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Oil Spill in Lac-Mégantic, Canada: Environmental Monitoring and Remediation

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Abstract

In North America, investment in unconventional oil extraction has increased due to the scarcity of conventional reserves. The rapid production growth has induced an extensive transportation activity, sometimes using aging pipelines and inadequate rail tank cars. Without surprise, in recent years, several high impact oil spills have occurred, as the taken place in Lac-Mégantic, the worst terrestrial oil spill in the history of North America. The accident caused dramatic human, material, and environmental damages. The transported petroleum hydrocarbons contained thousands of compounds, in varying proportions with a variety of properties making evaluations extremely complex. Despite the emergency actions had been undertaken, the pollution was detected in surface water, groundwater, sediments and soils, at different areas: Chaudière River, Lake Mégantic, and Lac-Mégantic City. After a brief return on the context of the Lac-Mégantic oil spill, this paper describes and discusses the undertaken pollution characterization and monitoring, as well as the applied remediation technologies. Several recommendations of unresolved issues are proposed. Indeed, the following issues are addressed: the lack of updated monitoring in some cases; the threshold of certain pollutants; the pollution release from sediments and its ecotoxicological impact; and the role played by complex mixtures of pollutants on ecotoxicity (case of polycyclic aromatic hydrocarbons and derivatives).

Keywords: Oil spill; Unconventional petroleum; Lac-Mégantic; Alkylated PAHs; Emergency actions; Pollution monitoring; Ecotoxicological impact; Bioremediation

Introduction

Petroleum hydrocarbons (PH) are one of the most frequent pollutants in the environment due to the increased usage of petroleum products and the seemingly increasing probability of accidents [1]. Hydrocarbons are highly toxic to microorganisms, invertebrates, and plants [2,3], and constitute a potential risk to health, which increases as hydrocarbon resistance to degradation increases. About 50-60% of polluted sites involve PHs that, left unaddressed, impairs the quality and uses of both land and water [4,5]. Oil spills are a matter of particular concern owing to the magnitude of the needed remediation work which exceeds the current annual capacity of the remediation industry by more than 100 times.

The extraction of PH will continue to increase as they are essential for the growth and progress of countries and contributes significantly to human prosperity and well-being. Currently, the investment on unconventional oils has augmented due to the increasing scarcity of conventional reserves [6]. This is the case of Canada (Alberta's oil sands which comprises the regions of Athabasca, Cold Lake and Peace River) or the USA (Bakken formation). The rapid increase in production has involved the use of old pipelines networks that still remain active to transport unconventional oils to refineries and markets (e.g. from Alberta and North Dakota to coastal ports). Over recent years, several high impact oil spills have occurred [7]. Some examples are the spills of Dilbit (diluted bitumen) from Alberta´s oil in Kalamazoo (USA) and Bakken oil in Lac-Mégantic (Canada), respectively. Common to these sites is the presence of complex mixtures of PH, trace metals (TM), and other toxic products (dispersants, washing solutions, solvents, etc.), all of which present high risks to ecosystems and human health [8]. This accident have highlighted the lack of preparedness to offer sound responses to unconventional oil emergencies and demonstrates the necessity to continue improving the risk analysis methods, to reinforce and apply legislation on risk management, to continue awareness and training in the field of risk management [9]. More specifically, the consequences of these disasters reveal paramount alarms: a) the rate of site rehabilitation is lower than the appearance of newer sites; b) the pollutants can reach urban populated areas and drinking water sources; c) the cost of decontamination can exceed billions of dollars per site; d) even with expensive remediation costs, these sites left irreversible impacts.

The objective of this article is to provide a critical overview of the actions undertaken during and after the Lac-Mégantic's oil spill, in particular concerning the environmental monitoring and remediation. The article, thus, presents: i) the context of the accident and the impacted areas; ii) the pollution characterisation and monitoring; and iii) the undertaken emergency actions and the applied remediation technologies. Special discussion is made on unresolved issues.

