CHEMICAL ENGINEERING TRANSACTIONS
VOL. 57, 2017
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet
Guest Editors: Sauro Pierucci, Jiří Jaromír Klemeš, Laura Piazza, Serafim Bakalis

ISBN 978-88-95608- 48-8; **ISSN** 2283-9216
DOI: 10.3303/CET1757059

Analysis of the Behaviour of Oil Spills in a Sector of the Magdalena River (Colombia)

Viatcheslav Kafarov[a], Crisóstomo Barajas Ferreira[a], Ágata Fernandes Romero[b], Ana Carolina da Rocha Lammardo[c], Aurelien Hospital[d], Natalia LeonBarrios[d], Lara Conti Ansanelli[c], Diana M. Ibarra-Mojica*[a]

[a]Universidad Industrial de Santander, Cra 27 calle 9, Bucaramanga-Santander (Colombia)
[b]Universidade Estadual Paulista, Praça Infante Dom Henrique, Parque Bitaru – CEP 11330-900 - São Vicente SP (Brazíl).
[c]Tetra Tech-Brazil, Rua Fidalga 711, São Paulo -SP (Brazil).
[d]Tetra Tech Canada, 10th Fl., 885 Dunsmuir Street, Vancouver, BC V6C 1N5 (Canada).
dibarramojica@gmail.com / diana.ibarra1@correo.uis.edu.co

In 2005, it was estimated that over 70% of oil spills in Colombia affected riverine areas. The Magdalena River is the longest navigable river in the country. It is home to countless species of flora and fauna, and provides important services as both a resource and a river transport route. Hydrocarbons represent 91% of products carried on the river.
Mitigation associated with oil spill impacts depends largely on the formulation and implementation of adequate contingency plans, which should incorporate the identification of sources of oil spills, the simulation of the respective dispersion patterns and the characterization of areas that could be affected by a spill.
Several different types of oil spills in the Magdalena River were simulated in order to assess the possible spill behavior, based on an analysis of sites at risk of releasing oil into the water stream, and considering the characteristics of the products most frequently transported along the river or used as fuel for boats.
Taking into account the seasonal variability in river level and river flow, two different scenarios were simulated: rainy season (which usually floods in the surrounding area of the river) and normal season (when the river is within its usual margins and is navigable on most of its reaches); the dry season was not simulated at the time of this paper because of missing shoreline information. The results show considerable differences in the behaviour of the spilled oil under different climatic seasons. Therefore, this type of analysis is suitable to use for the formulation of refined plans for effective and efficient spill response and mitigation.

1. Introduction

SPILLCALC, a proprietary oil spill model developed by Tetra Tech, was used to simulate oil spills in the Magdalena River located in Colombia. River currents were obtained from a hydrodynamic model implemented in the Magdalena River using Delft3D-FLOW (DELTARES, 2013).
Based on the wide range of water levels and river flows, two different seasons were simulated: the rainy season, and the normal season. For each one of these two seasons, one spill volume (1,257.96 barrels – 200 m^3) and one oil type (crude oil API 21.3) was simulated. The spill site was established in the immediate vicinity of Barrancabermeja – Santander, where the country's largest refinery is located.

2. Study area

The Magdalena River, with a length of 1,528 km, is Colombia's most important waterway. The navigable length of the river is estimated to be 886 km, and it is a dominant factor in the economic success of Colombia. Its watershed represents 17% of the national territory (19,294 km^2); 75% of Colombian agricultural production is generated, and 77% of the population is supplied with water for domestic uses, including drinking. Additionally, it is estimated that of the more than 200 recognized fish species in the river, 55% are endemic.

Please cite this article as: Kafarov V., Barajas Ferreira C., Fernandes Romero A., Da Rocha Lammardo A.C., Hospital A., Leonbarrios N., Ansanelli Conti L., Ibarra-Mojica D.M., 2017, Analysis of the behavior of oil spills in a sector of the magdalena river (colombia), Chemical Engineering Transactions, 57, 349-354 DOI: 10.3303/CET1757059

For these reasons, the Magdalene River is one of the basins with the highest degree of human pressure on the environment (Téllez et al., 2011).
The selected study area has a length of 200 km, between the municipality of Barrancabermeja -Santander and the municipality La Gloria -Cesar. Per information provided by the National Environmental Licensing Agency (ANLA), there have been 30 incidents of spills in this sector between 2004 and 2016, one of the most frequent being oil spills.

