Lessons from the Exxon Valdez Oil Spill disaster in Alaska

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Abstract

Oil spills are potentially the most destructive pollution source impacting beaches and marshes. The lingering of oil from the 1989 Exxon Valdez oil spill (EVOS) in some of the Prince William Sound (PWS) beaches, Alaska poses a scientific challenge, because various studies expected he oil to disappear almost 20 years after the spill. This paper reviews the fate, effects and remediation evaluations of the EVOS. The hydrogeological mechanism causing the oil persistence in tidal gravel beaches along PWS was highlighted. The experiences, lessons and results from the EVOS provide implications on locating and bioremediating spilled oil and on designing optimal bioremediation strategies in tidal gravel beaches (coarse-sediment beaches) widely distributed around the world, especially in mid- and high-latitude regions.

Keywords: Oil spill disasters; Exxon Valdez oil spill (EVOS); Lingering oil; Bioremediation; Alaska

1. Oil spill disasters

Today almost beaches and coastlines are threatened by human activities with intense coastal development. Seaborne oil trade has grown steadily from 1970 to the present, and such increased movements would normally signal increased risk of oil spills [*ITOPF*, 2009]. Oil spills are potentially the most destructive pollution source impacting gravel and sandy beaches [*Owens et al.*, 2008; *Defeo et al.*, 2009; *Hayes et al.*, 2010]. The 1970 Arrow Oil Spill approximately oiled 305 km of coastline in Chedabucto Bay, Nova Scotia, Canada. The total oiling extent of the 1978 Amoco Cadiz (Brittany, France) Oil Spill included 320 km of coastline. In July 1979 Greek tanker Atlantic Express spilled 287,000 tons off Trinidad and Tobago. The Gulf War oil spill is regarded as the worst oil spill in history, estimates on the volume spilled range from 780,000 to 1,500,000 tons. The 2002 Prestige Oil Spill in Spain spilled more than 60,000 tons of oil, polluting more than 1,300km of coastline. Recently, BP's Deepwater Horizon Incident in Gulf of Mexico (April 20, 2010) has spilled millions of gallons of oil (more than 210,000 gallons per day) into the Gulf, which are contaminating surrounding coastline, beaches and marshes. In China, the 1983 FEOSO AMBASSADOR spilt 3,343 tons of oil in Qingdao and contaminated around 230 km coastlines along Jiaozhou Bay and its adjacent areas. The 1995 TANJA JACOB 1995 spilt approximately 200 tons of crude oil after colliding with a jetty at Hangpu Harbour in China. Recent Hazardous and Noxious Substances (HNS) spills in China include M/V DAE MYONG (2001), which spilled approximately 600 tons of styrene in the mouth of the Yangzi River and M/V GG CHEMIST (2005), which spilled 64 tons of toluene in the same area [*ITOPF*, 2009].

In March 1989 the Exxon Valdez oil spill (EVOS) of about 38,000 tons of Alaskan North Slope crude oil polluted ~2,000 km of rocky intertidal shorelines within Prince William Sound (PWS) in Alaska, USA [*Bragg et al.*, 1994; *Neff et al.*, 1995]. It is considered one of the most devastating human-caused environmental disasters ever to occur at sea in USA history. Two decades after the EVOS, patches of subsurface oil still persist in most initially-polluted beaches along PWS [*Li and Boufadel*, 2010; *NOAA*, 2010; *Xia and Boufadel*, 2010]. Recent the National Oceanic and Atmospheric Administration (NOAA) [2010] reported that oil of around 97.2 metric tons is contained in discontinuous patches across beaches that were initially impacted by the spill.

The goal of this paper is to briefly review the fate and effects of the EVOS and its remediation evaluations in tidal gravel beaches along the PWS, providing implications on bioremediating spilled oil and on designing optimal bioremediation strategies in tidal gravel beaches.