Oil spill in Lac-Mégantic: Context of The Accident

On the night of July 5, 2013, a freight train carrying light crude oil derailed in the town of Lac-Mégantic (Quebec, Canada), causing the explosion of several wagons [10]. This catastrophe resulted in the destruction of part of downtown and significant environmental pollution. The Town of Lac-Mégantic is on the edge of the lake of the same name and it is crossed by the Chaudière River. A total of 5.7 million liter of crude Bakken oil was released into the environment, of which 100000 L were spilled into the river [11]. Pumping operations in the river recovered ~51 200 L of water containing PHs. The Chaudière River, 185 km long, empties into the Saint Lawrence River. Floating oil was found up to 186 km from Lac-Mégantic (in Charny). Overall, in the Chaudière Appalaches Region, 47% of the population is supplied by surface water [12]. Upon recommendation of the Ministry of Public Health some municipalities had to find alternative sources of water until fall 2013 [13]. Furthermore, the vanes of the municipal wastewater treatment plant released the accumulated oil and wastewater into the Chaudière River to prevent damages to the plant. By the volume spilled, the dangerousness of substances released and burned, the populated location, the intensity and the extent of pollution plumes (air, soil and water), the spill of Lac-Mégantic is the worst terrestrial oil spill in the history of North America [14,15].

Three main areas were impacted by the accident: Chaudière River, Lake Mégantic, and Lac-Mégantic City. Chaudière River and Lake Mégantic areas are particularly linked to the water network of the city. Indeed, the spilled oil migration from the impact zone to the river and to the lake took two main pathways: 1) the soil surface towards Lake Megantic, and 2) the underground water networks towards the Chaudière River [16]. In terms of impacted surface, the whole river was affected leading to the stop of the drinking water intake of several cities (Lévis, Charny, Sainte-Marie and Saint-Georges), as well as several farms and industries. In Lac-Mégantic City, the damage (human and material) was measured up to a distance of over 500 m from the impact zone. The environmental damage was evaluated in a surface of 31 hectares [17]. The soils of Lac-Mégantic City were highly affected by both the fire and the hydrocarbon pollution (and the subsequent leaching up to 3 m depth). After the accident, the town was divided in three protection zones or perimeters: green (progressive reintegration of population), yellow (controlled access area), and red (restricted area).

Pollution Characterisation and Monitoring

The properties of PH pollution vary with the source, environmental matrix, composition, degree of processing, site-specific circumstances, and the extent of weathering caused by exposure to the environment [4] what makes its evaluation extremely complex. Petroleum products released into the environment typically contain thousands of compounds, in varying proportions: polycyclic aromatic hydrocarbons (PAHs); volatile aromatic hydrocarbons (VOCs) such as benzene, toluene, ethyl benzene and xylene (BTEX); TMs and metalloids; and other products such as solvents, alcohols, biocides, surfactants, acids/bases, and corrosion inhibitors. As stated above, the train derailed in Lac-Mégantic carried Bakken crude petroleum (unconventional oil imported from North Dakota, USA). Certain physicochemical characteristics and composition were described by the MDDELCC in the report of the experts' committee [16]: light oil (>30 degrees API) consisting of a complex combination of paraffinic and aromatic hydrocarbons with a small amount of compounds of N, S, and O, as well as TMs (mainly Cr, Fe, Ni, Pb, and V). After the derailment, the majority of crude oil burned during the fire, resulting in: a) the loss of the lightest fractions ($<C_{12}$); b) the formation of combustion by-products; and c) the oil viscosity and density increase. Based on this report [16], the chemical composition of the crude petroleum (analyzed in wagons and wells) was: 1) PH of C_6-C_{50} range with predominance in the C_{10}-C_{34} region; 2) BTEX; and 3) PAHs and alkyl PAHs (naphthalene and methyl-, dimethyl-, and methylethyl-).

