, and Stanley Rice
Auke Bay Fisheries Laboratory
National Marine Fisheries Service, NOAA
Juneau, Alaska, USA
Jeff.Short@noaa.gov

Abstract

We monitored the efficacy of a cleaning method applied to 8-year-old spill oil from the *Exxon Valdez* that remained on armored portions of beaches in Prince William Sound, Alaska. Removal of oil was attempted in summer 1997 by high-pressure injection of PES-51®* into 10,000 m^2 of beach used historically for subsistence food-gathering.

Cleaning efficacy was evaluated by comparing amounts of oil beneath treated and un-treated quadrats before and within a month after cleaning, and again 1 year later. Material within each quadrat was excavated to below the depth of oil penetration, and the oil was extracted with dichloromethane and measured gravimetrically. Initial oil coverages ranged from 0.5 to 12 kg/m^2.

Cleaning resulted in a mean oiling reduction of 62% at treated quadrats 2 weeks following cleaning, which was significantly greater than reductions observed at un-treated reference quadrats. Further reduction occurred during the ensuing year, and the resultant of combined reduction was also significantly greater than at reference quadrats. However, the appearance of new visibly oiled sites exposed by winter storms the year following the 1997 cleanup indicates that substantial oil was buried and inaccessible to this cleanup technique.

1.0 Introduction

Oil stranded on gravel beaches following catastrophic spills can become a chronic pollution source. Crude oil forced into interstices of these beaches by high-energy waves has persisted for a decade following the 1989 *Exxon Valdez* oil spill (EVOS) in Prince William Sound (PWS), Alaska, and much of the remaining oil is still fluid at ambient conditions (Hayes and Michel, 1999). Toxic polycyclic aromatic hydrocarbons (PAH) may leach from remaining oil pockets to contaminate adjacent intertidal biota, including developing fish embryos (Murphy *et al*., 1999; Heintz *et al*., 1999; Carls *et al.*, 1999) and bivalves (Babcock *et al.*, 1996; Harris *et al.*, 1996). The latter may provide a PAH exposure route to bivalve predators through ingestion. Visual evidence of oil remaining on some of these beaches also contributes heavily to perceptions among subsistence food-gatherers that adjacent biota may not be fit for human consumption. Assessment of the likely persistence of the remaining oil, and of methods that promote elimination of it are consequently of considerable interest.

When spilled oil is introduced into cobble or boulder beaches under high-energy wave conditions, the subsurface oil may become protected from weathering.

*Reference to trade names does not imply endorsement by National Marine Fisheries Service, NOAA

The surface layer of cobbles or boulders serves to protect the subsurface oil from dispersion until the beach is again exposed to high-energy waves, which may disturb only a portion of the remaining oil (Hayes and Michel, 1999). Thus, stranded pockets of relatively unweathered interstitial oil can act as toxic reservoirs that could persist for years until dispersed by disturbances.

Methods for measuring the persistence oil on a beach are constrained by the notoriously high variability that typically characterizes the distribution of the oil (Owens and Robson, 1987). Oil can persist in scattered patches of varying size within some range of tidal exposure, and some these patches may be visible at the surface while other are entirely subsurface. A simple random sample of such a beach can lead to a statistically valid estimate of the oil content of the beach as a whole, but adequate precision may be prohibitively expensive (Humphrey *et al.*, 1991), especially on beaches armored by cobbles or boulders. Blocked sampling designs may greatly reduce variability by restricting sampling to visibly oiled portions of the beach, but extrapolation of estimates is restricted by the criteria used for blocking. However, a blocked design may be appropriate for investigation of the extent to which particular oiled portions of a beach become less oiled at a later time, as a result of natural oil-dispersion or human removal.

We report here our assessment of the efficacy of an oil-removal method applied to beaches in 1997 that remained oiled following initial clean-up attempts for the EVOS in PWS. These beaches had been heavily oiled in 1989 following the EVOS, and despite intensive clean-up attempts through 1991, the oil has remained readily evident on casual inspection after 8 years. The latest clean-up effort in 1997 came at the request of the local subsistence-use community, and involved the high-pressure injection of surfactant to mobilize remaining visible patches of oil. Our objective was to assess whether the treatment method resulted in more oil being lost from treated patches compared with un-treated patches. To evaluate changes, bulk oil per unit area beneath visibly oiled patches was measured in quadrats of a blocked sampling design that focused exclusively on these patches.

