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METHODOLOGICAL PROPOSAL FOR EVALUATION OF OIL SPILLS ENVIRONMENTAL VULNERABILITY IN RIVERS

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ABSTRACT 2017-397

Rivers have been a major part in the development of human activities since the beginning of civilization. Globally, increased navigation in rivers and construction of oil storage infrastructure along its banks has increased the risk of spillage of these substances in freshwater bodies.

Mitigation associated with such incidents impact depends largely on the formulation and implementation of adequate contingency plans. To make this possible the vulnerability assessment is a tool of primary information which integrates the identification of possible sources of hydrocarbon's spills and the respective dispersion patterns (evaluation of susceptibility); as well as analysis of areas that could be more seriously affected by the presence of those spills (sensitivity testing). There are known methodologies and study cases for assessing vulnerability to oil spills in marine and coastal environments; however, for rivers there are not references of this type of work.

This paper presents a methodological adaptation for assessing environmental vulnerability for oil spills in rivers, from the integration of known methodologies for evaluation of sensitivity and susceptibility in coastal marine and river environments. Given its standardization and wide use, the ESI (NOAA) method was selected for river sensitivity assessment. It was not considered necessary to have a standardized method for trajectory modeling and hydrocarbons spill degradation (susceptibility analysis), but it was established that in each case of study the selected tool must analyze the determinant processes as advection, adhesion to the edges, mechanical dispersion, evaporation, dissolution, and vertical mixing.

Finally, an adaptation of the Index of Environmental Vulnerability to Oil (IEVO) was proposed. At the moment, the application of the methodology is being carried out in a river of Colombia, however the results still unfinished will not be part of the discussion of the work below.

INTRODUCTION

Once hydrocarbons are released into a river, they spread and form a spot from which the lighter compounds evaporate, while the heavier fractions are emulsified in the water column and eventually precipitate to the bottom of the river, united to suspended particles (Zapata, Calle, and Parra, 2002), or are drawn towards the shore (Yapa, Shen, and Angammana, 1994).

Generally, the death of flora and fauna species is recognized as the most immediate and visible effect of a hydrocarbon spill in a body of water. However, it is not the only impact of this kind of incident, since in the medium and long term the reduction of food and oxygen availability for animals and aquatic plants in the water column should also be considered (Miranda and Restrepo, 2002); as well as the affectation to the environments associated to the banks, whose ecological recovery can take decades (Petersen et al., 2002). In addition, impacts on associated marshes and lagoons must be taken into account, since the first stages of the life cycle of thousands of species of plants and animals take place there (Miranda and Restrepo, 2005).

Due to the above, the impact on river ecosystems has a negative impact on the services that humans receive from them, such as water, food, farmland, and recreation sites, among others. Several studies have also shown that the interaction of hydrocarbons with these environments may facilitate their entry into the nutrient cycle and the different links in the food chain, eventually becoming consumed by humans (Miranda and Restrepo, 2002).

In addition to the characteristics of the spilled product, the impact of these events depends on the residence time of these substances in the environment (Miranda and Restrepo, 2002) and the characteristics of the areas that are affected by this type of incident. For this reason, many governments have developed guidelines for the formulation of contingency plans as a strategic tool to reduce, mitigate or prevent the negative socio-environmental effects of such incidents (Yapa et al., 1994).

Globally, organizations such as The National Oceanic and Atmospheric Administration, NOAA (USA) (Petersen et al., 2002), The International Petroleum Industry Environmental Conservation Association (IPIECA) (International Petroleum Industry Environmental Conservation Association -IPIECA, -IMO, and International Association of Oil & Gas Producers -OGP, 2011), and the Regional Association of Oil and Natural Gas Companies in Latin America and the Caribbean, ARPEL (ARPEL Asociación Regional de Empresas de Petróleo y Gas Natural en Latinoamérica, 1997), point out the importance of identifying sources of oil spill and their respective dispersion patterns through contingency plans; as well as areas that may be most severely affected by the presence of these substances.