Chaudière River and Lake Mégantic

From July to October 2013 (opening date of drinking water intakes in the Chaudière River), an intense water sampling was performed. As reported by the MDDELCC [18], PH concentrations were under the method detection limits, except for three samples, and no VOCs were detected. Concerning TMs, suspended solids, and dissolved organic carbon, the values were below the threshold concentrations that affect aquatic life and were of the same order of magnitude as the historical data of the Chaudière River [19]. Thus, given the limits proposed by the MDDELCC, data indicated no concern concentrations for aquatic life. However, limits should be reviewed and carefully interpreted considering that the concentration of any pollutant in water is heavily dependent on water-sediment interactions. In this regard, the upper level concentration of PH C_{10}-C_{50} in sediments considered by MDDELCC [20] is 8 times higher than the concentrations considered in other normative such as in the 310 CMR 40.0000: Massachusetts Contingency Plan. A large number of sediment samples (~600) were also characterized. Around 22% of sediment samples showed concentrations of PH C_{10}-C_{50} which can trigger chronic effects in aquatic life [21]. Also, some samples showed the presence of toluene, TMs et metalloids (As, Ni, Pb, and Zn) and PAHs (acenaphthene, acenaphthylene, fluoranthene, phenanthrene, pyrene, 2-methyl-naphthalene, benzo(a) anthracene, benzo (a) pyrene and chrysene) [14]. As discussed below, residual pollution can remain in these sediments, potentially affecting the water quality in the medium or the long-term. Eco-toxicity assays could provide with insights on real remaining risks and dangers for benthic and higher organisms.

Consequently, several sampling campaigns were conducted in 2013 to assess the level of contamination in the fish population in Lake Mégantic and in Chaudière River. Mercury, other TMs and metalloids, PAHs, polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs), chlorinated dioxins and furans, and perfluorinated compounds were measured in some fish tissues. A report was specifically published by the MDDELCC [22]. Results showed: 1) Hg levels 2.5–4 fold the Canadian standard (0.5 mg/kg) which was attributed to several years of Hg exposure (levels are comparable to those measured in many water bodies in natural conditions); 2) two overruns of PBDE limit values; 3) one overrun of per fluorinated compounds; and 4) no overruns for the other pollutants measured. The levels of PAHs in the flesh and in the liver of sampled fish increased after the accident (July, 2013) for then declining in the following months (October, 2013). Unfortunately, Canada has no standard for PAHs content in fish. The report concludes that there is no clear evidence that the oil spill in Lake Megantic and the Chaudière River have resulted in the increased levels of these pollutants on fish tissues.

Hydrocarbons trapped in sediments may decrease microbial and meiofauna density, biomass and diversity of benthic fauna, suppress photosynthesis of phytoplankton, as well as alter macrofauna community and feeding activity. An understanding of the impact of complex mixtures of pollutants on ecotoxicological processes, as well as the identification of organism groups recolonizing the impacted areas (water, sediments, or soils), are prerequisite for directing the management of PH-polluted ecosystems. To our knowledge, a comprehensive study of the ecotoxicological impact at different levels of the food chain has not been carried out.

Lac-Mégantic City

Concerning soils, a large number of samples (up to 480) were analysed and data were compared to the criterion B established by the MDDELCC. Criterion B corresponds to the maximum acceptable limit for residential, recreational, and institutional sites [23]. Commercial sites located in a residential district are also included. Results showed that around 80-85% of analysed soil samples (both natural and backfill) presented lower contamination values than the criterion B in the following detected compounds: PH C_{10}-C_{50}, VOCs (mainly BTEX and trimethylbenzene), HAPs (mainly methylnaphthalene, benzo(a)anthracene, benzo(a)pyrene, benzo(a) fluoranthene, chrysene, and phenanthrene), TMs and metalloids (As, Cu, Sn, Mo, Ni, Pb, and Zn), dioxins and furans, and glycols [17]. In all cases, the highest levels were found in the impact zone of the accident (red perimeter). Within this perimeter, about 66% of the soil excavated had higher concentrations in several pollutants than the criterion B. Despite alkylated PAHs were analysed the results have been not interpreted in the official reports since there is no standard of the MDDELCC.