2.0 Methods

2.1 Study Area

The oiled beaches are all located on Evans and Latouche Islands in PWS, Alaska (Figure 1). These northeasterly-facing beaches were all heavily oiled in 1989 as oil spilled from the T/V *Exxon Valdez* traveled southwesterly out of PWS. The surface of these beaches reposes at about 4° and consists of cobbles to boulders ($\phi <$ -7, Udden-Wentworth scale in Lewis, 1984) overlying finer sediments above a bedrock platform. The maximum oil penetration reached about 1 meter below the beach surface during the summer of 1989 (Hayes and Michel, 1999), but most of the remaining oil was within about 20 cm of the surface at the sites we sampled in 1997. Attempts to promote oil removal from these beaches included hot-water washing, bioremediation, and mechanical relocation ending in 1992. Most of the visible oiled patches remaining before cleaning in 1997 ranged from about 1 - 10 m^2 in area, and were located within a 1 - 2 vertical meter interval in the upper intertidal among the larger boulders. Most of these patches were aggregated within 3 nearly contiguous areas, 550, 450 and 100 m long, on beach segments LA020-B and LA020-C at Sleepy Bay (see Figure 1). The remaining patches were aggregated within smaller segments at Sleepy Bay (segments LA015-C and LA017-A) or on Evans Island (EV037-A and EV039-A). Other smaller and more widely scattered oiled patches were found outside these aggregates, but are not considered in this study.

