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Application of Free Software (GNOME) for Simulation of Oil Spills Trajectories in a Sector of Magdalena River (Colombia)

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According to the National Environmental Licenses Authority –ANLA, between 2004 and 2017, there were around 6.300 oil spills in Colombia, 40 % of which affected freshwater bodies. However, at the national level, the use of spill behavior prediction tools is not very extensive, due to the high costs of commercial software. Therefore, the main objective of this paper was to use the free software GNOME (General NOAA Operational Modeling Environment) in a sector of the Magdalena river (most important Colombian river). A collection of 54 instantaneous spills scenarios were simulated. Where a variation in the hydrocarbons type, volume spilled, wind direction and the time elapsed after effusion were considered. The comparison of the spill scenario's mass balance showed that during the first six hours regardless the wind direction most of the hydrocarbons are deposited on banks, except for gasoline. After this time, the hydrocarbons are affected by environmental conditions and are volatilized, decreasing the remaining in water surface and banks. The results obtained were consistent with the literature respect to the volume of evaporated product is greater in the lighter products. The primary fate of spilled oil coincided with the previous modeling in the same sector of the river with software for private use. In both cases, the most probable destination of the hydrocarbons were the riverbanks. Since there are no other similar studies in Colombia, there was not possible to establish a comparison of results regarding the effect of wind direction and hydrocarbon type (specifically for the study sector). In conclusion, GNOME is an open-access software which evaluates the main processes that influence the oil spill's displacement (diffusion, evaporation, and dispersion) offering consistent results. The novelty of this paper is that it is the first application of GNOME in a Colombian river, as an alternative for increasing the use of numerical modelling tools in the design of contingency plans in the country.

1. Introduction

In 2014, 2010 oil spills were reported in Latin America (ARPEL, 2015), while in Colombia, specifically from 2004 to 2017, about 6,300 of these incidents were reported (3.6 M barrels spilled), 40 % of which affected bodies of fresh water (Ibarra-Mojica et al., 2017a).

In the short, medium and long-term, oil spills generate adverse effects in the environment such as animal and plant species death, alteration of the life cycle of plants and animals, loss of ecosystem services, among others (Miranda and Restrepo, 2002). The mitigation of these impacts depends in no small extent on the formulation and implementation of adequate Contingency Plans. These should address, mainly, the identification of sources of oil spills, the patterns of dispersion of these substances in the environment and the characterization of areas reachable by the spill (IPIECA et al., 2011).

In this sense, there is a great variety of specialized software applications which define the area of influence through the simulation of hypothetical spill scenarios. These applications take into account the physicochemical properties of oil, the volume spilled into the body of water and weather conditions (Ibarra-Mojica et al., 2017b). However, in many cases, high costs limit the access to these models, and the free software could be a viable alternative for increasing the use of predicting models. This is why the primary objective of this paper was to evaluate the applicability of the free software GNOME (General NOAA Operational Modeling Environment), for

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the first time, in a Colombian river. The chosen study case is a sector of the Magdalena River, the most important waterway in the country.

2. Literature review

The dispersion patterns are usually evaluated using numerical modeling, for which several authors point out the importance of considering the following processes:

- Advection. It is a physical process that involves the dragging of the oil slick, mainly influenced by the current of the body of water, wind and waves (Guo and Wang, 2009). On the surface of water influenced by the superficial velocity of the current and the wind, while the water column is considered under the movement only by sub-surface currents (Yapa et al., 1994).
- Mechanical dispersion. It involves the propagation of the oil in the water. The gravity and the superficial tension of the water promote the diffusion of the stain, while the inertia and viscosity of the spilled product delay it (Giwa and Jimoh, 2010).
- Adhesion to the banks. Depend on factors such as the physical-chemical properties of the spilled product, the physical characteristics of the banks, the currents of the body of water and the wind (Guo and Wang, 2009).
- Evaporation. That occurs from the moment in which oil is released into the environment, generating changes in the mass and physical-chemical characteristics of the product dumped (Guo and Wang, 2009). It depends on the wind, ambient temperature, area of extension of the spot and type of oil (Yapa et al., 1994).
- Dissolution. Some fractions of the lighter hydrocarbons, such as benzene, are moderately soluble in water (Hospital et al., 2016). The toxicity associated with these soluble compounds frequently causes this process to be included in the analysis of hydrocarbon spills in rivers (Yapa et al., 1994).
- Vertical mixing and resuspension. The mixture of hydrocarbons in rivers is influenced mainly by turbulence, which favours the division of the spot into globules, which move through the water column. Some of these globules are precipitated and deposited in the riverbed, while others float and resurface to the surface; both influenced mainly by the properties of the spilled product and the presence of suspended material in the water column (Yapa et al., 1994).