2. Fate and effects of EVOS

The EVOS caused a massive damage to the environment and was unique in many ways, particularly with regard to the extent and degree of shoreline contamination [*Michel et al.*, 2009]. About 40 to 45% of the oil mass grounded in 1989 on 787 km of PWS beaches; another 7 to 11% was transported to contaminate 1203 km of Gulf of Alaska (GOA) shoreline. About 2% remained on intertidal PWS beaches after 3.5 years. Recent studies by scientists from the National Oceanic and Atmospheric Administration (NOAA) [*Short et al.*, 2004; *Short et al.*, 2006] estimated that between 60 and 100 tons of subsurface oil persists in many initially-polluted beaches along PWS. The overall statistical spatial distribution of the intertidal persistent subsurface oil was found to be nearly symmetrically with respect to tide height [*Short et al.*, 2006], and was most prevalent near the middle intertidal zone[*Short et al.*, 2004; *Short et al.*, 2006; *Taylor and Reimer*, 2008]. *NOAA* [2010] indicated that the oil from the EVOS is decreasing at a rate of zero to 4% yr^{-1}, with only a five percent chance that the rate is as high as 4%. As a result, it may persist for decades.

It is well recognized that oil spills can have immediate adverse effects on wildlife populations. The best estimates of animals died outright from the EVOS are around 250,000 seabirds, nearly 3,000 sea otters, 300 harbor seals, 250 bald eagles, up to 22 killer whales, and billions of salmon and herring eggs. The impact of the EVOS on otters is evident from morgue counts. *Golet et al.* [2002] demonstrated that recovery of pigeon guillemots following oil spills may take considerably longer for certain species than the few years that have been proposed as typical for marine birds. *Peterson et al.* [2003] reviewed the ecosystem response to the EVOS, they reported that unexpected persistence of toxic subsurface oil and chronic exposures, even at sublethal levels, have continued to affect wildlife. *Short et al.* [2006] reported that lingering oil from the EVOS may plausibly contribute to the slow recovery of sea otter populations.

Thus, the persistence of surface and subsurface oil from the EVOS may be causing on-going exposure and potential harm to living organisms, wilderness areas, recreational activities, and subsistence users in PWS and GOA [*Michel et al.*, 2009].

3. Remediation evaluations

Despite advances in preventative measures, recent events have demonstrated that accidental oil spills at sea will still occur [*Lee and de Mora*, 1999; *ITOPF*, 2009]. After the EVOS incident, various methods were used to remove oil from sea and beaches, including adding dispersants, burning, mechanical recovery equipment, spraying beaches with water from high-pressure hoses, and bioremediation efforts. While physical (e.g. booms and skimmers) and chemical (e.g. chemical dispersants) methods have been developed to recover and/or disperse oil spilled at sea, they are not 100% effective and are frequently limited by operational constraints attributed to sea state and/or nature of the contaminant [*Lee and de Mora*, 1999].

Bioremediation is an important treatment for oil spills on rocky intertidal shorelines of the type found in Alaska [*Prince and Bragg*, 1997]. *Pritchard* [1991] have demonstrated convincingly that fertilizers can be applied to oiled beaches to overcome nutrient limitations, thereby enhancing biodegradation of the oil. Field studies conducted by scientists from the U.S. Environmental Protection Agency (EPA) have demonstrated that oil degradation by indigenous microflora on the beaches of PWS was accelerated by adding fertilizer directly to the surfaces of oil-contaminated beaches [*Pritchard et al.*, 1992]. Many studies showed that the main factor limiting the biodegradation of oil on the beaches in PWS was the concentration of nutrients, particularly nitrogen [*Swannell et al.*, 1996]. Laboratory experiments and field trials [*Lee and de Mora*, 1999; *Lee and Merlin*, 1999] have demonstrated the feasibility and success of bioremediation strategies such as nutrient enrichment to enhance bacterial degradation of oil on cobble, sand beach and salt marsh environments. *Gallego et al.* [2007] showed that microbial activity in the presence of nutrients plus a surfactant removed a significant amount of toxic fuel compounds.