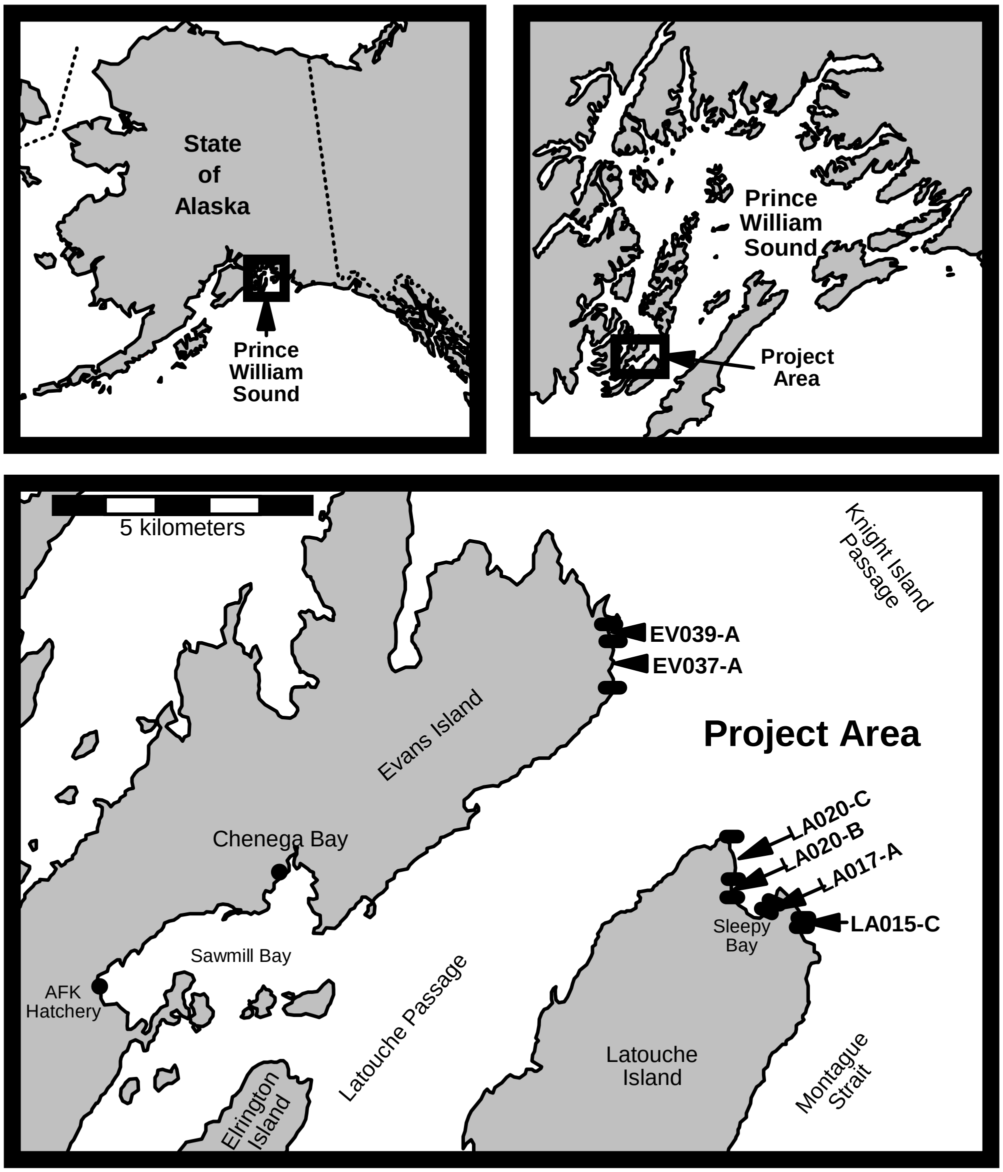

Figure 1. Map of Prince William Sound and study area.

Most of the oil in this area is between and below cobbles and boulders ($\phi <$ -7). Some of the oil is asphaltic to depths of several cm, but most consists of mobile oil mixed with gravel and sediment ($-6 < \phi < 4$), just below a thin asphaltic surface.

Oiled patches in two of the beach areas were not cleaned in 1997, and served as reference sites to assess the effects of natural factors on oil persistence. These areas included all of beach segment LA017-A, and a small portion of segment LA020-C that was beyond reach of the cleaning equipment. We denote these as "reference areas".

Oiled patches outside the reference areas were cleaned during the interval 17 June - 19 July 1997. Cleaning consisted of injection of PES-51® by compressed air to depths of about 0.5 m beneath oiled patches that occupied the interstices of the larger cobbles and boulders on the beach surface. PES-51® is a proprietary product described by the manufacturer as comprising two fractions: a *d*-limonene carrier fraction, and a second fraction consisting of exopolysaccharides, proteins and rhamnolipid byproducts of bacterial fermentation.

2.2 Sampling Design and Collection

The sampling strategy corresponded to a randomized block design within treated and reference areas, where each site was a block and quadrats within blocks were randomly assigned to sampling times – before cleaning, 1-month post-cleaning, and 1-year post-cleaning. Each site was approximately 3 m or less in diameter, and included a minimum of 3 oil patches sufficiently large to place 1/16 m^2 quadrats (Figure 2). Rock outcrops and boulders ($\phi < -9$) were not considered part of a site for purposes of quadrat placement. All sites that satisfied these criteria were included in this study: 54 sites later cleaned, and 9 sites in the reference areas not cleaned.

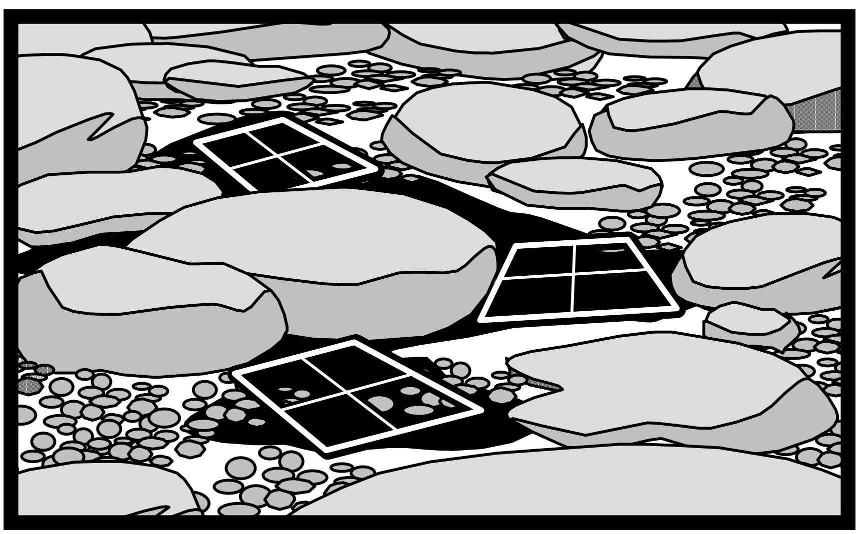

Figure 2. Typical sampling site.

