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Assessing the performance and cost of oil spill remediation technologies

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ABSTRACT

Oil spills are an especially challenging chemical contamination event to remediate. Predicting the fate and effects of spilled oil is a formidable task, complicated by its complex chemical composition and the potential for catastrophically large discharge volumes. The proper choice of cleanup technique is equally complex, and depends on a host of factors, including oil type, spill location, spill size, weather, and local regulations and standards. This paper aims to provide a broad review of the current technologies used to remediate oil spills, and the context in which they operate. The chemical characteristics of an oil spill are discussed, including implications for transport modeling, and impacts that arise from short-term and chronic toxicity. The most common remediation technologies (mechanical recovery, dispersants, and in-situ burning) are reviewed, as are emerging technologies (hydrophobic meshes). A comparative analysis is performed on these methods by calculating a maximum oil encounter rate for each device, which is a performance characteristic critical to planning a response effort. Finally, a review of cleanup cost estimation techniques is used to assess the cost-effectiveness of remediation methods. Analysis shows that waiving the legal penalty for recovered oil can result in significant cost savings for the liable party, and may drive improvements in recovery-focused technologies. The authors suggest continued research into improving oil spill recovery methods and understanding the fate of individual compounds in the spilled oil. This will both minimize potential environmental damages, and reduce the uncertainty of their impacts.

1. Introduction

The worldwide use and distribution of crude oil and its derivatives continue to impose a potential threat to aquatic environments. Accidental releases can occur from a variety of sources including tankers, pipelines, storage tanks, refineries, drilling rigs, wells, and platforms (Vanem et al., 2008). Fortunately spill frequency and volume from all international sources have decreased since the 1970's (Burgherr, 2006) due to the identification of management-based risk factors (Bergh et al., 2013), increasing implementation of preventative regulations, and the development of corporate social responsibility practices by the oil production and transportation industries (Rauffleta et al., 2014). Despite these global improvements, there may be an increased risk of spills on a local level due to increased industrial activities in countries with high economic growth, e.g. in the South China Sea (Woolgar, 2008). Additionally, catastrophic spills remain a possibility from all sources. Noteworthy examples include: the 1989 sinking of the *Exxon Valdez* oil tanker off the coast of Alaska (Peterson et al., 2003), the subsea blowout in the Gulf of Mexico of the *Deepwater Horizon* drilling rig in 2010 (Camilli et al., 2011), and the 2010 pipeline spill of diluted bitumen in Michigan (EPA, 2013). The inability of responders to prevent the spilled oil from reaching sensitive areas led to economic, social, and environmental damages. These large-scale spills in highly mobile aquatic environments highlight the need for remediation technologies that can respond swiftly to mitigate potential damages.

Oil spill clean-up technology has expanded to include a variety of approaches in the past 50 years. Spill response techniques are typically classified as mechanical/physical, chemical, and biological (Dave and Ghaly, 2011). While only briefly described below, detailed reviews of these techniques have been published, including their operational limitations (Ventikos et al., 2004) and a qualitative assessment of their strengths and weaknesses (Dave and Ghaly, 2011). The mechanical/physical class includes

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deployment of oil booms, which are floating barriers designed to control the movement of surface oil slicks. Skimmers are a broad category of stationary or mobile mechanical devices specifically designed to recover oil from the water's surface (Schulze, 1998). To separate the water and oil, they typically take advantage of the difference in density or adhesive properties of water and oil. An example of a chemical technique is the application of dispersants, which are surfactants sprayed on the oil slick from aircraft or boats in order to reduce the water/oil interfacial tension and cause the oil to break-up into smaller drops. This promotes dissolution and biodegradation while limiting movements of large volumes of oils to sensitive receptors such as coastal wetlands. Bioremediation consists of the addition of nutrients and/or oxygen to stimulate the growth of indigenous microbes that can utilize oil as a carbon source. Microbes designed to degrade the oil can also be added, if it is felt that natural oil-degrading strains are not present in sufficient numbers. Most recent research has focused on chemical surfactants or bioremediation applications, in order to improve their efficiency and/or the impact of their addition into the environment (Dave and Ghaly, 2011).

Newer techniques are also becoming well-known and applied in the oil spill response community. One such technique, in-situ burning, consists of using specially designed high-temperature boom to corral oil slicks into a smaller area, where the oil is ignited in a controlled burn (Allen and Ferek, 1993). This technique was widely used in the Deepwater Horizon response (Allen et al., 2011). Absorbents also see widespread use, especially when cleanup goals require a maximal removal of oil. However, due to the difficulties in handling oil-soaked materials, this technique is typically confined to small areas, and is not examined in this paper.

