Marine Pollution Bulletin 62 (2011) 1261–1269

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

A tracer study in an Alaskan gravel beach and its implications on the persistence of the Exxon Valdez oil

Hailong Li [a,b,*], Michel C. Boufadel [b,*]

[a] School of Water Resources and Environmental Science, China University of Geosciences-Beijing, Beijing 100083, PR China
[b] Dept. of Civil and Environmental Engineering, Temple University, 1947 N. 12th Street, Philadelphia, PA 19122, USA

ARTICLE INFO

Keywords:
Oil-spills
Tracer study
Tidal beach
Bioremediation
Nutrient application
Seawater–groundwater interaction

ABSTRACT

Despite great efforts including bioremediation, the 1989 Exxon Valdez oil spills persist in many gravel beaches in Prince William Sound, Alaska, USA. To explore this mystery, a lithium tracer study was conducted along two transects on one of these beaches. The tracer injections and transports were successfully simulated using the 2-dimensional numerical model MARUN. The tracer stayed much longer in the oil-persisting, right transect (facing landwand) than in the clean, left transect. If the tracer is approximately regarded as oils, oils in the upper layer would have more opportunities to enter the lower layer in the right transect than in the left one. This may qualitatively explain the oil persistence within the right transect. When the tracer is regarded as nutrients, the long stay of nutrients within the right transect implies that the oil persistence along the right transect was not due to the lack of nutrients during the bioremediation.

1. Introduction

In March 1989 the Exxon Valdez spill of about 41 million liters of Alaskan North Slope crude oil polluted ~800 km of rocky intertidal shorelines within Prince William Sound, Alaska (Bragg et al., 1994; Neff et al., 1995). Despite of the great efforts of remediation immediately following the spill and the large-scale bioremediation projects conducted in summers from 1989 to 1992 (Bragg et al., 1994; Taylor and Reimer, 2008), subsurface oil residues persist on many initially-polluted beaches (Hayes and Michel, 1999; Li and Boufadel, 2010; Owens et al., 2008; Short et al., 2007, 2004, 2006; Taylor and Reimer, 2008; Xia et al., 2010). In 2001 oil residues were found on 78 of 91 beaches randomly selected according to the oiling history (Short et al., 2004). With annualized loss rates decreasing from ~68% yr^{-1} before 1992 to ~4% yr^{-1} after 2001, weathering processes are slowed in sediments, and retention of toxic polycyclic aromatic hydrocarbons is prolonged (Michel and Hayes, 1999; Short et al., 2007).

In a study conducted on a gravel beach (EL-056C, see Fig. 1) located at (147° 34′ 17.42″ W, 60° 33′ 45.57″ N), Li and Boufadel (2010) found that the beach is made up of two layers: an upper layer of loose and coarse material with a very large hydraulic conductivity underlain by a layer with fine material whose hydraulic conductivity is around 1000 folds smaller. Their findings corroborated the general structure of beaches in mid- and high-latitude regions (Davies, 1980; Hayes, 1967; Owens et al., 2008). They also found that the elevation of the water table during low tide with respect to the interface of the two layers plays a crucial role in the persistence of oil. At locations where the seaward flow was small, the water table dropped into the lower layer, and subsequently, oil floating on it entered the lower layer and remained entrapped there due to capillary forces. At locations where the seaward flow was high, the water table during low tide did not drop into the lower layer, and the oil floating on it remained in the upper layer, and eventually got washed out to sea due to the high permeability of the upper layer.

It is still a mystery as to why the bioremediation conducted on the beach EL-056C did not successfully prevent the oil from persisting in the beach. In order to quantify the beach groundwater hydraulics, and to analogize the tidal effects on transport and resident time of nutrient applied for oil bioremediation in the beach, all of which are closely related to the oil-persistence in beaches, a tracer study was conducted using lithium as a conservative tracer on the beach EL-056C. The design of the tracer application is an analog to the nutrient application for oil bioremediation of oil polluted beaches proposed by Li et al. (2007). The tracer solution was lithium nitrate solution and was applied equally and simultaneously onto two transects of the beach. The left (facing landward) transect is clean and the right transect contains oils at the amount considered as heavy oil residue (HOR) as defined in Gibeaut and Piper (1998). The water table, the pore water concentrations of

* Corresponding author at: Dept. of Civil and Environmental Engineering, Temple University, 1947 N. 12th Street, Philadelphia, PA 19122, USA. Tel.: +1 215 204 7871; fax: +1 215 204 4696.

E-mail addresses: hailongli@cugb.edu.cn (H. Li), boufadel@temple.edu (M.C. Boufadel).

0025-326X/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.marpolbul.2011.03.011