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Groundwater was monitored for C_{10}-C_{50}, VOCs, BTEX and TMs. From the last Golder & Associates report [24] and based on available data, there was not plume of hydrocarbons. However, there was risk of displacement and dispersion of HP during ice thawing and spring rain. At this moment, the information is not yet accessible. Another study was performed by Laforest Nova Aqua inc. in 2014 [25]. They concluded that at long-term, the risk of groundwater contamination ranged from very low to zero. The parameters analysed were PH C_{10}-C_{50}, VOCs, HAPs, TMs and metalloids (15 elements including As), dioxins and furans, phenolic compounds and total phosphorus. The time of vertical water transfer from the surface to the aquifer was estimated to 705 years. When the water finally reaches the surface aquifer, the time of horizontal water migration from the accident area to the municipal wells is estimated in 14 years. In conclusion, an annual monitoring of PH C_{10}-C_{50}, VOCs, HAPs for 5 years was recommended.

Undertaken Emergency Actions and Remediation Technologies

It has been almost 20 years since the Exxon Valdez spill (1989). Since then, international environmental debate and activity has been intense, and other significant spills throughout the world (the Prestige in Spain, the Deepwater Horizon in the Gulf of Mexico, the Estrella Pampeana in Argentina, the West Falmouth in USA, or the OSSA II pipeline in Bolivia) focused attention on oil pollution. Since Exxon Valdez accident, the Shoreline Clean-up and Assessment Technique (SCAT) program has become an integral component of spill response, and consists in a five step process to assess shoreline conditions, determine needed clean-up actions, conduct the clean-up, inspect the results, and sign-off on the satisfactory performance [26,27]. The SCAT program was applied to the Lac-Mégantic accident.

Overall, according to MDDELCC, the mitigation plan of Lac-Mégantic oil spill has alleviated achieved 90% of decontamination in the intervention area in two years but it is not indicated in which data this statement is based on [21]. The pollution levels of soils, surface water and river banks were minimized with the application of initial responses and emergency actions. At short term, in order to prevent the environmental pollution the initial action was to protect unpolluted zones by containing the crude oil. Booms (temporary floating barriers) were thus, deployed in Chaudière River and Lake Mégantic. Few hours after the accident the oil pumping started. The flow of Lac-Mégantic Dam was regulated to limit the spread of pollution to the Chaudière River. In Lac-Mégantic City the emergency actions consisted in oil containment and pumping, preventing flowing and leaching in soils, as well as oil flowing in the water networks of the city (sewer, aqueduct system, and pluvial). Retention measures were also installed (e.g. recovery wells, trenches, temporary basins, oil absorbent socks) [14]. These measures allowed the recovering of 46678 m^3 of oily water from the lake, sewage, and soil by November 27th, 2013; and avoided the pollution of groundwater [17].

Chaudière River and Lake Mégantic

As stated above, ~51 200 L of water was pumped. Water was treated by physico-chemical processes. Firstly, oily water was directed to a water/oil separator basin. Then, the extracted water passed through a sand/anthracite filter, a clay filter, and two activated charcoal filters prior to its release to the environment [28].

In 2013, more than 40 km of Chaudière riverbanks and the affected banks of Lake Mégantic were cleaned with flushing and manual removal of rocks, vegetation and sediments [16,29]. The PH C_{10}-C_{50} content in sediments was reduced in one year. The samples collected in 2013 were 26% >164 mg/kg, 26% >832 mg/kg; and samples collected in 2014 were 18% >164 mg/kg, 4% >832 mg/kg [21]. Similar measures were undertaken in the case of Kalamazoo accident in USA, in which a pipeline transporting Alberta's Cold Lake Crude Oil broke: a fraction of the released oil was contained installing a series of underflow dams, weirs and containment booms; and 40 miles of river (80 miles of shoreline, i.e. ~129 km) were cleaned [30]. In 2014, the most polluted segment of Chaudière River, located at km 4.5 downriver Lac-Mégantic dam, was restored capping 2500 m^2 of sediments [31]. Then, sediments were dried in shaking platforms prior to be confined thereafter in authorized landfills [21].