In the literature, different methods can be identified for the separate assessment of environmental *sensitivity* and *susceptibility* to oil spills. However, some authors refer that in practice, to ensure effective mitigation of ecological impacts, these two tools must be integrated into what they have termed vulnerability analysis (Silva, Lima, Araújo, and Gomes, 2011), (Rocha-Oliveira, Klein, Petermann, Menezes, and Sperb, 2008), (Á. F. Romero, Riedel, Milanelli, and Lammardo, 2011). Most of the known case studies have been developed for coastal marine environments and to date no specific river references are known.

METHODS

A review of existing global methodologies was carried out to assess environmental sensitivity and susceptibility to oil spills in aquatic environments. The methodologies most commonly used, or applicable to rivers, were selected. An adaptation was proposed for vulnerability analysis in river environments.

RESULTS/DISCUSSION

The evaluation of sensitivity, susceptibility and vulnerability to hydrocarbon spills in aquatic environments have been studied since the 1970s by different authors. During this time, different definitions and specific methodologies have been developed for the management of these incidents in marine-coastal and river environments.

Existing Methodologies for the Evaluation of Environmental Sensitivity to Oil Spills

In general, environmental sensitivity to oil spills is understood as the expected response level of a given ecosystem, given the presence of this type of substances (Rocha-Oliveira et al., 2008). To carry out such an evaluation, the Environmental Sensitivity Index (ESI) method, developed by Gundlach and Hayes in the late 1970s, stands out for its worldwide diffusion and acceptance (Gundlach and Hayes, 1978). Through this technique, the coastal ecosystems are classified on a scale of 1 to 10 (lower to higher sensitivity), taking into account mainly their physical characteristics (S I Araújo, Silva, Muehe, and Pereira, 2002).

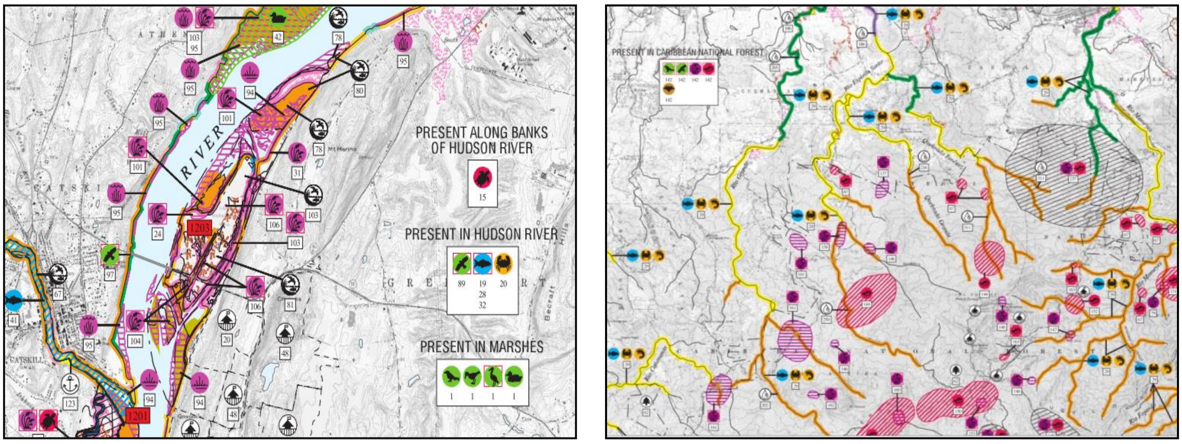
The sensitivity attributed to an area, through the ESI method, is presented through Environmental Sensitivity Maps - MSA's, which also provide timely information on the location of biological, socio-economic and cultural resources (International Petroleum Industry Environmental Conservation Association -IPIECA et al., 2011), such as shown in Figure 1A.

Currently, the ESI method is recommended by entities such as NOAA (Petersen et al., 2002), IPIECA (International Petroleum Industry Environmental Conservation Association -IPIECA et al., 2011), ARPEL (ARPEL Asociación Regional de Empresas de Petróleo y Gas Natural en Latinoamérica, 1997), Petróleo Brasileiro S.A. -PETROBRAS (Araujo, Silva, and Muehe, 2001) and the Brazilian Ministry of Environment (Ministerio de Medio Ambiente-Brasil, 2002), for the construction of Sensitivity Maps to Hydrocarbon Spills in Marine-Coastal Environments.