However, bioremediation is not a rapid cleanup process, and visual effects may not be evident for at least 15 days after treatment [*Pritchard and Costa*, 1991]. Bioremediation of oil was affected by many environmental factors. *OTA* [1994]'s background paper evaluated the current state of knowledge and assessed the potential of bioremediation for responding to marine oil spills. Their basic message was a dual one: they cautioned that there are still many uncertainties about the use of bioremediation as a practical oil spill response technology; nevertheless, it could be appropriate in certain circumstances, and further research and development of bioremediation technologies could lead to enhancing the capability to fight marine oil spills. *Bragg et al.* [1994] pointed out that the effectiveness of bioremediation for oil spills has been difficult to establish on dynamic, heterogeneous marine shorelines. *Lee and Merlin* [1999] suggested that decision making should include information on the type of oil, application methodologies available (form and type of bioremediation agent, type and frequency of application), environmental conditions (availability of nutrients, bacteria, oxygen, temperature, and wave/tidal immersion), as well as the time available for cleanup. *Venosa and Zhu* [2003] reported that the most important factors affecting biological removal of hydrocarbons are the presence of oxygen and sufficient nutrients in the form of nitrogen and phosphorus to support the biodegradation process. Responders must take into consideration the oxygen and nutrient balance at the site. *Nikolopoulou and Kalogerakis* [2009] stated that oxygen represents another very significant and potentially rate limiting nutrient that should be kept in mind before embarking on a biostimulation program in the field.

In addition, bioremediation may also have a long-term cumulative impact on local ecosystems. *Nordstrom* [2005] suggested that site-specific evaluations of recovery rates in dredge and fill areas will always be required to minimize adverse effects on existing biota, but more emphasis should be placed on identifying and addressing cumulative, long-term losses. *Speybroeck et al.* [2006] reviewed sizeable impacts of beach nourishment on several beach ecosystem components described in the literature. They stated that negative, ecosystem-component specific effects of beach nourishment dominate in the short to medium term, and these effects cannot be neglected in an overall impact assessment.

4. Hydrogeological mechanism on lingering oil

To restore oiled beaches, it is necessary for scientists to have a thorough understanding of the beach hydrogeological characteristics [*Owens et al.*, 2008]. The armor protecting the subsurface oil from the erosion and removal and the long-term storage effect of the fine-grained sediments have been recognized as the primary reason for heavy oil residues in the fine sediments under the armor [*Hayes and Michel*, 1999; *Owens et al.*, 2008; *Taylor and Reimer*, 2008]. The hydrogeological mechanism causing the oil persistence was not fully understood due to the complex surface and groundwater interactions in the intertidal zone including tides, inland freshwater recharge, sediment heterogeneity, seawater density-effect and beach landforms.

Recently, *Li and Boufadel* [2010] demonstrated the hydrogeological mechanism contributing to the persistence of subsurface EVOS in a gravel beach on Eleanor Island (PWS), Alaska. They reported that a two-layered beach structure and anoxic or near-anoxic conditions existed in the lower layer which would result in the persistence of the EVOS. The surface layer might act as funnel and buffer for the oil to fill the interstices of fine materials in the lower layer during the initial oiling, once the oil enters the lower layer, it gets entrapped there by the capillary forces of the fine-grained sediments. These studies also indicated that the freshwater recharge promotes the removal of oil by sustaining a high water table in the beach during low tides and subsequently preventing the oil from dropping into the lower layer. *Xia and Boufadel* [2010] investigated the role of beach stratigraphy and geomorphology on the persistence of the EVOS in Alaska. They found that a two-layer stratigraphy along with a mild beach slope were the major factors for oil persistence. Flat slopes of the middle beach enhancing the retention of the oil. Large slopes suggest a high degree of turnover of the pore water, which would replenishment of the beach with nutrients. This could be enhanced if the seaward flow is made up of freshwater whose interfacial tension with oil is larger than that of saltwater, which would minimize the breakup of oil into smaller droplets that could be lodged within the pore matrix.

5. Lessons from EVOS

The EVOS triggered major improvements in oil spill prevention and response planning around the world. The overall lessons reached by this review are as follows: First, the persistence of oil in sediments produces chronic, long-term exposure risks from some species and local ecosystems. Second, effective measures of biodegradation and interpretation of resulting data are a key element in bioremediation success. Environmental conditions (nutrients, bacteria, oxygen, temperature, and wave/tidal immersion) should be considered in the bioremediation of oiled tidal beaches. Third, beach hydrogeological factors play an important role in lingering oil in tidal gravel beaches. Oil is always sequestered under boulders and cobbles, which provided a local wave shadow that protected the oil from removal by water motion. Two-layered structure promotes the persistence of oil in beaches. Slope-enhanced tide-induced high seaward flow caused the dislodgement of oil and its washout to sea. Fourth, the feasibility of other remediation strategies such as phytoremediation, enhanced oil-mineral fines interaction, and the addition of oxygen or alternative electron acceptors are now being evaluated. Fifth, effective protection and cleanup of spilled oil in the Arctic will be challenging, considering the difficult environmental conditions and a general lack of responder expertise in cold water oil spill response. Sixth, gravel and mixed sand-gravel beaches are widely distributed around the shorelines of the world, especially in mid- and high-latitude regions. All such beaches most likely have the two-layered structure [*Li and Boufadel*, 2010]. Finally, oil spills are known to cause severe and long-term damage to mangrove and salt marsh ecosystems [e.g., *Krebs and Burns*, 1977], all aforementioned lessons from gravel beaches of the EVOS would provide insights into the prevention and response of oil spill disasters in such coastal ecosystems.