The location and extent of each site, and of each randomly-placed quadrat within the site, was mapped and recorded as distances from at least 2 fixed eyehooks attached to living trees on the shoreline at an intersection angle of at least 30°, which allowed identification of points on the beach at a precision of about ± 5 cm. Each site with emplaced quadrats was photographed, and in many cases location precision was greatly improved by reference to previous site photographs. Each quadrat supplied one sample within a site (= block).

After initial random placement of the 3 quadrats within a site, their order of sampling was randomly assigned. Sampling order here refers to sampling: (1) before cleaning during the interval 20 - 25 May 1997, (2) following cleaning during the interval 16 - 22 July 1997, or (3) a year later during 23-29 May 1998. The first quadrat was then sampled, and the other two quadrats were either left undisturbed (in reference areas) or exposed to cleaning (in treatment areas). During the later sampling intervals, the unsampled quadrats were located in their original positions according to map coordinates and photographs. Each site was also photographed at each sampling to evaluate site disturbance during the intervening period. Note that with this sampling design, the expected value of changes in beach oiling between quadrats sampled initially and those sampled later within the same site are zero under the null hypothesis that neither natural factors nor cleaning affect oil persistence.

Sampling consisted of collecting all sediment beneath a quadrat to below the layer of oil or until encountering immovable rock. Oil was scraped from larger rocks into the collection bucket, and smaller rocks were included in the collected material. If the collected sample weighed more than about 5.5 kg, it was thoroughly mixed and subsampled (by weight) to about 5 kg.

2.3 Sample Analysis

Each sample was extracted with 3 successive 1 L aliquots of dichloromethane (DCM). Sample and DCM were stirred for 2 h during the first extraction, 4 h during the second, and 8 h during the third. Each extract was decanted sequentially through a 250 µm sieve containing 100 ml of sodium sulfate, a 63 µm sieve, and a funnel with a glass wool plug. The DCM was evaporated on a steam bath, and the oil residue weighed. Results are presented as kg of oil/m^2 of beach surface, denoted hereafter as beach oiling. In addition, six oil samples from each collecting trip were further analyzed by GC/MS (see Short et al., 1996 for methods) to determine PAH concentrations for oil source verification and comparison of weathering state as described by Short and Heintz (1997).

2.4 Statistical Analysis

Tests were conducted to determine if (1) the treated and reference areas differed in beach oiling prior to the treatment; (2) changes in oiling could be detected between initial sampling and later times; and (3) oiling reduction in the treated areas was greater than in the reference area. Standard one- and two-sample t-statistics were computed for these tests, but their statistical significance was evaluated empirically rather than by reference to standard tables. Certain assumptions underlying standard tables, particularly normality of observations, were dubious for at least some of the data. Therefore, statistical significance was determined by the randomization method (Edgington 1980), whereby the distribution of an arbitrary test statistic under the null hypothesis (null distribution) can be evaluated exactly by computing its value for all possible permutations of the observations between test groups. In our applications, the numbers of possible permutations were very large, so a large sample of 1000 random permutations was used to approximate the null distribution. Each random permutation was obtained by randomly partitioning the available observations between the test samples without regard to actual group membership, but with numbers in the partitions equal to the original sample sizes. The test statistic was evaluated for each such permutation. With the one-tailed tests used, the significance of the statistic from the observed sample was the proportion of the 1000 permutation values that were larger.

Levels of beach oiling in the treated and reference areas prior to treatment were compared from a two-sample test for equality of means for the measurements at first sampling with statistic computed as:

$$t = \frac{\bar{y}_T - \bar{y}_R}{s_p\sqrt{\frac{1}{54}+\frac{1}{9}}} \quad \text{where} \quad s_p^2 = \frac{\sum_{k=1}^{k=54}(y_{T,k} - \bar{y}_T)^2 + \sum_{k=1}^{k=9}(y_{R,k} - \bar{y}_R)^2}{54 + 9 - 2} \qquad (1)$$

and $\bar{y}_T$ and $\bar{y}_R$ denote the sample means of individual observations, $y_{T,k}$ ($k=1,2,\ldots,54$) and $y_{R,k}$ ($k=1,2,\ldots,9$), for the treated and reference areas, respectively. The significance of the test was evaluated by randomly permuting the 63 values to two groups of size 54 and 9. At each permutation, the t-statistic was computed. We denote this test as randomization test I.