There are few reports of specific methods to evaluate a river's sensitivity. However, the adaptation of the ESI method by NOAA for large rivers (Petersen et al., 2002) and by PETROBRAS for the Amazon River (Solange Irene de Araújo and Santos, 2006). are relevant. In Colombia, ECOPETROL adapted the same method for marine-coastal ecosystems (Gil-Agudelo, Nieto-Bernal, Ibarra-Mojica, Guevara-Vargas, and Gundlach, 2015) and is conducting the process for ecosystems of large rivers.

Since the ESI method was adapted for large rivers, it does not necessarily meet the information requirements for response to hydrocarbon spills in small rivers (Hayes, Michel, Montello, and Street, 1997). In the 1990s, the US Environmental Protection Agency -USEPA, in association with NOAA, developed the Reach Sensitivity Index (RSI) method (Environmental Protection Agency -USEPA, 1994), applicable to small rivers and streams (Hayes et al., 1997). At present, the ESI and RSI methods continue to be implemented by NOAA in the generation of Regional

Atlas of Environmental Sensitivity to Hydrocarbon Spills (RPI -Louisiana, 2005), (National Oceanic and Atmospheric Administration -NOAA., 2000), as show in **Figure 1B.**



A) ESI Hudson river. NOAA (2006). **B) RSI Puerto Rico's rivers. NOAA (2004)**.

Figure 1. ESI and RSI comparison.

Existing methodologies for susceptibility assessment

Environmental *susceptibility* to oil spills is understood as the tendency or probability that an incident of this type affects an area (Silva et al., 2011). This probability is generally evaluated through simulation of spill scenarios, in which the expected trajectory of the polluting pen or spot is analyzed through mathematical models (Á. F. Romero, 2009).

The literature report many and varied free and commercial software, with two dimensional (2D) and three dimensional (3D) analysis, in which it is possible to generate stochastic or deterministic models of the trajectory and degradation of the spilled products. All these tools start from hydrodynamic models of the area of study. Several authors relate the fate and degradation of the spilled hydrocarbons with processes such as the drag of the stain by currents (advection), adhesion to the edges, mechanical dispersion, evaporation, dissolution, and vertical mixing (Yapa et al., 1994), (Guo and Wang, 2009), (Gundlach, 1987), (Yapa, Shen, Wang, and Angammana, 1992), (Fay, 1971), (Giwa and Jimoh, 2010) (Wu, 2007), (Hibbs, Chen, Gulliver, and Voller, 1997), (French and Rines, 1997), (National Oceanic and Atmospheric Administration (NOAA), 2002), (Per S. Daling et al., 2014); as show in Figure 2.

According to Green and Trett (Green and Trett, 2012), factors such as sediments load, flow and river turbulence are involved in the emulsification, solubilizing, dissolution, dispersion and sedimentation of the product.

Existing methodologies for vulnerability assessment

The Department of Ecology of the State of Washington (French-McCay et al., 2005), modeled several scenarios of hydrocarbon spills in coastal areas and river sectors where there were Environmental Sensitivity Maps to Spills of Hydrocarbons - MSA, showed that it is theoretically possible to expect the removal of 50-70% of the spilled hydrocarbons if the response team also has full knowledge of the trajectory of the polluting plume.