Lac-Mégantic City

Complete soil remediation is expected to end by March 2017. For such purpose, the excavated soil (280000 m^3) has been temporarily stored on site and in several platforms (~70000 m^3 each) specifically built in Lac-Mégantic [21]. The soil is mainly treated at Lac-Mégantic's platforms along with the sites at Sherbrook and at Sainte-Rosaire [21]. Bioremediation was the chosen approach, injecting air and nutrients to boost PH degradation by microorganisms [32]. Then, the remediated soil has been employed in the backfilling of the asbestos Jeffrey Mine (Quebec, Canada). Currently, the impacted area in the city is backfilled with clean sand and cracked stone from off-site borrows [21].

After the accident, 43 million litres of liquid recovered from the derailment site (water, crude oil, and sludges) had to be treated. A mobile processing unit of water and sludge contaminated with oil was installed to manage the pollution [17]. The water to be treated contained a mixture of pollutants: unburnt crude oil, pyrolyzed oil, soot and ashes, soil particles, firefighting foams, and burnt debris forming a challenge in treatment steps [33]. The company commissioned for the treatment had to use an unconventional process (UltrasorptionTM) to help deal with surfactants and colloids.

Unresolved Issues

Previous sections have revealed several issues to cope with, such as: the permissive PH levels in sediments; the monitoring of treated soils, surface waters and sediments; the pollution release from sediments; the ecotoxicological assessment; and the assessment of the role played by the complex mixtures of pollutants on ecotoxicity.

Threshold of PH in sediments

The MDDEFP established PH C10-C50>164 mg/kg as the upper concentration level for the existence of chronic effects in aquatic life [20]. According to these criteria 78% of sediment samples collected in 2014 was below the threshold to produce chronic effects [21]. As discussed above, the established limit is more permissive than other normative such as the 310 CMR 40.0000: Massachusetts Contingency Plan. However, more restricting levels could help minimizing the risk of chronic effects in aquatic life; could permit to know better the retention time of PH in sediments; and could indicate whether polluted sediments require further treatment or management.

Monitoring the pollutant content in treated soils, surface waters and sediments

As described above, the available information of pollution levels in soils, surface waters and sediments is from 2013 to 2014 mainly via public communications. Updated information, from open data or reports, is required to understand the current extent of decontamination process. Degradation of PH may produce the formation of toxic sub-products [34]. Therefore, chemicals content in treated soils and surface waters can be used to provide recommendations for the treatment of future spills of unconventional oils. Thus, further characterization of soils can confirm when bioremediation degrades recalcitrant compounds such as PAHs.

Monitoring the pollution release from sediments and its ecotoxicological impact

Most of the oil spill events are well documented in the literature. However, some differences can be found in the case of the Lac-Mégantic scenario. In contrast to heavy oils, light oils are readily dispersed in the water column, mainly under turbulent water mass, increasing the risk that the oil settles to the river bottom. Chaudière River presents a quite variable flow (from 11 to 470 m^3/s), meanders with areas of high sediment accumulation, and rapids with areas of high erosion by water flow and more importantly by the dynamics of ice. So, there is a large risk of dispersion of oil in the Chaudière River due to its turbulent flow [14]. Moreover, after the initial chemical processes up to 50% of spilled PH, enriched in heavier recalcitrant compounds, may be deposited in bottom sediments acting as long-term reservoirs and secondary sources. This pattern has been previously observed in other similar events, as the Kalamazoo accident [30]. The release of any pollutant from sediments to the interstitial water, and subsequently to water body (being more potentially available to aquatic flore and fauna), can increase as a function of a number of biogeochemical and climate factors. These factors will determine if sediments act as a source (release > adsorption), as a sink (release < adsorption) or at equilibrium (release = adsorption). During thawing in spring, water and melting ice could re-mobilize the pollutants accumulated in sediments, increasing their (bio) availability and thus affecting the chain food in the medium/long-term. Indeed, several studies have reported higher PH levels in water, sediments, soils, and biota, even several months or even years after an oil spill [35-37]. The complexity of these processes, especially under Nordic climate conditions, highlights the vulnerability of this multipollution scenario and makes essential monitoring the availability of PHs and co-pollutants (such as TMs) and their transfer from one environmental echelon to another over a long time interval. A study focused on pollution release from sediments to the water body and its impact on ecotoxicity is required.

