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ENVIRONMENTAL SENSITIVITY INDEX FOR OIL SPILLS IN MARINE AND COASTAL AREAS IN COLOMBIA

ÍNDICES DE SENSIBILIDAD AMBIENTAL ANTE DERRAMES DE HIDROCARBUROS EN LAS ÁREAS MARINAS Y COSTERAS DE COLOMBIA

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ABSTRACT

The implementation of tools to prevent and mitigate the potential impact of oil spills in marine and coastal environments is an issue of interest not only for oil and gas companies, but also for environmental authorities and the general society of the country as they seek to avoid possible damages to the natural realm and human-use resources of an area affected by these events. One of these tools that is useful both for planning and response of oil spills is the Environmental Sensitivity Index (ESI), which establishes the degree of sensitivity of different coastal areas depending on their geophysics, hydrodynamic and biological characteristics. ESI contributes and prioritize to improve response actions to minimize potential environmental impacts. This index is a key element for the construction of the Environmental Sensitivity Maps for oil spills (ESM), but for its correct application, it has to be adjusted to the needs and conditions of each country. This paper presents the adaptation of the ESI for Colombian coastal environments, which has been constructed through the revision of experiences in other countries and the collaboration of national and international experts during workshops. The ESI presented here is the main tool for the elaboration of ESM for Colombia, an instrument that will help in the planning and response process for oil spills in the country.

Keywords: *Environmental sensitivity maps, Oil spills, Permeability, Biodiversity, Geomorphology, Contingency plans, Socioeconomic resources.*

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RESUMEN

La implementación de herramientas para prevenir y mitigar el potencial impacto de los derrames de hidrocarburos en ambientes costeros es un tema de interés no sólo para las compañías de gas y petróleo, sino también para autoridades ambientales y la sociedad en general, ya que ellos buscan evitar y prevenir daños en los ambientes naturales y los recursos de uso humano en áreas afectadas por estos eventos. Una de estas herramientas que es usada tanto para planear como para responder a derrames de hidrocarburos es el Índice de Sensibilidad Ambiental (ESI, de sus siglas en inglés), el cual establece el grado de sensibilidad de diferentes áreas costeras dependiendo de sus características geofísicas, hidrodinámicas y biológicas. El ESI contribuye a priorizar y mejorar las acciones de respuesta y así minimizar el potencial impacto ambiental de estos eventos. Este índice es un elemento clave para la construcción de los Mapas de Sensibilidad Ambiental ante derrames de hidrocarburos (ESM, de sus siglas en inglés), pero para su correcta aplicación deben ser ajustados a las necesidades y condiciones de cada país. Este artículo presenta la adaptación del ESI para los ambientes costeros colombianos, el cual ha sido construido mediante la revisión de experiencias de otros países y en colaboración con expertos nacionales e internacionales a través de talleres. El ESI presentado aquí es la herramienta fundamental para la elaboración de los ESM para Colombia, un instrumento que servirá en el proceso de planificación y respuestas a derrames de hidrocarburos en el país.

Palabras clave: Mapas de sensibilidad ambiental, Derrames de petróleo, Permeabilidad, Biodiversidad, Geomorfología, Planes de contingencia, Recursos socioeconómicos.

RESUMO

A implantação de ferramentas de prevenção e mitigação do impacto potencial dos vazamentos de óleo em ambientes costeiros é uma questão de interesse não apenas para as companhias de gás e óleo, mas também para as autoridades ambientais e a sociedade em geral, sendo que eles procuram evitar e prevenir prejuízos nos ambientes naturais e nos recursos de uso humano nas áreas afetadas por estes eventos. Uma destas ferramentas, que é usada tanto para planejamento quanto para resposta em eventos de vazamento de óleo, é o Índice de Sensibilidade Ambiental (ESI, por suas siglas em inglês), que estabelece o grau de sensibilidade de diferentes áreas costeiras dependendo das características geofísicas, hidrodinâmicas e biológicas da área. O ESI contribui a priorizar e aprimorar as ações de resposta visando minimizar o potencial impacto ambiental destes eventos. Este índice é um elemento chave para a construção dos Mapas de Sensibilidade Ambiental perante derrames de óleo (ESM, por suas siglas em inglês), mas para sua aplicação correte é necessário se adaptar às necessidades e condições de cada país. Este trabalho apresenta a adaptação do ESI aos ambientes costeiros colombianos, sendo construído mediante a revisão de experiências de outros países e em colaboração com especialistas nacionais e internacionais através de oficinas. O ESI ora apresentado é a ferramenta fundamental para a elaboração dos EMS para a Colômbia, um instrumento que servirá no processo de planejamento e resposta a vazamentos de óleo no país.