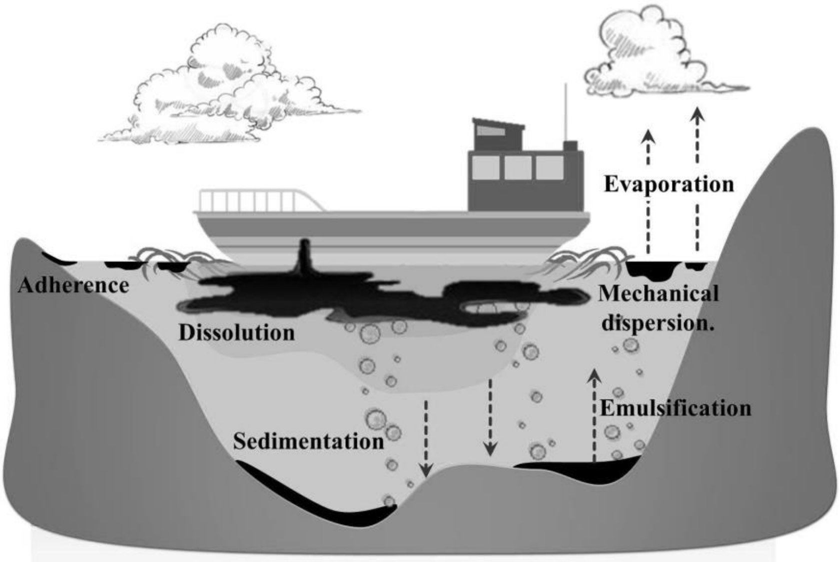


Figure 2. Behavior of oil spills in rivers.

In Latin America stands out the studies developed by Romero et al. (2011) and Da Silva et al. (2011), for the assessment of environmental *vulnerability* to oil spills on the coast of Santos, Sao Paulo-Brazil. In both cases, the authors evaluated the sensitivity of an area of study by applying the index sensitivity index of the littoral -ISL, adapted from the ESI method by PETROBRAS (Araujo et al., 2001) and the Brazilian Environment Ministry (Ministerio de Medio Ambiente-Brasil, 2002). Additionally, they applied techniques of mathematical modeling of trajectory and degradation of hydrocarbon spill scenarios for the susceptibility analysis. However, while Romero et al. (2011) proposed to perform the vulnerability analysis by overlapping the layers of sensitivity and susceptibility information (Figure 3), Da Silva et al. (2011) proposed to integrate the two parameters into a vulnerability index (Figure 4).

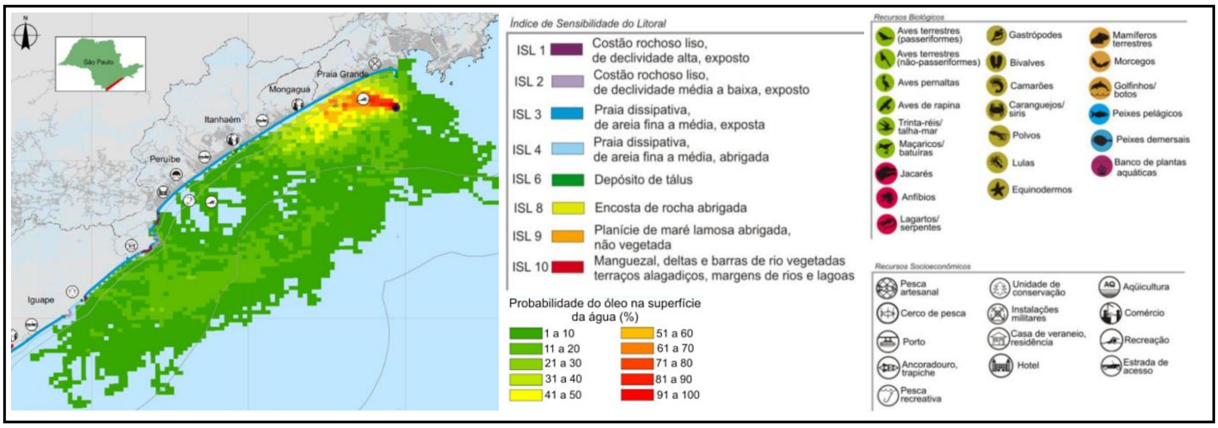


Figure 3. Vulnerability analysis proposed by Romero et al. (2009).