Changes in oiling between initial and later samplings at 1-month and 1-year following the cleaning were evaluated by one sample tests for either area. These tests for change used the observed percent change of beach oiling within each site of the treated and reference areas, which was calculated as:

$$z_{ijk} = \left(\frac{y_{i1k} - y_{ijk}}{y_{i1k}}\right) 100\%, \quad j = 2,3 \qquad (2)$$

where *i* indicates the area (*i*=T, treated; or *i*=R, reference), *j* indicates the sampling time (*j* = 1, before cleaning; *j* = 2 or 3, 1-month or 1-year following cleaning, respectively), *k* indicates the site, and y_{i1k} indicates the amount of oil measured initially at site *k* within area *i*. A test for difference from zero in the mean percentage change of beach oiling within treated and reference areas used the one-sample t-statistic:

$$t_{i,j>1} = \frac{\bar{z}_{ij}}{s_{ij}/\sqrt{n}} \quad \text{where} \quad s_{ij}^2 = \frac{1}{n-1}\sum_{k=1}^{n}(z_{ijk} - \bar{z}_{ij})^2 \qquad (3)$$

and *n* is the number of sites in the area. The statistical significance of the difference was determined by randomly permuting the observations within each site to initial or later sampling without regard to when they were actually obtained. We denote this test as randomization test II.

Differences in percent change between the treated and reference areas at 1-month or 1-year sampling times were tested using the two-sample *t*-statistic:

$$t_{j>1} = \frac{\bar{z}_{Tj} - \bar{z}_{Rj}}{\sqrt{\left(\frac{s_j^2}{54} + \frac{s_j^2}{9}\right)}} \quad \text{where} \quad s_j^2 = \frac{\sum_{k=1}^{54}(z_{Tjk} - \bar{z}_{Tj})^2 + \sum_{k=1}^{9}(z_{Rjk} - \bar{z}_{Rj})^2}{54 + 9 - 2} \qquad (4)$$

A one-tailed test was performed for each of the two sampling times after cleaning–within a month and at a year. We denote this test as randomization test III.

3.0 Results

Before cleaning, beach oiling (kg of oil/m^2 of beach surface) was lower at the treatment sites compared to the reference sites. At the reference sites the mean beach oiling was 4.4 kg/m^2 (range 1.6 - 7.6 kg/m^2, n = 9), compared to a mean of 2.9 kg/m^2 (range 0.5 - 12.6 kg/m^2, n = 54) at the treatment sites (Figure 3A). This difference was just significant (P = 0.0475, randomization test I), indicating the presence of about 52% more oil per unit surface area at the reference sites compared to the sites to be cleaned. The measured concentrations of oil in samples from combined treatment and reference sites ranged from 0.6 to 63.3 g oil/kg sediment.