3. Hydrodynamic Modelling

The Delft3D-FLOW modelling software (DELTARES, 2013) used for this study can simulate hydrodynamic circulation in response to baroclinic and barotropic forces, as well as the transfer of momentum to the hydrodynamic system due to wind forcing. The possibility of working with highly adjustable contour grids was another determining factor for the choice of this modelling software. The accommodation of the numerical grid to the shoreline allows an accurate representation of the Magdalena River. The model includes flooding and drying algorithms, so is well suited to modelling a river with large changes in depth and river width over the course of a year. Figure 1 shows the domain of study (left panel) and a snapshot of velocity field during the flood season (right panel). Velocities exceed 0.5 m/s in the main channel.
For the implementation of the hydrodynamic model, bathymetric information was collected in the study area at a scale of 1: 25.000, through the Regional Autonomous Corporation of the Rio Grande de la Magdalena - CORMAGDALENA. In addition, information on hydrological and hydro-meteorological stations of the Institute of Hydrology, Meteorology and Environmental Studies of Colombia - IDEAM was analyzed to establish the characteristics of the zone in terms of flows and river levels; as well as wind speed and direction. Met station 23155030 (Barrancabermeja airport) provided wind speed for this study. The year 1999 was simulated as a representative year in terms of flow and levels conditions, according to information taken from met stations 23157080 (close to Barrancabermeja, Santander) and 25027410 (close to La Gloria, Cesar).
Through this analysis, it was established that the behavior of the river in terms of levels and flows is due to the quarterly bimodal climatology characteristic of the country: two periods of high flow, and two periods of low flow per year. Each high and low flow period is separated by a transient period. Thus, over a full year, the river presents changes every two months from high levels, in the rainy season, to transient levels to low levels during the dry season (Figure 2). The hydrograph, i.e. river flow conditions and water level, provided boundary conditions to drive the hydrodynamic model.

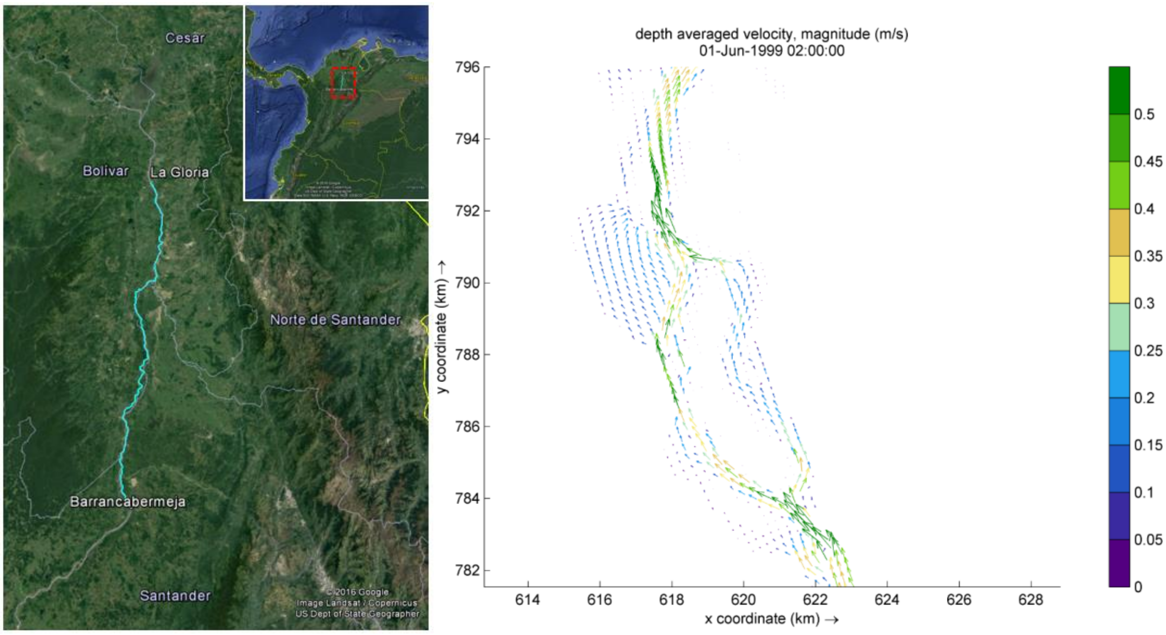

Figure 1. Domain of Study: Magdalena River in Colombia (Left Panel) and Hydrodynamic Current Field Snapshot during Flood Season (Right Panel)