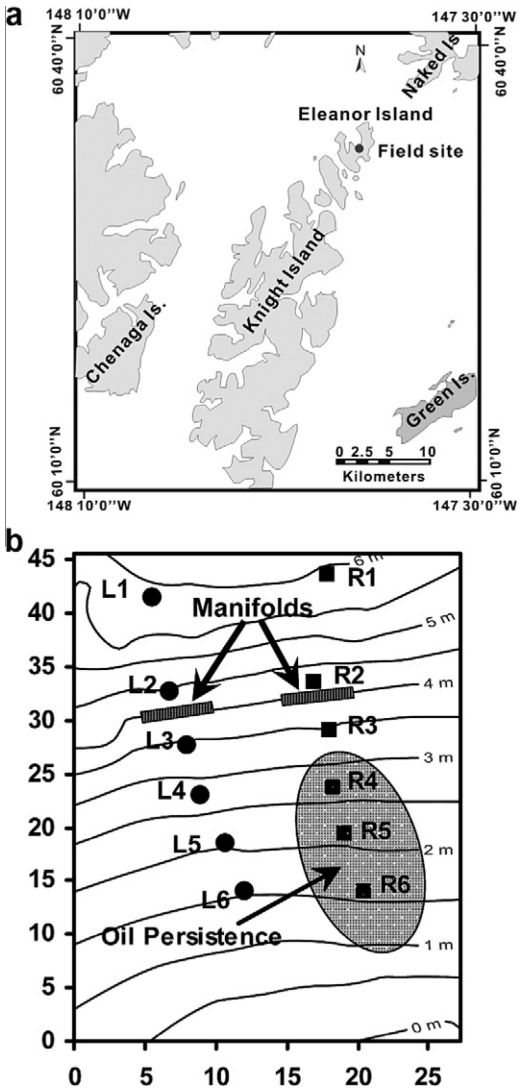

Fig. 1. (a) Location of the beach EL-056C (filled circles); (b) beach topographical contours, layout of observation wells and lithium tracer application manifolds. The elevation datum (0.0 m) is the low tide line during spring tides. All dimensions are in meter. Well names are marked with "L" for the left transect (as one stands landward on the beach) and with "R" for the right. Subsurface oil residues were found at locations R4, R5 and R6 in summer of 2007.

salinity (TDS) and lithium in the variably-saturated beach aquifer were observed during the tracer study. The results of the observations and 2-dimensional numerical simulations of the water table and pore water salinity have been reported in Li and Boufadel (2010). Here we report and analyze the results of the tracer concentration. Our goal herein is to better understand the hydrodynamics within the beach and how it affected the persistence of oil in the beach. We also discussed the implications of the tracer study for the effects of bioremediation on the oil degradation. An attempt was made to explain why the bioremediation conducted on the beach EL-056C did not successfully prevent the oil from persisting.

The layout of the paper is as follows: first the background information of the field work is given such as the study site, the tracer experiment and field measurements. Then the details for the numerical simulations are introduced, which include the numerical model, simulation domain, model parameters, boundary and initial conditions, and numerical simulation results when considering the disturbance of the beach sediments during installation of the observation wells. Finally, we numerically simulated the same tracer experiment in the intact beach (i.e., without any beach sediment disturbance). Then the results are used to discuss the reasons for the long-term persistence of the oil spills in the beach, and the effects of bioremediation on the oil degradation.

2. Field work

2.1. Study site

The beach EL-056C is a single pocket beach with an along-shore width of only 60 m and across-shore length of 50 m. The original 1989 shoreline cleanup assessment team (SCAT) survey (Taylor and Reimer, 2008) data indicated that initial oiling at this beach was in form of continuous oil pools, with mousse and fluid oil documented to depths greater than 30 cm (Owens et al., 2008). Tides in Prince William Sound have a very large range: ~5 m during spring tides and ~2.6 m during neap tides.

2.2. Tracer study

The tracer study was conducted on two transects of the beach (see Fig. 1b, Fig. 2a and b) in summer of 2007. The left transect was clean (no oil) and the right transect was heavily oiled. The distance between the two transects was around 10 m. Lithium in a technical grade anhydrous $LiNO_3$ (Cyprus Foote Mineral, Kings Mountain, NC) was used as the conservative tracer (Wrenn et al., 1997b) in a seawater solution (salinity 26.5 g/L). The lithium concentration in the solution was 360 mg/L. The tracer was used successfully in previous beach tracer studies (Wrenn et al., 1997a,b). Along each of the two transects, 1050 L of tracer solution was poured on the beach surface through small holes (diameter 2 mm, inter-hole distance 10 cm) uniformly distributed along the whole length of the manifold (PVC pipe with inner diameter of 38 mm) placed on the beach surface at the elevation of 4 m above the lowest tide line (Figs. 1 and 2). The tracer was applied during the falling tide following the highest spring tide, and started when the tidal level was about 3.39 m above the lowest tide line at 3:54 AM, July 30th 2007. The tracer application lasted for 2 h and 6 min. The highest spring tide (4.61 m above the lowest tide line) occurred at 1:50 AM, July 30th 2007. This time is taken as initial time ($t = 0$) for all the time-dependent physical parameters such as the tracer concentration and tidal level throughout this paper. The length of the manifold is 5 m. The flow rate per unit length manifold was $100 \pm 3.6\ \mathrm{L\,h^{-1}\,m^{-1}}$. No ponding occurred on the beach surface during tracer injection. The measurement of the tracer (Lithium) concentration began immediately at the end of the tracer injection.

2.3. Field measurements

Six pairs of well locations with similar surface elevations were chosen (Fig. 1b) along the two transects. At each well location a pit was dug down to a depth from 0.66 m to 1.17 m, and then a whole-length-slotted PVC pipe and a multiport sampling well were installed vertically. A pressure transducer (MiniDiver, Data Logger-DL501, Schlumberger) was placed at the bottom of the PVC pipe to provide the water pressure every 10 min. The readings of the pressure transducer were compensated for the barometric pressure monitored by an air-pressure sensor (BaroLogger, DL-500, Schlumberger) during the same period. No rains or strong winds occurred during the experiment.

The stainless-steel multiport sampling well contained 4 ports labeled A, B, C and D from the bottom up. They were covered with fine stainless-steel screen to prevent the blockage by fine sediments. The distance between any two adjacent ports is 22 cm. Each