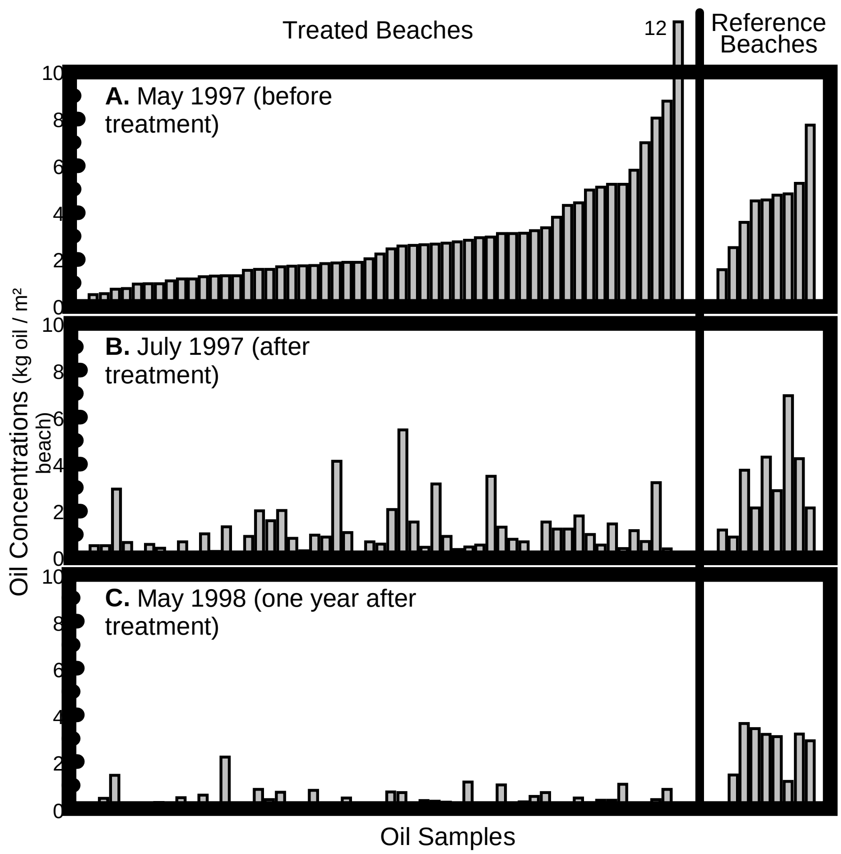

Figure 3. Beach oiling at treated and reference sites A: before cleaning, ordered from lowest to highest oiling, B: immediately following cleaning, and C: one year later. Vertically aligned bars in panels A - C are from the same sampling site.

Beach oiling declined significantly in both treatment and reference sites immediately following cleaning ($P<0.001$, randomization test II; Figure 3A&B). The mean of the reference sites declined by 28% to 3.2 kg/m^2 (range 0.9 - 6.9 kg/m^2 , n = 9). The mean of the treatment sites declined by 62% to 1.1 kg/m^2 (range 0.02 - 5.5 kg/m^2 , n = 54). The increased decline of the treatment sites compared with the reference sites was also significant ($P < 0.001$, randomization test III).

Additional declines of beach oiling occurred during the ensuing year (Figure 3C). At the reference sites in May, 1998, the mean beach oiling was 2.5 kg/m^2 (range 0.2 - 3.6 kg/m^2 , n = 9), or 56% of the initial mean. At the treatment sites, the mean was 0.4 kg/m^2 (range <0.01 - 2.2 kg/m^2 , n = 54), or 14% of the initial mean, and both declines from initial sampling were significant ($P < 0.001$, randomization test II). The increased decline of the treated sites compared with the reference sites remained significant as well ($P < 0.001$, randomization test III).