3. General NOAA Operational Modeling Environment -GNOME

GNOME is interactive environmental simulation software, written in C++ and designed for the modeling of trajectories of oil spills in aquatic environments. The software uses a Eulerian / Lagrangian two-dimensional model (2-D) where the oil released on the water surface is represented as independent floating particles (Lagrangian elements -LE). Each one of these particles counts with an initial spatial location, volume and physicochemical characteristics. Inputs to GNOME include maps, bathymetry, numerical hydrodynamics models, location and type of the spilled substance and meteorological information (Zelenke et al., 2012).
The GNOME models are more simplistic than other models, but this free program can output reasonably accurate trajectories (Lee, 2012). This work was intended to study the oil spills trajectories on the river Magdalena using open access software GNOME as an alternative to high costs for commercial software.

4. Methodology

First, a compilation of existing information of the case study was carried out (bathymetry, flow rates, current speed and wind speed). From this information the sector hydrodynamic model was carried out using free software HECRAS (developed by the United States Army Corps of Engineers), to obtain the water speed. Finally, the GNOME software was applied to model the trajectory of hypothetical cases of oil spills, using different volumes and spilled product, as well as steering conditions and wind speed, as described below.

4.1 Case study

With an estimated navigable length of 886 km, the Magdalena River is a dominant factor in the economic success of Colombia. The Magdalena River´s basin generates the 75 % of the agricultural production and supplies the 77 % of the population with water for domestic uses, including drinking. Additionally, it is estimated that 55 % of it is over 200 known fish species are endemic (Téllez et al., 2011).
Also, this river constitutes the country´s most important fluvial transport route, thus has suffered the highest number of oil spill incidents in the last 15 years, according to information provided by the National Environmental Licensing Agency (ANLA).
In this work, the free software GNOME (General NOAA Operational Modeling Environment) was used to analyze the trajectory of oil spills in an 18 km sector of the Magdalena River, from the municipality of Barrancabermeja -Santander and the mouth of the Sogamoso River.

4.2 Oil spill modelling

GNOME has integrated maps and hydrodynamic models to simulate spills in marine-coastal environments, and a few selected rivers in the United States. For study cases outside the United States, GNOME has a diagnostic module, in which it is possible to incorporate base information for the trajectory simulation of oil spill scenarios. In this case study, the physical-chemical properties of the hydrocarbons were taken from the GNOME's database. The water speed (m/s) and flow direction were obtained with hydrodynamic modeling using HECRAS (free software developed by the United States Army Corps of Engineers).

For the implementation of the hydrodynamic model, bathymetric information (scale of 1:25.000) was collected from the Regional Autonomous Corporation of the Rio Grande de la Magdalena -CORMAGDALENA. To establish the zone characteristics (flows and river levels) information from hydrological and hydro-meteorological stations of the Institute of Hydrology, Meteorology and Environmental Studies of Colombia - IDEAM was analyzed. According to information collected from a local meteorological station, wind speed (m/s) and direction were established. The river channel was assumed to be uniform (without branches) to simplify the hydrodynamic model, and the income flow of the Sogamoso River was not considered.

The spill area´s limit was configured using the BNA format (Atlas Boundary) from shape format maps, using ArcGIS. The simulation of 54 scenarios of instantaneous spills was carried out, with variations in the type of hydrocarbons (diesel, kerosene, medium crude oil, gasoline, fuel oil No. 4 and fuel oil No. 6), volume spilled (22.25 m^3, 332.25 m^3 and 2,228.5 m^3), the time elapsed after of the effusion (6, 12, 24, 48 and 72 hours) and the direction of the wind: constant speed downriver (1.8 m/s, North), constant speed upriver (1.8 m/s, South) and variable direction and speed.

The diffusion coefficient was calculated for each type of hydrocarbon and spilled volume using Betancourt's equation (Betancourt, 2001), from the studies carried out by Fay (1971).

$$\alpha = 0{,}5\left(\frac{\Delta\rho}{\rho_w} V g\right)^{\frac{1}{2}} \tag{1}$$

Where α is the diffusivity coefficient (m^2/s), g is the gravity acceleration (m^2/s), $\Delta\rho$ is the difference in densities of water and oil, respectively (kg/m^3), ρ_w is the water's density and V is the initial oil volume spilled (m^3). The dissipation coefficients calculated for each hydrocarbon type, and simulated volume, are presented in Table 1.