Palavras-chave: Mapas de sensibilidade ambiental, Vazamentos de petróleo, Permeabilidade, Biodiversidade, Geomorfologia, Planos de contingência, Recursos socioeconômicos.

1. INTRODUCTION

The impact of oil spills (and other oil products) in the marine and coastal realm is one of the major concerns for ecosystems and services they provide, such as fishery resources, tourism, aquaculture, port activities, among many others (Clark, 1995; Gundlach, 2006; Gil-Agudelo & Wells, 2011). Historically, major oils spills in the marine realm have been the result of accidents involving transportation activities through vessels and coastal facilities, but the offshore exploration and production of oil have also caused important impacts to marine and coastal areas (GESAMP, 2007; Griggs, 2011; Upton, 2011).

The risk of spills throughout the chain of production and transportation of oil and by-products, and their potential impact to ecosystems and human resources, requires appropriate contingency plans in order to respond properly and minimize the risk to the environment. One of the most important elements in the process of contingency planning is the definition of the sensitivity of the areas that can be reached by oil spills (Gundlach & Hayes, 1978; Nansingh & Jurawan, 1999; Petersen *et al.*, 2002).

The first coastal Environmental Sensitivity Index (ESI) for oil spills was developed in the late 1970s (Gundlach & Hayes, 1978; ARPEL, 1997), which were later complemented by Geographic Information System (GIS) technology (Petersen *et al.*, 2002) generating what is now known as Environmental Sensitivity Maps for Oil Spills (ESM) in marine and coastal waters. ESM are key for the generation of Contingency Plans because they incorporate the ESI and biological and socioeconomic information of the area, which together help in the decision making process during a spill event (ARPEL, 1997).

One component of the ESI is the scoring of the sensitivity of the different types of coastal ecosystems to oil exposure. This scoring depends on the persistence of oil in the coastal line due to its penetration in the substratum, easy of removal by cleaning crews without causing any additional damage to the ecosystems, and the possible harm to sensitive biological communities

or their productivity. Scores are determined by a series of geomorphological elements of the coastline such as the exposure to waves and tidal energy, type of substrate, slope of the coastline, among others (Gundlach & Hayes, 1978; Petersen *et al.*, 2002; SQA/MMA, 2004).

IPIECA (The Global Oil and Gas Industry Association for Environmental and Social Issues) states in its guidelines for ESM that the ESI shoreline ranking must be adapted for the conditions of the coastline of each nation and region (IPIECA-IMO-OGP, 2011). Different countries had followed this recommendation when developing their ESM, mainly adapting NOAA's (National Oceanic and Atmospheric Administration) methodology (Jensen, Halls & Michel, 1998; Gundlach *et al.*, 2001; Adler & Inbar, 2007; Castañedo *et al.*, 2008) to their own conditions, since it was constructed based on the experience of oil spills around the world involving different types of coastlines and cleaning actions. The approach of this index simplifies its adaptation and application into the ESM, facilitating fieldwork and generating better results in less time (Petersen *et al.*, 2002).

The main goal of this work was to develop an ESI for oil spill for Colombia, with the aim of standardizing this index for application at a national scale so it can be used for the elaboration of ESM and other oil spill contingency planning tools for the country's coastal and marine areas.

2. METHODS

In order to construct an ESI for Colombia, two workshops were conducted with national and international experts (including experts in oil spill contingency planning, government organizations and academia). During the first workshop, discussions revolved around the different factors and criteria to be taken into account in order to establish such an index, bearing in mind that geomorphologic, hydrodynamic, and biotic characteristics of the coast line are the main determinants of oil behavior and, for instance, the degree of environmental impact they can cause (Gundlach & Hayes, 1978; Petersen *et al.*, 2002; SQA/MMA, 2004).

Table 1. Criteria used for the construction of ESI for the Colombian coastline.