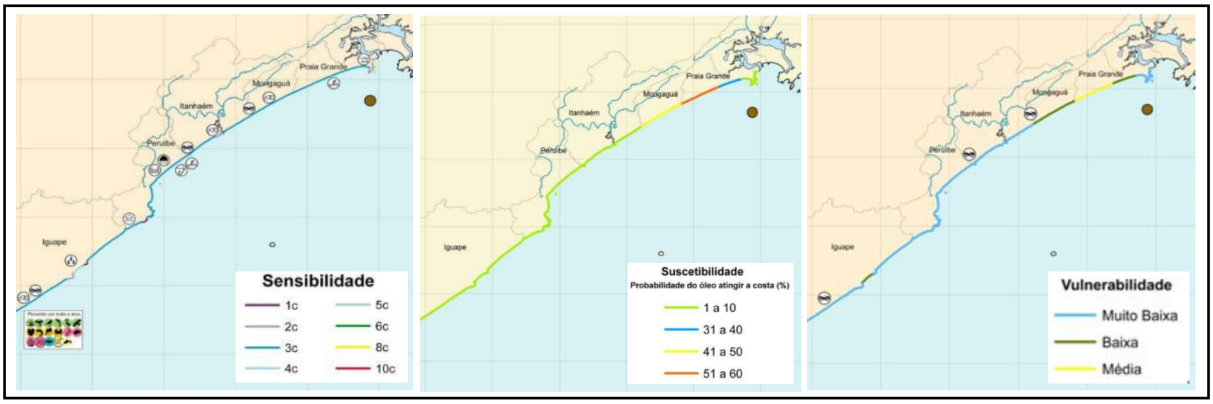


Figure 4. **Vulnerability analysis proposed by Da Silva et al. (2011)**.

It is worth mentioning that there are not specific works reported in the literature for vulnerability analysis of hydrocarbon spills in rivers.

In 2013, Romero et al. propose a joint methodology for vulnerability assessment, through the unification of the studies carried out by them on the coast of Santos, São Paulo (Brazil) (A. F. Romero, Abessa, Fontes, and Silva, 2013). In this case, they propose the *Index of Environmental Vulnerability to Oil (IEVO).* For that purpose, they design a matrix crossing the Environmental Sensitivity Index (ESI) adapted by Ministry of Environment for Brazil (Ministerio de Medio Ambiente-Brasil, 2002), with the probabilities of oil reaching the coastal environments. The ESIs and probabilities received a code for low levels, medium, high, and very high **(Table 1).**

Table 1. ESI and probabilities code attribution. Romero et al. (2013).

ESI	Probability (%)	Code	Descrition
1	1-10	-	Low sensitivity or low probability
2	11-20		
3	21-30	+/-	Medium sensitivity or medium probability
4	31-40	+	High sensitivity or high probability
5	41-50		
6	51-60		
7	61-70	++	Very high sensitivity or very high probability
8	71-80		
9	81-90		
10	91-100		

With the integration of sensitivity and probability, using the assigned codes, was designed the IEVO **(**Table 2**).** Finally, crossing the ESI scale and the probability scale they constructed the IEVO matrix (Table 3).

Table 2. Results from crossing the codes used to generate the Index of Environmental Sensitivity to Oil (IEVO). Romero et al. (2013).

Crossing (sensibility and probability)	Vulnerability	IEVO
(-) (-) ; (-)(+/-)	Low	2
(-)(+) ; (+/-)(+/-)	Medium	3
(+/-)(+) ; (+)(+) ; (+/-)(++) ; (-)(++)	High	4
(++)(++) ; (+)(++)	Very high	5

Table 3. Environmental Vulnerability to Oil (IEVO) matrix. Romero et al. (2013).

ESI	Probability (%)										
	0	**1-10**	**11-20**	**21-30**	**31-40**	**41-50**	**51-60**	**61-70**	**71-80**	**81-90**	**91-100**
1	1	2	2	3	4	4	4	4	4	4	4
2	1	2	2	3	4	4	4	4	4	4	4
3	1	3	3	3	4	4	4	5	5	5	5
4	1	3	3	4	4	4	4	5	5	5	5
5	1	3	3	4	4	4	4	5	5	5	5
6	1	3	3	4	4	4	4	5	5	5	5
7	1	4	4	4	5	5	5	5	5	5	5
8	1	4	4	4	5	5	5	5	5	5	5
9	1	4	4	4	5	5	5	5	5	5	5
10	1	4	4	4	5	5	5	5	5	5	5

For the sensitivity assessment, we have the sensitivity index for rivers proposed by NOAA, ESI Riverine (Petersen et al., 2002) and the adaptation proposed by PETROBRAS, *Amazon Riverine Sensitivity* ISA (Araujo et al., 2001). However, it should be considered that the IEVO was raised from the adaptation of the marine-coastal ESI method carried out by PETROBRAS and the Brazilian Ministry of Environment.