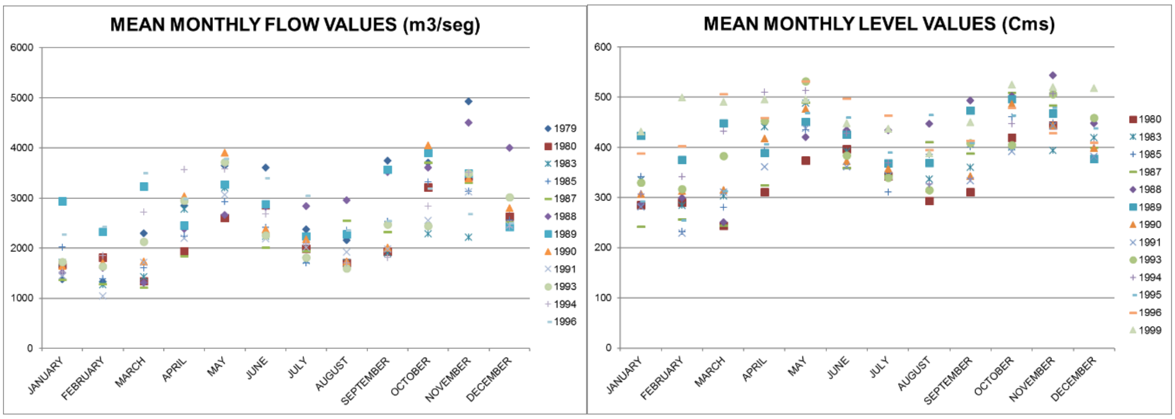

Figure 2. Variation of Levels and Flows of the Magdalena River.

4. Oil Spill Modelling

The SPILLCALC model developed by Tetra Tech was selected to simulate the trajectory and fate of liquid hydrocarbon spills. Oil released on the water surface is represented as a large number of independent floating particles, referred to as slicklets. For this study 30,000 particles were used for the modelling. Individual slicklets are not intended to be physically meaningful. Instead, the cloud of particles as a whole is the area covered by the spill, and its progress is the spill's dispersion and trajectory. Each particle's velocity is computed as the vector sum of three components (currents, wind drag and random velocity).

$$\vec{V}_{Oil} = \vec{V}_{Oil:\,advection} + \vec{V}_{Oil:\,wind} + \vec{V}_{Oil:\,diffusion} \tag{1}$$

A stochastic approach was used in this study to assess the impact of a spill in the area of study in the Magdalena River. A stochastic simulation is essentially a collection of separate spill simulations in which some or all of spill location, spill volume, oil type, start time and date are allowed to vary. The resulting set of spills can be analyzed to obtain statistical information on the probable extent of a spill, the likelihood that a spill may reach a certain area, and the amount of shoreline that can be potentially contacted. The intent of a stochastic simulation is to simulate a wide range of environmental conditions without bias to any particular set of conditions, and thereby delineate the maximum predicted footprint of the spill from a particular location.

4.1 Oil Properties

Typically, once released into the riverine, or marine, environment, crude oil will begin to "weather": lighter components of the crude oil will begin to evaporate and dissolve into the water column; the remainder will float as long as the density of the remaining oil is less than the density of the water into which it was released. Depending on the river stage, shoreline contact can occur at any time following the release.

