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Effect of evaporative weathering and oil-sediment interaction on the fate and behavior of diluted bitumen in marine environments. Part 2. The water accommodated and particle-laden hydrocarbon species and toxicity of the aqueous phase

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HIGHLIGHTS

- Sediment-laden TPH contained fewer <C10, but higher C16–C34 and >C34 range hydrocarbons.
- Increased oil viscosity, asphaltene content, and sediment size decreased sediment-laden TPH.
- Less water accommodated TPH and PAHs were observed for weathered CLB products.
- Oil and sediment types did not clearly affect the water accommodated TPH and PAHs.
- Toxicity of the water phase did not vary with sediment type, but vary with oil type.

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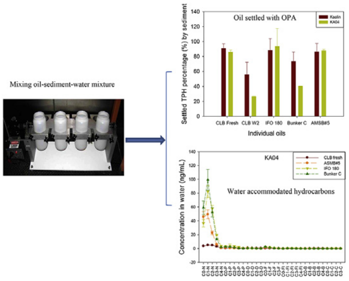
GRAPHICAL ABSTRACT



ABSTRACT

In this study, the water accommodated and particle-laden hydrocarbon species, and the toxicity of the aqueous phase after oil-sediment interactions by varying the weathering states of diluted bitumen (Cold Lake blend (CLB)), oil type from light to heavy, and sediment type. Compared to the original oils, the sediment-laden total petroleum hydrocarbons (TPH) contained fewer hydrocarbons in the carbon range $<C_{10}$, comparable contents in C_{10}–C_{16} range, higher contents in both the C_{16}–C_{34} and $>C_{34}$ range. Sediment-laden oil amounts generally decreased with an increased viscosity and asphaltene content of the test oils, as well as with increased sediment particle size. The presence of sediments significantly decreased the oil accommodated in water due to the formation of oil particulate aggregates (OPA) after mixing and settling. Less water accommodated TPH and polycyclic aromatic hydrocarbons (PAHs) were observed for weathered CLB products. However, oil and sediment types did not clearly affect the water accommodated TPH and PAHs. Light molecular PAHs and their alkylated congeners accounted for most of the water accommodated PAH congeners. A microtoxicity test demonstrated that with or without sediment, and regardless of sediment type, the toxicity of the water phase did not change significantly. Light oil of Alberta sweet mixed blend (ASMB) had the highest toxicity, followed by fresh CLB, and then

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all other oils, suggesting that ASMB and fresh CLB had relatively higher levels of light toxic components dissolved in the water phase compared with the other tested oils.

1. Introduction

Diluted bitumen (dilbit) is an oil sand product made by diluting bitumen with light condensates (20–30% condensates, 70–80% bitumen) (Crosby et al., 2013) to enable the transport of bitumen through pipelines. The transportation of dilbit poses a heightened environmental threat if a spill occurs. Once oil is spilled into the marine environment, it is immediately subject to a variety of abiotic and biotic processes including spreading, drifting, dispersion, stranding, evaporation, dissolution, biodegradation, photooxidation, and emulsification. Oil is a mixture of complex hydrocarbon compounds varying in volatility, solubility, and toxicity. Many of the components in oil are potentially toxic to marine organisms, but have limited bioavailability in the environment due to their low solubility (Faksness et al., 2015b). Light molecular weight hydrocarbons such as mono-aromatic hydrocarbons, phenols, as well as nitrogen and sulfur-containing hetero-cyclic compounds are relatively more soluble in water compared to the heavy components. In marine systems, the fate and transport of dissolved oil components is associated with various processes, such as solubilisation, biodegradation, sorption on and desorption from sediments and suspended particulate materials (SPM), and dilution into the water column. Therefore, understanding the dissolved oil components in water is of high priority due to their mobility and toxicity, despite that they usually only make up <1% of crude oil (Carls et al., 2008; Gong et al., 2014; Faksness et al., 2015b).