The comparison of these indices (Table 4) allows to show that all three are governed by the same principles to establish the scale of sensitivity (Figure 5).

However, the Amazon Riverine Sensitivity Index proposes a specific scale for a body of water, which could present difficulties for its implementation in other rivers. For this reason, the Riverine ESI method was established as the base scale for adapting the IEVO vulnerability index to river conditions.

Table 4. ESI vs ISA comparisson.

IDX	ENVIRONMENTAL SENSITIVITY INDEX -ESI-	AMAZON RIVERINE SENSITIVITY	BRASILIAN SHORELINE SENSITIVITY -ISL-
1	Exposed, Impermeable Vertical Substrates.	Man-made structures.	Exposed waterproof substrates, high to medium slope.
2	Exposed, Impermeable Substrates, Non-Vertical.	Rocky shoals.	Exposed impervious substrates, sub-horizontal.
3	Semi-Permeable Substrate, Low Potential for Oil Penetration and Burial; infauna present but not usually abundant.	Rapids Waterfalls.	Semipermeable substrates; low penetration / underground oil:
4	Medium Permeability, Moderate Potential for Oil Penetration and Burial; infauna present but not usually abundant.	Scarps / high banks in unconsolidated sediments.	Substrates of medium permeability; Moderate penetration / underground oil.
5	Medium-to-High Permeability, High Potential for Oil Penetration and Burial; infauna present but not usually abundant.	Exposed beaches and sand/gravel bars.	Substrates of medium to high permeability, with high oil penetration / burial; Or parallel limestone rock structure and in direct contact with the shoreline.
6	High Permeability, High Potential for Oil Penetration and Burial.	Sheltered beaches and sand/gravel bars.	Substrates of high permeability; High penetration / underground oil.
7	Exposed, Flat, Permeable Substrate; infauna usually abundant.	Exposed mud beaches and bars.	Sub-horizontal, permeable, exposed substrates: Exposed sandy tide.
8	Sheltered Impermeable Substrate, Hard; epibiota usually abundant.	Sheltered mud beaches and bars.	Substrates impermeable to moderately permeable, sheltered, with abundant epifauna.
9	Sheltered, Flat, Semi-Permeable Substrate, Soft; infauna usually abundant.	Zones of confluence rivers and lakes.	Semipermeable substrates, flat, sheltered, or reefs with bioconstructional concretions.
10	Vegetated Emergent Wetlands.	**(10a).** Aquatic manrophyte bars **(10b)**. Scrub-shrub wetlands.	Wetlands with vegetation above water.

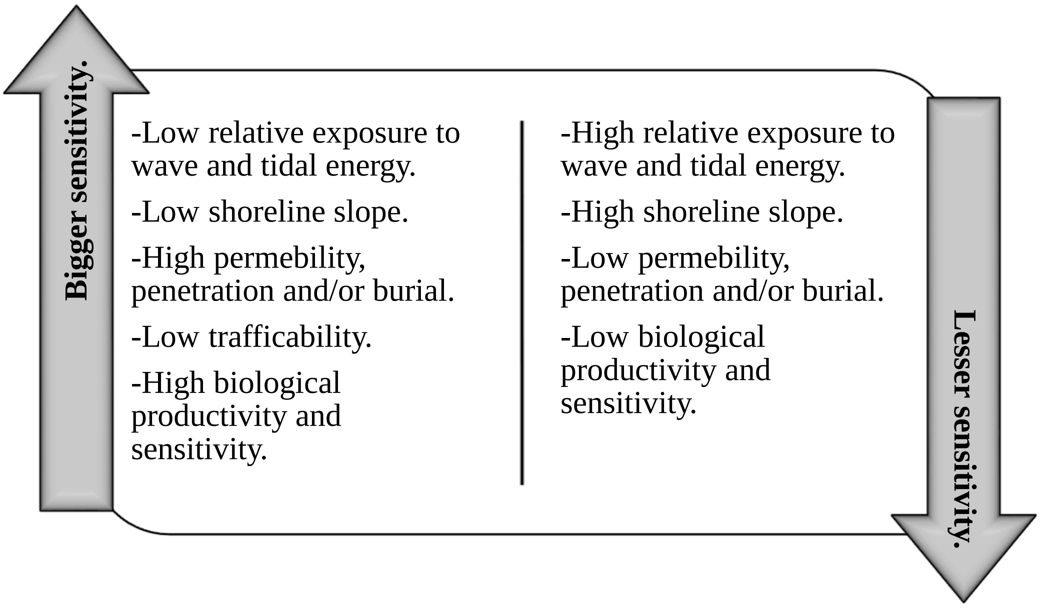


Figure 5. Sensitivity Features.