A

B

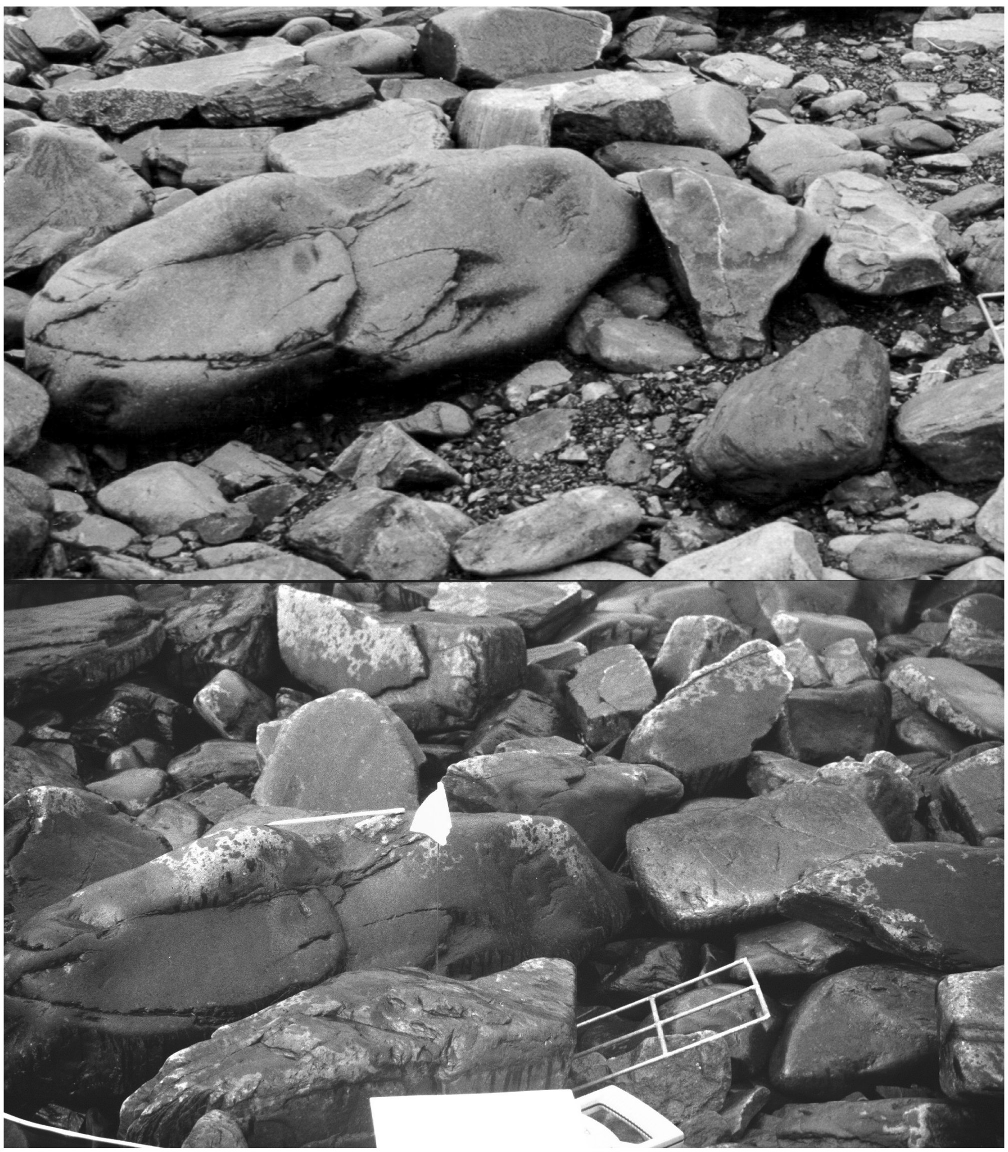

Figure 4. Photograph of typical sampling site in A: July 1997 after cleaning, and B: May 1998.

Comparison of photographs taken during the samplings revealed considerable site disturbance before the final sampling. Boulders up to 1 m diameter moved enough to obscure some quadrats, and revealed new untreated oil patches or extensions of patches in May 1998 compared with their positions in July 1997. For example, in Figure 4, the large boulder center-left in A and B (with the pencil on top in B) remained unmoved during this interval. Two of the 3 quadrat locations identified for this site are shown in A, just in front of the large boulder and in the upper-right corner. The third quadrat edge is visible on center-right in A. These boulders were removed when they interfered with the final quadrat sampling, so that all the quadrats initially identified were successfully sampled.

All of the oil samples collected for source identification had PAH distributions consistent with *Exxon Valdez* oil, and ranged from moderately to very weathered ($3 < w < 10$; see Short and Heintz, 1997 for source identification criteria and definition of the weathering parameter w).

4.0 Discussion

Our results indicate that the cleaning method used on these beaches was more effective than natural forces at removing oil. Immediately following the cleaning, about twice as much oil was removed (percentwise) from cleaned sites compared with reference sites. These cleaning effects also appear to persist. By the following year, about 3 times as much oil was lost from cleaned compared with reference sites. Evidently the cleaning procedure exposed a significant portion of the remaining oil to natural dispersive forces operating over the following months. These results corroborate the conclusion of Tumeo *et al.* (1994) that this cleaning treatment "...is an effective method of removing contamination within the beach material below the surface"; however, the method may not be practical for cleaning the beaches in this study.

The most serious limitation of the cleaning method involves the accessibility of oil remaining on these beaches to this procedure. The larger boulders protect the interstitial sediments between and under the boulders, and these fine grain sediments continue to retain the trapped oil. The boulders interfered with the large scale cleaning efforts immediately after the spill, and they interfered with the recent cleaning efforts. In both cases, the cleaning efforts were significant and intensive. Visible oil was removed, but the boulders prevented access to the contaminated sediments protected by the overlying boulders (Figure 4). Bedrock beaches are more easily cleaned, by intervention or nature, while boulder armored beaches cannot be cleaned with 100% effectiveness without the large scale removal of the armoring boulders.