Table 1: Dissipation coefficients calculated for each hydrocarbon type and simulated volume.

Product	API	Density (kg/m^3)	Dissipation Coefficient (m^2/s)		
			23.85 (m^3)	332.8 (m^3)	2,225.8 (m^3)
Gasoline	57	626	46,670	174,334	450,850
Kerosene	43	785	35,298	131,855	340,994
Diesel	37	829	31,456	117,504	303,881
Fuel Oil # 4	32	826	31,706	118,439	306,299
Medium Crude	30	870	27,429	102,462	264,980
Fuel Oil # 6	14	960	14,975	55,938	144,664

As an example, Figure 1 shows the study area (a, b) and the results obtained for 1 of the 54 simulation scenarios (c).

Figure 1: Example of results obtained for one of the 54 scenarios evaluated

5. Results and analysis

The comparison of results obtained in the scenarios, with constant downriver and upriver wind direction, did not show a dominant relationship of this factor with the destination of hydrocarbons in the river. However, all study cases showed that, during a spill in the study area, most of the hydrocarbons would deposit in the river margin. This fraction corresponds to 60 - 80 % of the volume spilled for products of lower API (fuel oil # 6, fuel oil # 4, medium crude, diesel) and 40 - 60 % for kerosene. Only in the case of gasoline (the largest API) the most significant proportion of product would be evaporated or dispersed (Figure 2). These results coincide with those obtained in the analysis of the behavior of oil spills for a similar sector of the Magdalena River, using the spill model SPILLCALC (Ibarra-Mojica et al., 2017b).