No	Criteria	Definition
1	Capability to recover from an oil spill.	Geomorphological characteristics of the coastline that facilitates its recovery after an oil spill.
2	Difficulty for contention, recovery or elimination of spilled oil by cleaning crews.	Physical characteristics of the coastline that restricts its access and transit, determining the difficulty of oil cleaning recovery by cleaning crews.
3	Ecological importance.	Biotic elements present in the coastline that gives a grade of importance for the ecology of the area or region.

Factors and criteria established during the first workshop were tested in the field in four different sites of the Colombian coastlines, both in the Caribbean and the Pacific coasts. Descriptions of the different coastlines were performed using the factors and criteria previously discussed which were later grouped and assigned to preliminary index values.

Determination of Factors and Criteria for ESI Construction

Three basic criteria were proposed for the construction of the ESI: geomorphology of the coast line, which determines the natural recovery of the area; possibility of implementation of cleaning techniques, allowing the recovery of oil and avoiding further damages; and ecological importance of the ecosystems present, determining the biodiversity at risk from an oil spill (Table 1).

These three basic criteria allowed the identification of eight (8) factors used to allocate a degree of sensitivity for the different types of coastlines present in the country. Table 2 shows these eight factors and ranks used to evaluate and classify the sensitivity to oil spills of different types of coastlines based on their geomorphologic, hydrodynamic characteristics.

Evaluation factors are:

Artificial Substrate

Man-made structures on the coastline (Figure 1a and 1b). Compact structures (i.e. concrete walls) are considered less sensitive than structures with crevices (i.e. wave breakers) since the latter offer refuge to organisms and oil is difficult to clean from these structures (NOAA, 2002; Gundlach, 2006).

Table 2. Factors defined to evaluate coastline sensitivity to oil spills.

Factors	Ranges
Natural substrate	Bedrocks
	Boulders
	Rubble and Pebbles
	Sand
	Mud flats
Artificial substrate	Compact structures
	Non compact structures (with crevices)
Permeability*	Non-permeable
	Semi-permeable (Oil penetration into sediment <50 cm)
	Permeable (Oil penetration into sediment >50 cm)
Slope	High (>30°)
	Medium (5° - 30°)
	Low (<5°)
Tide range	Narrow (Non-formation of mud or sand flats)
	Ample (Formation of mud or sand flats)
Wave exposure	Exposed
	Protected
Biodiversity*	Low
	Medium
	High
Access and transit on the coastline	Possible
	Moderated
	Not possible

* Valuation established through experts opinion or secondary information.

Natural Substrate

The degree of sensitivity is mainly determined by the characteristics of the substrates found on the coastline (Figures 1c-1f). The relation between grain size and sensitivity is given by the possibility and depth of oil penetration into the substrate, the potential for burial, and the time that the oil will remain in contact with the substrate and biota, which determines the kind of cleaning technique required; grain size also

determines the biodiversity present in the coastline. Coastlines with consolidated compact rocks and beaches with fine compacted sand that prevent oil to percolate into the substratum are considered to be less sensitive than beaches of gravel or coarse sand where oil can easily penetrate (Gundlach & Hayes, 1978; Petersen *et al.*, 2002).

Wave Exposure

Degree of contact of the coastline with wave action (Figure 2). The energy of waves breaking in the coast may promote the movement of sediments possibly burying the oil, but it can also help in the natural cleaning of the coastline by removing oil from rocks and other surfaces, influencing the persistence of oil in



Figure 1. Substrate type as a factor that conditions the level of sensitivity of coastlines to oil spills. Artificial Substrate: (a) concrete walls, (b) wave breakers. Natural Substrates: (c) compact rocky shores, (d) rubble, (e) sands, (f) mud flats.

the ecosystem. Protected coastlines are deemed more sensitive to oil spills than exposed coastlines, since this oil is not naturally removed from the system by wave energy. Protected coastlines are those where structures, such as sand bars, fringing reefs or others are present in front of the coastline and dissipate the energy of the waves (Petersen *et al.*, 2002; SQA/MMA, 2004; Gundlach, 2006).