Material science offers the potential for innovation beyond current techniques. Skimmers have been modified to have oleophilic surfaces, and this advance has seen widespread implementation in the oil spill response industry (Broje and Keller, 2006). Magnetic particles offer many advantages over traditional absorbent techniques. They can be synthesized to be oleophilic, making them extremely efficient separators, and their uptake capacity can match or exceed current absorbents (Chun and Park, 2001). In addition, their inherent magnetic properties provide a facile method of recovering and handing oil-sorbent amalgam. Another technique originating from materials research involves hydrophobic meshes, which can separate oil and water in-situ without additional energy input (Deng et al., 2013). While these techniques remain largely untested under field conditions, their potential to improve the rate and efficiency of cleanup operations is worth investigating.

This paper has three primary objectives. The first is to review the inherent complexity in predicting the fate and impact of spilled oil in the marine environment. Crude oil and its derivatives are extremely complex mixtures of organic chemicals. Recent advances in fate modeling are reviewed, while highlighting the uncertainties and gaps in current knowledge. Ideally, perfect knowledge leads to an optimal response to an oil spill, defined as one that balances response costs with environmental damages. However, the literature shows that quantifying the damage to social, economic, and environmental resources from oil spills is an uncertain endeavor. Thus, the second objective is to review and reanalyze the performance of the major classes of oil spill cleanup techniques in order to assess the current technological capabilities for responding to a large-scale oil spill. Emphasis will be placed on the encounter rate of each technique, a common limiting factor for large spills. The third objective is to review how the costs of response efforts are currently estimated. These methods are then used to establish a financial incentive to recover oil, under the hypothetical scenario whereby the responsible party is not fined for oil that is recovered from the environment at or very near the point of discharge. This scenario will highlight the financial benefits of recovering, rather than dispersing or destroying, spilled oil, and show how it complements the mitigation of environmental damage.

2. Method of review

This study relies solely on peer-reviewed scientific papers, publically available government reports, and published results of remediation technique performances. Preference was given to recent reviews of a given topic, and papers that first identified a phenomenon. Using this literature, the most common approaches to oil spill remediation are identified, and their performance metrics are compiled. In a parallel effort, the factors controlling the fate and impact of oil spills are identified, as are the quantitative models that predict these factors. Only models that had published the scientific basis and validation of their algorithms are included in this review. These models are assessed for their adherence to physical mechanisms, and ability to predict the transport and impact of oil spills. We then introduce the idea of a theoretical maximum oil encounter rate, and show how the underlying formulation is consistent with published predictive tools currently used by oil spill response community. After identifying the major classes of oil spill response technology, published methodologies for estimating the cost of each response are used to assess the economic implications of oil spill recovery.

3. The composition and fate of spilled oil

3.1. Oil composition and characterization

Oil is not a single-component substance with well-defined physical properties and behavior. For example, crude oil is a mixture of individual chemicals with more than 10,000 unique elemental compositions (Marshall and Rodgers, 2008). Each unique elemental composition, in turn, potentially represents thousands of unique chemical structures. The total number of individual compounds is estimated to be in the billions (Beens and Brinkman, 2000). The compounds mostly consist of hydrocarbons, but also include organic compounds with various heteroatom substituents, notably oxygen, nitrogen, sulfur, and trace metals (Shi et al., 2010). More processed forms of oil, such as diesel fuel, lubricating oils, or diluted bitumen, represent a subset of the composition of crude oil which has been separated or modified to produce desired physical or chemical properties. The origin of biofuels is distinct from that of crude oil, and as such is considered separately in performance and analysis (although they may have many components in common) (Brynolf et al., 2014). Desired properties of any fuel depend on individual chemical composition, which has been limited by the overwhelming complexity of the mixture.

Gas chromatography coupled with mass spectrometry (GC–MS) is the conventional method used to elucidate oil composition. The columns used to separate oil components largely do so based on their London dispersive interactions as reflected by their boiling points. In order to resolve compounds with similar boiling points, two-dimensional gas chromatography (GC × GC) can be used (developed by Liu and Phillips (1991), with recent applications by Ventura et al. (2008) and Reddy et al. (2012)), which separates by both the London interactions with the first stationary phase as well as polar interactions with the second stationary phase. Unfortunately, GC is only effective at separating compounds with a boiling point of less than about 400 °C. For crude oil, this can represent a significant blind spot: only about half of the mass in the Macondo oil well was resolvable by conventional gas chromatography (McKenna et al., 2013). Only very recently have these high-boiling