Ecotoxicity of complex mixtures: case of PAHs and alkylated PAHs

As stated above, the results of sample characterization (wagons and wells) have revealed the presence of both PAHs as its alkyl derivatives (naphthalene and methyl-, dimethyl-, and methylethyl-) [16]. A complex petrogenic-pyrogenic mixture, partially determined by the fire, was also observed in other accidents (e.g.: the Prestige oil spill in Spain or the fire accident of the HMCE Chicoutimi submarine in Ireland) [38,39]. Unfortunately, alkylated PAHs are little or not considered in the criteria for the protection of the environment in Quebec [40,41]. Alkylated PAHs have been shown to contribute significantly to the toxicity of PAH mixtures up to ~80% of the toxic load [42], demonstrating the importance of the composition of complex mixtures rather than the total concentration [43]. Despite the fact that most studies on toxicity, bioaccumulation and/or bioavailability focus on parent PAHs, several studies have been conducted with alkylated PAHs. Thus, alkylated PAHs have shown to be more toxic than their counterparts parent PAHs, or be better correlated with toxicity patterns on amphipod crustaceans [42,44], aquatic insects [45], fish [43,46], benthic and algal communities [47-49], and earthworms [50]. The effects of alkylated PAHs in different ecosystem compartments are strongly determined by their bioavailability. While the factors that determine the bioavailability of PAHs (alkylated and non-alkylated) are not yet fully understood, several studies have shown the importance of the combined action of several factors: the characteristics of PAHs (molecular weight, alkyl, hydrophobicity) [51,52], environmental variables (pH, electrical conductivity, organic matter, clay) [47,53-56] and target organisms (routes of exposure, etc.). Moreover, interactions between pollutants are likely to occur. Thus, Maliszewska-Kordybach and Smreczak [57] reported that PAHs enhance the toxicity of TMs to microorganisms due to lipophilic PAHs interaction with membranes, increasing the permeability to TMs. An analysis of toxic effects on several trophic levels considering the complex mixture of pollutants is required for a more comprehensive and representative understanding of toxicity risk [58].

Conclusions

Within the mitigation plan, several actions were undertaken in the short-term (emergency actions) and in the medium/long-term (characterisation, monitoring, and remediation) after the Lac-Mégantic accident. This plan has currently reached an unclear decontamination ratio of 90%. Indeed, there are several aspects that can and should be improved. The most important remaining tasks are: 1) to conduct an ecotoxicological impact assessment taking into consideration the effect of complex mixtures of pollutants, 2) to implement regulation criteria for certain pollutants (case of alkyl derivatives polycyclic aromatic hydrocarbons), and 3) to consider reservoirs and secondary sources of pollutants (e.g. sediments). In order to make more reliable risk assessments, polluted site management paradigms should evolve from concentration-based to based-risk approach. This approach will not only give valuable information on the bioavailability of pollutants (more realistic than the total concentration of a compound), but also will advance the understanding on soil/sediment-water-biota-pollutant interactions. Working in this direction, the Lac-Mégantic oil spill offers an excellent opportunity to increase scientific knowledge and management in a multipollution scenario with unconventional oils on: i) the transfer of pollutants from one environmental compartment and level to another, ii) the responses of the organisms against complex mixtures, iii) the natural or assisted recovery of the ecosystem, and iv) the optimization of remediation technologies.

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