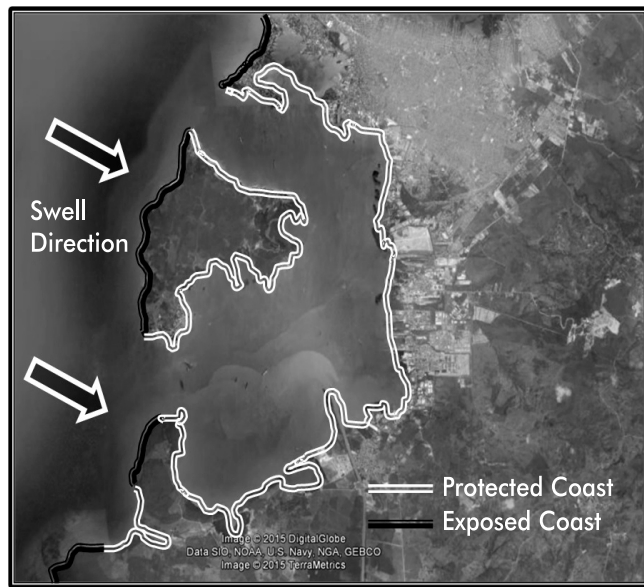


Figure 2. Wave exposure, factor that contributes to the sensitivity of coastlines to oil spills.

Tidal Range

This factor is important to establish the amplitude of the coastline and, as such, the area potentially exposed to the impact of oil spills; it also generates changes in the hydrodynamic processes of the coast (Figure 1f). The formation of wide beaches or mud flats due to large tidal ranges results in a large area potentially impacted that has to be cleaned (Petersen *et al.*, 2002; SQA/MMA, 2004).

Slope

Angle of the coastline related to the horizon. This factor determines the energy of waves breaking into the shore promoting the natural cleaning of the coastline and the movement of sediments, influencing the persistence of oil in the area. Slope and tidal range govern the area of coastline potentially exposed to oil spills. It is considered that coastlines with low slopes ($<5^\circ$) are more sensitive than coastlines with high slopes ($>30^\circ$) (Petersen *et al.*, 2002).

Permeability

Penetration of oil into the substratum through the interstitial pores of the sediment. Cleaning techniques to be used are in part determined by this condition since removal of large quantities of sediment might be necessary in highly permeable substrates. Non-permeable substrate (i.e. consolidated rock) are less sensitive than semi-permeable (penetration <50 cm) and highly permeable substrates (penetration >50 cm) (Petersen *et al.*, 2002; SQA/MMA, 2004).

Biodiversity

Areas with high (mangroves, coastal lagoons, etc.) or moderate (mud flats, crevices, areas protected from wave action, etc.) biological diversity are more sensitive to oil spills than areas with relatively low diversity (coarse sand beaches, rocky shores with high wave action) (Gundlach & Hayes, 1978; Petersen *et al.*, 2002; SQA/MMA, 2004).

Accessibility of the Coastline

Complexity of the coastline that determines how difficult will be for cleaning crews to access and transit the coastline to reach and work on the oil spill without causing more impacts to the environment. Areas where cleaning activities can be easily performed (i.e. wide beaches with fine sand) are considered less sensitive than areas with restricted accessibility, areas that might pose risks for the cleaning crew or areas where cleaning activities might result in further damage to the environment (high energy beaches or rocky shores, mangroves, etc.) (Petersen *et al.*, 2002; SQA/MMA, 2004).

During the second workshop results of this first effort to establish an ESI were submitted to the experts and resulted in the construction of the definitive ESI for Colombian coastline.

3. RESULTS

ESI for Colombian Coastlines

A total of 16 different types of coastlines were identified and evaluated with the previously mentioned factors that were later grouped into 10 different categories for the ESI (Tables 3 and 4). Lower ESI values corresponded to less sensitive coastlines, while high values correspond to coastlines and ecosystems with high sensitivity.

Table 3. Description of coastline types and factors that determine their sensitivity.