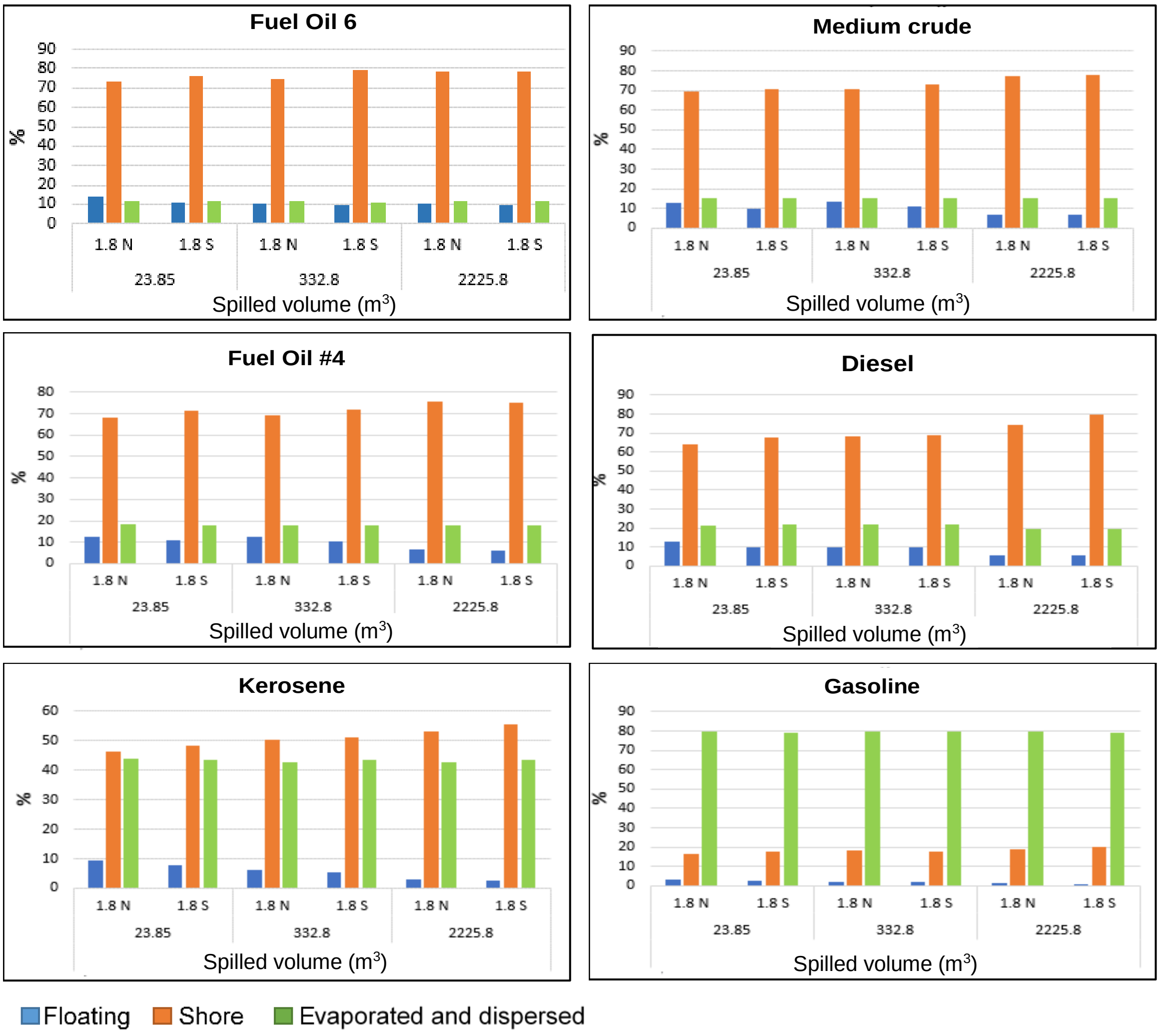

Figure 2: Spill's behavior in scenarios with constant wind´s speed

Regarding the extent of the spill downstream of the dumping site, it was evident that regardless of the type of hydrocarbon, the reach of the spot is greater with downstream wind direction. The greater the volume spilled, the lesser the distance traveled by the product. This could be explained by considering that the calculated diffusion coefficient is directly proportional to the spilled volume and this favors the dispersion of the stain in smaller units, causing them to be transported by the current to the banks or the water column (Figure 3).
Regarding the behavior over time, it was evident that during the 6 hours after the incident most of the product would be retained on the banks, except gasoline for which the dominant process is evaporation and dispersion. In the case of the densest hydrocarbons (fuel oil # 6, fuel oil # 4, medium crude), even after 72 hours more than 40 % of the volume spilled remained on the banks. In the case of kerosene and diesel, after 12 and 48 hours respectively, the situation changes and more than 40 % of the spilled volume is evaporated or dispersed in the water, as shown in Figure 4.

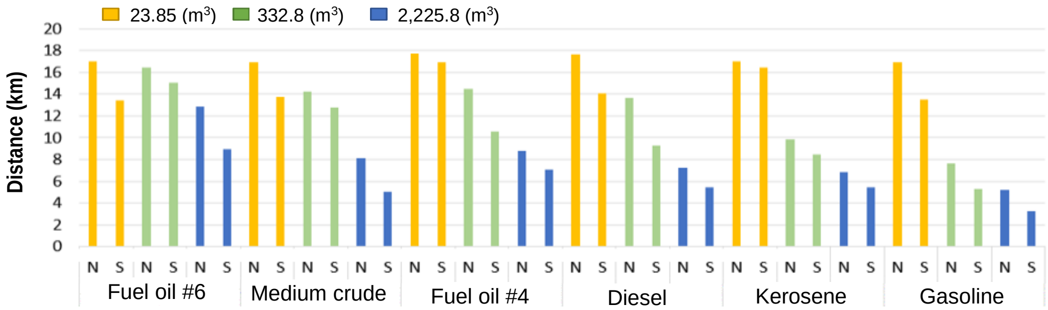

Figure 3: Behavior of spills in scenarios with constant downriver and upriver wind direction