Table 1: Pseudo-Component Information for Western Canadian Select Type Oil (Surrogate for Crude Magdalena)

Pseudo-Component	Volatiles	Benzene	TEX	Aromatics >C8-C10	Aromatics >C10-C12	Aromatics >C12-C16	Aromatics >C16-C21	Aromatics >C21-C34
Concentration (mg/kg)	58,800	1,100	3,760	3,000	7,700	14,000	27,000	69,000

Pseudo-Component	Aliphatics C6-C8	Aliphatics >C8-C10	Aliphatics >C10-C12	Aliphatics >C12-C16	Aliphatics >C16-C21	Aliphatics >C21-C34	F4 (>C34-C50)	Resins	Asphaltenes
Concentration (mg/kg)	23,000	6,400	26,000	62,000	72,000	110,000	110,000	335,240	71,000

Oil is characterized by its pseudo-component composition, facilitating the calculation of the effects of weathering on oil in the riverine environment. Whereas a product such as crude oil contains many chemical species (e.g., benzene, heptane, octane, etc.), a pseudo-component is a group of these chemical species with relatively similar properties (e.g. aromatics with carbon numbers 6 to 10). Crude Magdalena (a mixture of crudes extracted in the middle basin of the Magdalena Medio River) was selected for this analysis. Since the information about the pseudo-component structure of Crude Magdalena was not available, a surrogate oil was selected, based on their density and the similarity of their distillation curves, reflection a similar hydrocarbon composition. Western Canadian Select oil was thus selected for the stochastic modelling. It is a crude oil similar to Crude Magdalena and has a measured relative density at 15ºC is 926.6 kg/m^3. Table 1 describes the mass fraction of the 17 pseudo-components. For each pseudo-component, a corresponding set of physical and chemical properties was associated: molar weight, density, vapor pressure and solubility, characterizing the potential of each pseudo-component to weather.

4.2 Oil Weathering

The SPILLCALC model includes the following weathering processes (Hospital and Stronach, 2014):

- Evaporation:
  Two processes determine the rate of evaporation. First, the standard bulk aerodynamic process, which calculates the mass flux from the surface slick based on wind speed, temperature, equilibrium pressure for each the pseudo-component and molar concentration of the pseudo-component in the total product.
  Second, SPILLCALC limits the rate of evaporation to the rate at which molecular diffusion can supply each pseudo-component to the evaporating surface from the interior of the slick: important during the initial phases of a spill.
- Biodegradation
  SPILLCALC uses a first order bacterial decay process in which the rate of oil biodegraded is proportional to the mass of oil and an empirical decay coefficient.
- Dissolution
  Some of the lighter hydrocarbon fractions, such as benzene, are soluble in water; they will dissolve into the underlying water column. The potential for dissolution is a function of the pure component solubility, the mole fraction of the hydrocarbon in the source (spilled product) and the receptor (surface waters of the study area) and the mass transfer coefficient. The rate of dissolution is computed according to an equation published by MacKay and Leinonen (1977) and uses their value for a mass transfer coefficient: 2.36 x 10^{-6} m/s.
- Shoreline retention
  Each segment of shoreline can retain a certain maximum volume of oil, based on the shore type, the tabulated retention capacity of that type of shoreline, and the length of the shoreline segment. The Magdalena River shoreline was classified following the Environmental Sensitivity Index by the NOAA (Petersen et al., 2002). Shore types were primarily made of sandy bars and gently sloping banks, exposed eroding banks in unconsolidated sediments, vegetated low banks, riprap and exposed rocky banks /exposed solid man-made structures. Since time did not permit an investigation in detail of the width of each shore segment, a width of 2m was assumed for the shoreline. The holding capacity of each shore segment was then determined, based on the shoreline type and the oil viscosity (high viscosity > 2000 cSt for crude oil), as documented in Schmidt-Etkin et al. (2007).

5. Results and Analysis

The Magdalena River system responds to oil spills differently, according to season. Two characteristic seasons were selected for this study: the rainy season (which usually floods into the surrounding areas of the river) and the normal season (when the river is within its usual margins and is navigable on most of its sectors). At the time of this study, shoreline information for the dry season was missing, hence the dry season was not simulated. In addition, a particular focus was put on the maximum downstream extent of a potential spill, hence the focus on both flood and normal seasons. Stochastic modelling was conducted for each season and spanned a two-month period: March-April for the normal season and May-June for the flood season. An independent simulation was started every day. The spill was assumed to occur instantaneously in the immediate vicinity of Barrancabermeja (7.062ºN, -73.878ºW).