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References

1. Bragg, J. R., R. C. Prince, E. J. Harner, and R. M. Atlas **(1994)**, Effectiveness of bioremediation for the Exxon Valdez oil spill, *Nature*, *368*, 413-418.

2. Defeo, O., A. McLachlan, D. S. Schoeman, T. A. Schlacher, J. Dugan, A. Jones, M. Lastra, and F. Scapini **(2009)**, Threats to sandy beach ecosystems: A review, *Estuarine, Coastal and Shelf Science*, *81*, 1-12.

3. Gallego, J. R., J. R. Fernández, F. Díez-Sanz, S. Ordoñez, H. Sastre, E. González-Rojas, A. I. Peláez, and J. Sánchez **(2007)**, Bioremediation for Shoreline Cleanup: In Situ vs. On-Site Treatments, *Environmental Engineering Science*, *24*, 493-504.

4. Golet, G. H., P. E. Seiser, A. D. McGuire, D. D. Roby, J. B. Fischer, K. J. Kuletz, D. B. Irons, T. A. Dean, S. C. Jewett, and S. H. Newman **(2002)**, Long-term direct and indirect effects of the Exxon Valdez oil spill on pigeon guillemots in Prince William Sound, Alaska, *Marine Ecology Progress Series*, *241*, 287-304.

5. Hayes, M. O., and J. Michel **(1999)**, Factors determining the long-term persistence of Exxon Valdez oil in gravel beaches, *Marine Pollution Bulletin*, *38*, 92-101.

6. Hayes, M. O., J. Michel, and D. V. Betenbaugh **(2010)**, The Intermittently Exposed, Coarse-Grained Gravel Beaches of Prince William Sound, Alaska: Comparison with Open-Ocean Gravel Beaches, *Journal of Coastal Research, 26*, 4-30, doi:10.2112/2108-1071.2111.