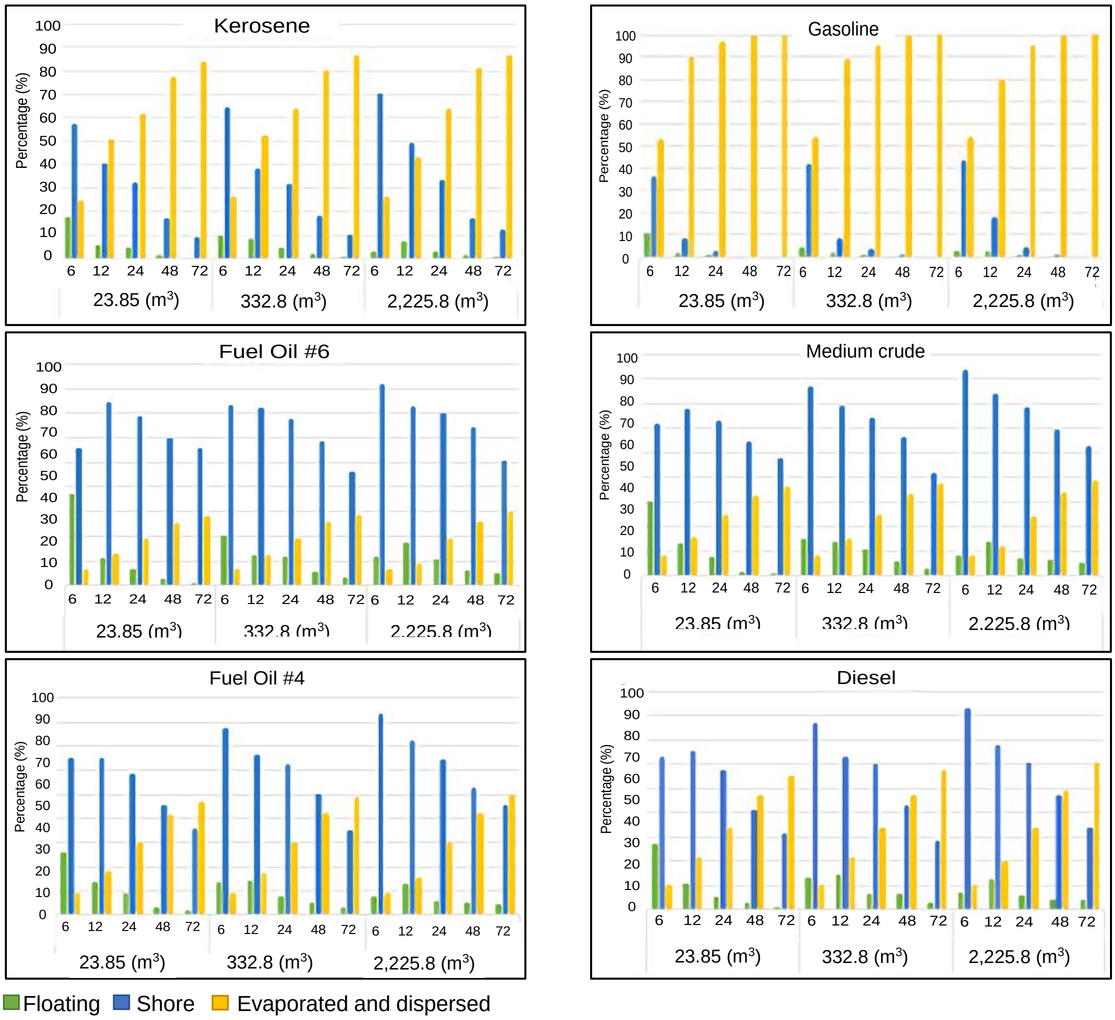

Figure 4: Behavior of spills over time

In general, the results obtained were compared whit the literature and a previous study in the same sector of the river with a private use software. The volume of evaporated product is more significant in the lighter products than heavy products in concordance with is described in the literature (Spaulding, 2017). Respect to the primary fate of spilled oil, the results obtained coincided with those of the previous modeling while in both cases the most probable destination of the hydrocarbons were the riverbanks (Ibarra-Mojica et al., 2017b). It was not possible to establish a comparison of results regarding the effect of wind direction and hydrocarbon type (specifically for the study sector) since there are no other similar studies in Colombia.

6. Conclusions

In the analysis of the oil spills behavior on the Magdalena River, the product type and the quantity spilled would be the characteristics with greater influence in the reach of the spill downstream of the spill site.
The comparison of the spill scenario's mass balance (6 types of hydrocarbons with constant wind speed) showed that, regardless of whether the direction of the wind, most of the hydrocarbons deposited on the banks (40 - 70 % of the spilled volume), during the 6 hours following the spill occurrence. For the lightest product evaluated (gasoline) the dominant processes were evaporation and dispersion. After this, the hydrocarbons are affected by environmental conditions and volatilized, especially the kerosene and diesel, for which after 12 and 48 h respectively the situation changes, and more than 40 % of the spilled volume is evaporated or dispersed in the water.
In conclusion, GNOME evaluates the primary processes that influence the oil spill's displacement (diffusion, evaporation, and dispersion) and offers consistent results according to literature and previous models carried in the case study area, with a private software. It was possible evidence that its software could be applied in a case study in Colombia since it allows modeling with basic information, which can be acquired from national geographic and meteorological information systems. Use GNOME could be an alternative for increasing the use of predictive tools in the design of contingency plans in the country. However, it is necessary to carry more case study evaluations.

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