In this paper, the results and analysis are focused on the worst-case scenario, i.e. spills with a release of 1,258 bbls (200 m^3). The stochastic modelling encompasses 61 independent simulations for each season, representing a total of 122 simulations for both seasons for a worst-case spill scenario. The large number of simulations enables a representative sampling of the Magdalena River flow and level conditions as well as wind conditions.

Trajectory, shoreline contact and oil weathering were calculated for each independent simulation, allowing a probabilistic analysis of the spills. Table 2 summarizes the mass balance results as well as shoreline contact. Figure 3 (left panel) shows the potential extent of the spill through the probability of oil presence. The black arrow indicates the location of the release. The right panel of Figure 3 shows the time to first contact, a useful indicator for mitigation planning. As expected, the flood season results in the largest potential downstream extent of the oil, due to high river flow. However, because the river is in flood stage, many islands in the river are flooded, so there is reduced availability of shorelines that could retain oil, resulting in a smaller length of shoreline contacted compared to the normal season. It should be noted though that the shoreline associated with the river in its flood stage presents higher retention capacity (marsh areas…), which results in a greater amount of oil retained by the shoreline in average during the flood season compared to the normal season. As one would expect, the normal season shows a much smaller footprint compared to the flood season. One could note the evaporation rate appearing to be slightly on the high side for heavy crude oil. It should be noted that the evaporation module was turned on for oil retained by the shore. The evaporation of stranded oil is directly linked to the area of oil on the shore, which was only roughly estimated. Further work can be pursued with a more detailed assessment of the shoreline width and the corresponding shore retention and loss of evaporated oil.