7. ITOPF **(2009)**, Oil tanker spill statistics: 2009, The International Tanker Owners Pollution Federation (ITOPF).

8. Krebs, C. T., and K. A. Burns **(1977)**, Long-Term Effects of an Oil

Spill on Populations of the Salt-Marsh Crab Uca pugnax, *Science*, *197*, 484-487.
9. Lee, K., and S. de Mora **(1999)**, In situ bioremediation strategies for oiled shoreline environments, *Environmental Technology*, *20*, 783-794.
10. Lee, K., and F. X. Merlin **(1999)**, Bioremediation of oil on shoreline environments: development of techniques and guidelines, *Pure and Applied Chemistry*, *71*, 161-171.
11. Li, H. L., and M. C. Boufadel **(2010)**, Long-term persistence of oil from the Exxon Valdez spill in two-layer beaches, *Nature Geoscience*, *3*, 96-99, doi:10.1038/ngeo1749.
12. Michel, J., Z. Nixon, M. O. Hayes, J. Short, G. Irvine, D. Betenbaugh, and C. Boring **(2009)**, Modeling the distribution of lingering subsurface oil from the *Exxon Valdez* oil spill, Exxon Valdez Oil Spill Restoration Project Final Report (Restoration Project 070801), National Oceanic and Atmospheric Administration, Juneau, AK.
13. Neff, J. M., E. H. Owens, S. W. Stoker, and D. M. McCormick **(1995)**, Shoreline oiling conditions in Prince William Sound following the "Exxon Valdez" oil spill, in *Exxon Valdez Oil Spill – Fate and Effects in Alaskan Waters*, *ASTM STP 1219 American Society for Testing and Materials*, edited by P. G. Wells, J. N. Butler and J. S. Hughes, pp. 312–346, Philadelphia, PA.
14. Nikolopoulou, M., and N. Kalogerakis **(2009)**, Biostimulation strategies for fresh and chronically polluted marine environments with petroleum hydrocarbons, *Journal of Chemical Technology & Biotechnology*, *84*, 802-807.
15. NOAA **(2010)**, Intent to Prepare a Supplemental Environmental Impact Statement on the Exxon Valdez Oil Spill Trustee Council's Restoration Efforts, *Federal Register*, *75*, 3706-3709.
16. Nordstrom, K. F. **(2005)**, Beach Nourishment and Coastal Habitats: Research Needs to Improve Compatibility, *Restoration Ecology*, *13*, 215-222.
17. Owens, E. H., E. Taylor, and B. Humphrey **(2008)**, The persistence and character of stranded oil on coarse-sediment beaches, *Marine Pollution Bulletin*, *56*, 14-26.
18. Peterson, C. H., S. D. Rice, J. W. Short, D. Esler, J. L. Bodkin, B. E. Ballachey, and D. B. Irons **(2003)**, Long-term ecosystem response to the Exxon Valdez oil spill, *Science*, *302*, 2082-2806.
19. Prince, R. C., and J. R. Bragg **(1997)**, Shoreline Bioremediation Following the Exxon Valdez Oil Spill in Alaska, *Bioremediation Journal*, *1*, 97-104.
20. Pritchard, P. H. **(1991)**, Bioremediation as a technology: Experiences with the Exxon Valdez oil spill, *Journal of Hazardous Materials*, *28*, 115-130.
21. Pritchard, P. H., and C. F. Costa **(1991)**, EPA's Alaska oil spill bioremediation project, *Environmental Science & Technology*, *25*, 372-379.
22. Pritchard, P. H., J. G. Mueller, J. C. Rogers, F. V. Kremer, and J. A. Glaser **(1992)**, Oil spill bioremediation: experiences, lessons and results from the Exxon Valdez oil spill in Alaska, *Biodegradation*, *3*, 315-335.
23. Short, J. W., M. R. Lindeberg, P. M. Harris, J. M. Maselko, J. J. Pella, and S. D. Rice **(2004)**, Estimate of oil persisting on the beaches of Prince William Sound 12 years after the Exxon Valdez oil spill, *Environmental Science & Technology*, *38*, 19-25.
24. Short, J. W., J. M. Maselko, M. R. Lindeberg, P. M. Harris, and S. D. Rice **(2006)**, Vertical distribution and probability of encountering intertidal Exxon Valdez oil on shorelines of three embayments within Prince William Sound, Alaska, *Environmental Science & Technology*, *40*, 3723-3729.
25. Speybroeck, J., D. Bonte, W. Courtens, T. Gheskiere, P. Grootaert, J.-P. Maelfait, M. Mathys, S. Provoost, K. Sabbe, E. W. M. Stienen, V. V. Lancker, M. Vincx, and S. Degraer **(2006)**, Beach nourishment: an ecologically sound coastal defence alternative? A review, *Aquatic Conservation: Marine and Freshwater Ecosystems*, *16*, 419-435.
26. Swannell, R. P. J., K. Lee, and M. McDonagh **(1996)**, Field evaluations of marine oil spill bioremediation, *Microbiological Reviews*, *60*, 342-365.
27. Taylor, E., and D. Reimer **(2008)**, Oil persistence on beaches in Prince William Sound–A review of SCAT surveys conducted from 1989 to 2002, *Marine Pollution Bulletin*, *56*, 458-474.
28. Venosa, A. D., and X. Zhu **(2003)**, Biodegradation of Crude Oil Contaminating Marine Shorelines and Freshwater Wetlands, *Spill Science & Technology Bulletin*, *8*, 163-178.
29. Xia, Y. Q., and M. C. Boufadel **(2010)**, The role of stratigraphy and geomorphology on the persistence of the Exxon Valdez oil spill in Alaska, paper presented at GSA Northeastern Section (45th Annual) and Southeastern Section (59th Annual) Joint Meeting, Geological Society of America *Abstracts with Programs*, 42(1): 94. Paper No. 25-2, Baltimore, Maryland, USA, 13-16 March **2010**.