Regarding the susceptibility assessment, since there is a variety of free and commercial tools for the numerical modeling of trajectory and degradation of the spilled products, it is not considered relevant to establish a specific software tool for the methodology. However, for the software tool selected must analyze and model numerically the main phenomena, which according to different authors have a direct influence on the behavior of the product released in aquatic environments: advection, adhesion to the edges, mechanical dispersion, evaporation, dissolution and vertical mixing (Hospital, Henderson, Mazzocco, and St-amand, 2016).

The Table 5 presents the Matrix IEVO, adapted to river conditions, based on which maps of vulnerability would be constructed, as proposed by Da Silva et al. (2011).

Finally, it is important to point out that the main objective of using vulnerability maps is to facilitate decision-making by response teams, even though they do not have the presence of experts (A. F. Romero et al., 2013). However, sensitivity maps and graphical outputs of numerical probability models or susceptibility maps should be available in all cases to provide detailed information that may lead to improvements in contingency strategies and / or remediation of specific sites.

In addition, it is advisable to establish the three types of analysis (sensitivity, susceptibility, and vulnerability) for the different climatic seasons that are present in the study area, since these are determinants in the current conditions and therefore the area of influence of the Spilled substances (Á. F. Romero et al., 2011).

Table 5. IVE Matrix adapted for rivers.

Environmental sensitivity	**Probability (%)**										
ESI Riverine NOAA.	**0**	**1-10**	**11-20**	**21-30**	**31-40**	**41-50**	**51-60**	**61-70**	**71-80**	**81-90**	**91-100**
1A. Exposed rocky banks **1B.** Exposed, solid man-made structures **1C.** Exposed rocky cliffs with boulder talus base	1	2	2	3	4	4	4	4	4	4	4
2A. Rocky shoals; bedrock ledges	1	2	2	3	4	4	4	4	4	4	4
3B. Exposed, eroding banks in unconsolidated sediments	1	3	3	3	4	4	4	5	5	5	5
4. Sandy bars and gently sloping banks	1	3	3	4	4	4	4	5	5	5	5
5. Mixed sand and gravel bars and gently sloping banks	1	3	3	4	4	4	4	5	5	5	5
6A. Gravel bars and gently sloping banks **6B.** Riprap	1	3	3	4	4	4	4	5	5	5	5
7. Exposed tidal flats.	1	4	4	4	5	5	5	5	5	5	5
8B. Sheltered, solid man-made structures **8C.** Sheltered riprap **8F.** Vegetated, steeply-sloping bluffs	1	4	4	4	5	5	5	5	5	5	5
9B. Vegetated low banks	1	4	4	4	5	5	5	5	5	5	5
10B. Freshwater marshes **10C.** Swamps **10D.** Scrub-shrub wetlands	1	4	4	4	5	5	5	5	5	5	5

CONCLUSIONS

Although methods for separately assessing sensitivity and susceptibility to oil spills in marine-coastal environments have been developed for decades, in practice different authors have highlighted the need to integrate this type of information to facilitate decision making during the contingency of such incidents, even without the presence of experts.

There are several numerical models for the preparation of susceptibility maps, so it is not necessary to establish a software, or standard programming code, for this type of analysis.

However, it should be taken into account that the tool selected in each case study addresses the analysis of determining factors in the behavior of spilled products such as advection, edge adhesion, mechanical dispersion, evaporation, dissolution and vertical mixing.

There are few specific methods for sensitivity analysis and vulnerability to hydrocarbon spills in river environments. However, the extensive application of the NOAA ESI method, and the standardization of the Romero et al. methodology, provides the opportunity to make river´s applicable adaptations.

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