Our sampling design was key to our ability to detect changes in oil loadings on these beaches. Simple random sampling designs are often promoted because of they are representative, so statistical inferences apply to the sampled environment as a whole. However, this design has two potentially serious drawbacks. First, adequate precision may require very large sample sizes when the geographic variability is high (Humphrey *et al.*, 1991). This holds in the present case, with the patchy distribution exacerbated by the physical boulder armoring that interferes with sampling. Second, simple random sampling can result in misleading conclusions regarding absence of effects when precision is too low to detect actual effects. The blocked design we used here avoids both these problems, but at the cost of limitations on our inferences, which apply only to visibly oiled patches on these beaches, and not to the beach as a whole. In particular, our results showing a substantial decline of beach oiling at the reference area cannot be used to estimate the rate of oil loss from these beaches as a whole absent cleanup effort, because these results only apply to oil patches that have been visibly exposed to the surface. Although once exposed the oil disappears relatively quickly, the rate that new patches of oil are worked to the surface by disturbance events is not known, so we cannot assess the rate that oil is lost from these beaches *per se*.

To measure the effectiveness of the cleaning procedures, each site served as its own control with the "before" measurement. To compare cleaning effectiveness with natural processes, we used a group of reference sites that were not cleaned. Initial measurements indicate a significant difference between reference and treated sites in the amount of oil present. Although the sites were adjacent, some protection from high-energy waves was afforded by a bedrock outcropping near the 3 reference sites in segment LA020-C. The other six reference sites were on beach segment LA017-A, which is less exposed to high-energy waves than the other beaches. This reduced exposure may explain the higher mean oiling found initially at the reference beaches, if less wave energy during the previous years led to less oil loss. The lower wave energy, particularly in the stormy winter probably accounts for a higher oil retention at the reference sites for the 8 years before this test, and also probably contributes to the slower rate of loss during the winter to year 9 compared to cleaned sites. However, the magnitude of this effect is probably negligible compared with the cleaning effects and the physical disruption of the thin asphaltic protective layer during the cleaning process.

Despite the cleaning efforts of man and nature, oil persists and will likely remain on these beaches for decades. After 10 winters and 4 summers of cleaning efforts, oil still remains on these beaches. Each year, winter storms are capable of reworking these beaches to a considerable extent (Figure 4), burying exposed oiled patches and exposing others. Pockets of oil will likely disappear each winter with storm-waves, yet the armor protection of the boulders is formidable, and oil will be protected in some pockets for many years as it has been for the last decade. The relatively moderate weathering ($w < 5$) characteristic of some of this oil indicates that it remains potentially toxic to fish following dispersal by storm events (Heintz et al., 1999; Carls et al., 1999).

The benefits of cleaning remain controversial. The initial cleaning through 1991 removed large quantities of visible oil from these beaches. Surface oil would have had long-term impacts to a variety of species, particularly to birds and other predators of the intertidal zone. Different types of cleaning may be more effective than other methods, or less destructive, but little doubt remains that the initial oil removal decreased long-term damage to habitat and vulnerable species from the oil.

However, the benefits of cleaning the remaining pockets several years later is less clear. The toxicity of the oil in these pockets may lead to new impacts when exposed and made available to biota. Cleaning may damage existing biota directly in the cleaned patches, or downslope in the lower intertidal. In the present case, gross biological damage was not evident based on visual inspections made after the cleaning effort. If pockets of oil are not removed, oil exposures will occur slowly over time, and although population impacts are not likely, the habitat cannot be considered fully recovered until all of the available oil is removed.

Human perceptions of cleaned beaches are important, as evidenced by the avoidance of these beaches by the local subsistence community, despite chemical monitoring of food organisms demonstrating absence of contamination. Because the boulder armoring prevents access to all of the oil, cleaning was not completely effective here. Although cleaning removed more oil than natural processes did, oil still persists, and because human perceptions are important, the beaches are not likely to used for human subsistence until no oil can be found.

5.0 References

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