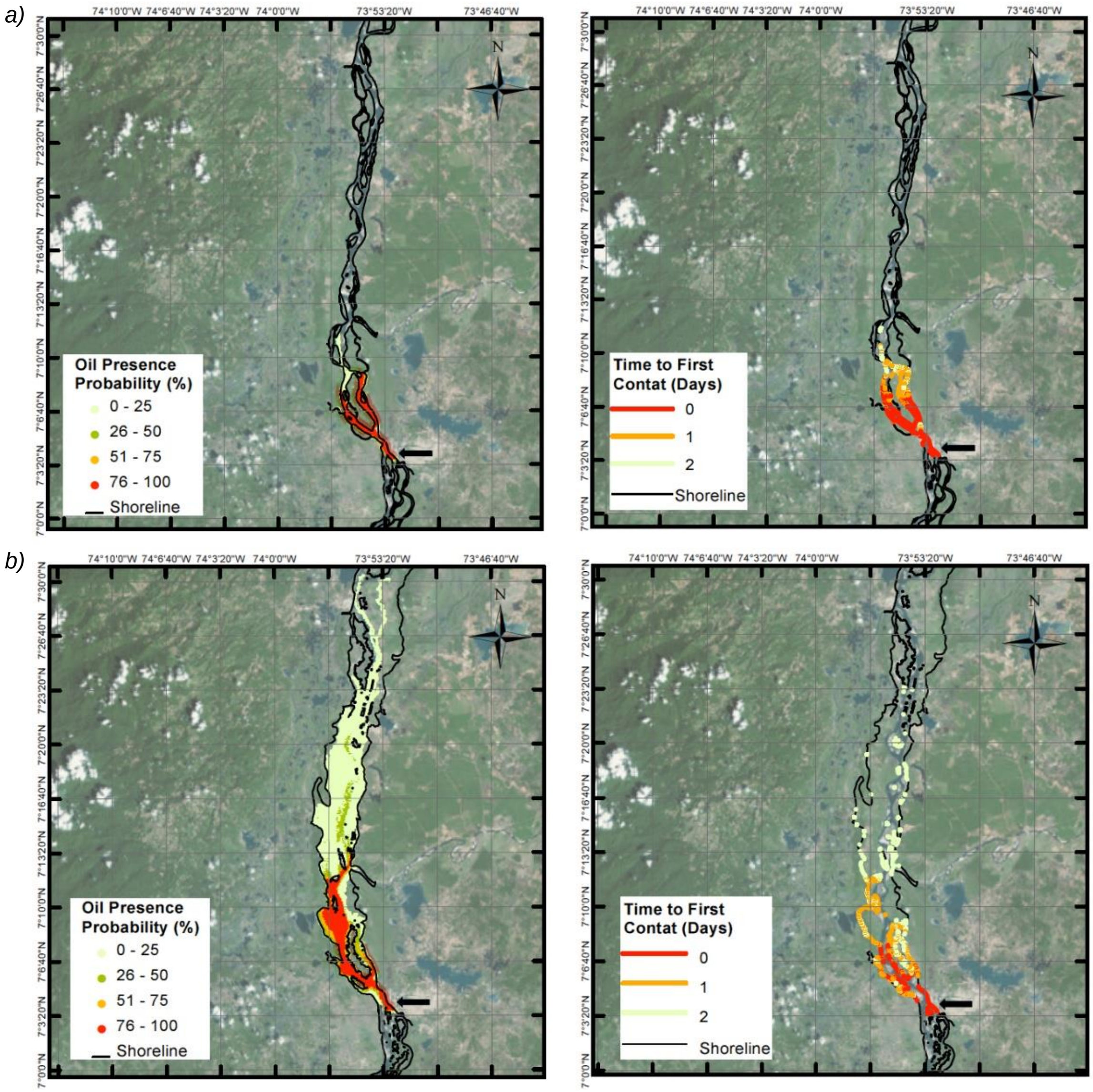

Figure 3. Oil Presence Probability (Left Panel) and Time to First Contact for Shoreline (Right Panel). a) Transient Season. b) Flood Season.

Table 2: Mass Balance and Shoreline Contact for a 200 m^3 spill

Item	Normal (March-April)	Flood (May-June)
Average Length of shoreline contacted (km)	19.9 km	15.4 km
Minimum Length of shoreline contacted (km)	9.6 km	7.2 km
Maximum Length of shoreline contacted (km)	25.5 km	24.9 km
Amount of oil retained by the shore	108.3 m^3	122.6 m^3
Amount of oil evaporated	79.0 m^3	68.4 m^3
Amount of oil dissolved and biodegraded	6.4 m^3	5.5 m^3
Amount of oil left on water after 3 days	6.3 m^3	3.5 m^3

6. Conclusions

Stochastic modelling was conducted to assess the potential fate and behaviour of a crude oil spill occurring in the Magdalena River near Barrancabermeja, Colombia. Two seasons (normal and flood) were simulated, allowing an assessment of seasonal patterns. A three-dimensional hydrodynamic model, Delft 3D, provided surface currents to the spill model, SPILLCALC.

The modelling showed that the primary fate of spilled oil is the retention by the shoreline, regardless of the season. The flood season showed a higher amount of oil retained by the shoreline due to a greater shoreline retention capacity when the river is in its flood stage. However, the flood season also resulted in a smaller length of shoreline contacted by the oil compared to the normal season, which can be explained by high river water levels resulting in extensive banks and islands being no longer exposed. The maximum length of shoreline contacted was 26 km, occurring during the normal season, and the minimum 7 km, occurring during the flood season.

The SPILLCALC tool allows the development of mitigation plans, differentiated according to season, which can be designed for the protection of sensitive shorelines and water intakes, based on the time to first contact and the extent of the slick.

References

DELTARES, 2013, User Manual Delft3D-FLOW. Simulation of Multi-Dimensional Hydrodynamic and Transport Phenomena, Including Sediments. Deltares, Delft, The Netherlands. 702pp

MacKay D. and Leinonen P.J., 1977, Mathematical Model of the Behaviour of Oil Spills on Water with Natural and Chemical Dispersion, Report Submitted to Environmental Protein Service, Department of Fisheries and the Environment. EPS-3-EC-77-19.

Petersen J., Michel J., Zengel S., White M., Lord C. and Plank C., 2002, Environmental Sensitivity Index Guidelines Version 3.0, NOAA Technical Memorandum NOS OR&R 11.

Stronach J.A., and Hospital A., 2014, The Implementation of Molecular Diffusion to Simulate the Fate and Behaviour of a Diluted Bitumen Oil Spill and its Application to Stochastic Modelling, Proceedings of the Thirty-Seventh AMOP Technical Seminar on Environmental Contamination and Response, Environment Canada, Ottawa, ON, 1:353-373.