Sediments have long been considered as important vectors in the transport of oil from one environmental matrix to another following an oil spill in aquatic environments. It highly likely that oil present in the water can interact with sediments or SPM to form oil particulate aggregates (OPA), or adsorb on or be incorporated into the sediment phase (Lee et al., 2003; Gong et al., 2014) especially in near shore waters. A simulation by a numerical model of oil-sediment interaction revealed that up to 65% of the released oil can be removed from the water column as OPA, while limited amounts of oil can partition into water (Bandara et al., 2011). Therefore, these interactions can change the fate and transport of oil by removing oil from the aqueous phase through the formation of OPA thereby decreasing oil bioavailability and toxicity to aquatic organisms. However, the dissolved fraction of oil hydrocarbons is harmful to aquatic organisms. Furthermore, the re-suspension of toxic oil components from sunken OPA remains a secondary source of toxic threat (Luo et al., 2004).

Dilbit spills present a new challenge for assessing the related environmental impacts as their properties are different from conventional oil. Mesoscale laboratory tests in tanks and observations made from actual spills (Government of Canada, 2013; SL Ross Environmental Research Limited, 2013; US EPA, 2013; King et al., 2014; Zhou et al., 2015) have provided insight into the behavior of spilled dilbit in water. One of the more significant findings is that dilbit products tend to float on the water surface until the oil densities change through weathering and/or sediment uptake (Government of Canada, 2013). The specific chemical composition of the dilbit product was also reported to affect the sinking behavior of diluted bitumen in the environment (King et al., 2014). Relative to conventional petroleum products, dilbit products evaporate faster, mix more rapidly with sediments, sink faster than conventional oils and disperse less when interacting with some chemical dispersants (Fieldhouse et al., 2013; Government of Canada, 2013). These previous studies indicate a stark difference between conventional crude oil and diluted bitumen with respect to spill behavior, fate, and remediation options in the marine/freshwater environment, as well as their potential alteration by evaporation, solar exposure, or mixing with water and sediment. Therefore, the novelty of this study is to focus on dilbit not conventional crude oil, to address the gap of the fate and behavior of oil components between dilbit and conventional oil.

This paper is the second part of study looking at the effects of evaporative weathering and oil-sediment interaction on the fate and behavior of diluted bitumen in marine environments. The first part evaluated the formation of OPA by varying the weathering states of oils, the oil species, and the sediment types by evaluating the physical properties of the formed OPA, including density, particle size, and microscopic profile. We concluded that sediments having fine-to medium-sized particles were more likely to form OPA for fresh and moderately-weathered diluted bitumen. Here, we investigate the factors (oil and sediment type, oil weathering states) affecting water accommodated and particle-laden hydrocarbon species, and the toxicity of aqueous phase by simulating the interaction processes between representative diluted bitumen/conventional oils within the water-sediment system.

Specifically, Cold Lake blend (CLB) oils at various states of weathering (CLB fresh, CLB W2 (15.8% mass loss relative to CLB fresh), and CLB W4 (25.2% mass loss relative to CLB fresh)) were selected as representatives of different forms of dilbits. Several other light to heavy fuel oils, such as Alberta sweet mixed blend (ASMB), intermediate fuel oil (IFO 180), and the heavy oil Bunker C, were compared with the dilbit products for their environmental fate and behavior. Sediments, including kaolin, a natural sediment, and sand, were tested to evaluate the effects of sediment type on the water accommodated or sediment-laden oil amounts. Total petroleum hydrocarbons (TPH) were analyzed from sediment layer samples to evaluate the discriminating effects of sediment-laden oil. To investigate the effect of sediment, oil type, and oil weathering state on their water accommodated fraction (WAF), we measured the water phase TPH, non-alkylated polycyclic aromatic hydrocarbons (PAHs), and their alkylated congeners (APAHs). The microtoxicity of the collected water samples was also tested to compare their toxic potential after saltwater interacted with oil alone or oil and sediment together. This study will provide insights into predicting the fate of dilbit during a spill at sea and improve the selection of an appropriate spill response and remediation approach.

2. Materials and methods

2.1. Chemicals and materials

All used solvents were distilled in glass for liquid and gas chromatography, residue and spectrophotometry analysis (Caledon, Canada). Silica gel (100–200 mesh) was supplied by Spectrum Chemicals (Gardena, CA, USA). Silica gel, sodium sulfate, and glass wool were sequentially rinsed three times with acetone, dichloromethane (DCM), and hexane each and then completely dried in a