ESI	Coastline description	Wave exposure	Slope	Type of substrate	Substrate mobility	Substrate permeability to oil	Biodiversity	Accessibility to the coastline	Natural elimination of oil	Characteristics of the response	Coastline types
1	Non-permeable, exposed substrate with high slope	High exposition	High (> 30°)	Rocky Shore	Non-mobile	Non-permeable	Low, adapted to high wave exposition	Non-accessible	Fast (weeks)	Usually not required	Exposed rocky cliffs. Exposed artificial structures
2	Exposed, non-permeable shoreline with medium slope	High exposition	High (> 30°)	Coastline with rocky terraces, some sand and loose rocks	Non-mobile	Non-permeable	Generally low, adapted to high wave exposition; biota associated to pools in rock	Non-accessible	Fast (weeks to months)	Usually not required, except for tidal pools	Exposed rocky and shores with terraces
3	Semi-permeable substrate with low abundance of infauna	Low to medium exposition	Medium (5 to 30°)	Sand of fine to mid-size grain. Rocky scarps	Low mobility (compact sediments), but may move during storms	Limited permeability (oil penetration < 10 cm)	Presence of infauna in low densities	Allow the transit of vehicles and machinery	Medium (months)	Usually not required, except for recovery of oil on the top part of the wave braking	Exposed sandy beaches with grain size fine to medium. Exposed sandy, rocky and mixed scarps
4	Permeable substrates with low abundance of biota	Low to medium exposition	Medium (5 to 30°)	Mid to coarse sand grain	Mid to high mobility (unconsolidated sediments)	Semi-permeable (oil penetration < 25 cm)	Presence of infauna in low densities	Allow the transit of vehicles and machinery. Transit may mix oil with sediments	Medium (months)	May need the removal of large quantities of sediment	Protected fine and medium grain beaches. Exposed beaches with coarse grain sand.
5	Medium permeable substrates with low abundance of biota	Low to medium exposition	Medium (5 to 30°)	Mixed sediments (sand, gravel, rubble)	Generally low mobility, but mobile during storms	Mid to high-permeability (< 50 cm)	Presence of infauna in low densities	Allow the transit of vehicles and machinery. Transit may mix oil with sediments	Slow (months to years)	May need the removal of large quantities of sediment	Mixed (sand with gravel) beaches
6	High permeability substrates with low abundance of biota	Low to medium exposition	Medium (5 to 30°)	Rubble, gravel and Pebbles	Mobile only during storms	Very high permeability (< 100 cm)	Presence of infauna and epifauna in low densities	Moderate to non-accessible (sometimes only accessible by foot)	Slow (months to years)	May need the total clean-up of gravel and the partial removal of rocks (wave breakers)	Gravel beaches Rocky shorelines Wave breakers and ripraps
7	Exposed tidal flats with Semi-permeable substrate and abundant infauna	Low to medium exposition	Low (< 5°)	Fine grain sand and mud	Low mobility (compact sediments), but mobile during storms	Non-permeable when saturated with water and semi-permeable when dry	Presence of infauna usually in high densities	Low accessibility (Transit may mix oil with sediments)	Medium (months)	Difficult, usually preferred that oil removes naturally form coastline surface	Exposed muddy and sandy tidal flats
8	Protected rocky shorelines with crevices and abundant biota	Protected (Low exposition)	Medium (5 to 30°)	Rocks with some sand and/or gravel	Usually non-mobile	Oil stays in the surface or in between the rocks, penetrating crevices	Presence of infauna and epifauna in high densities	Moderate to low accessibility	Slow (months to years)	Difficult, mainly in crevices. May need removal and cleaning of large rocks	Protected scarps Protected shorelines with rubble Protected artificial structures
9	Protected tidal flats with semi-permeable substrate and high abundance of biota	Protected (Low exposition)	Low (< 5°)	Fine sand and muds	Low mobility (compact sediments), but mobile during storms	Non-permeable when saturated with water and semi-permeable when dry	Presence of infauna and epifauna in high densities	Low accessibility (Transit may mix oil with sediments)	Slow (months to years)	Difficult due to the substrate softness. Some methods might be restricted	Protected muddy and sandy tidal flats.
10	Wetlands with abundant vegetation and related biota	Protected (Low exposition)	Low (< 5°)	Sand and muds, vegetated, rich in organic matter	Usually non-mobile	Non-permeable when saturated with water and semi-permeable when dry	High biodiversity	Low accessibility, transit may cause further damage to biodiversity	Slow (years to decades)	Very difficult to clean; may cause further damage to the ecosystem. Non-cleaning preferred	Mangroves. River deltas with abundant vegetation

Table 4. Levels of sensitivity to oil spills of different Colombian coastline types.

















ESI	Coastline description	Coastline type	Photographic reference	
1	Non-permeable, exposed substrate with high slope	Exposed rocky cliffs Exposed artificial structures		
2	Exposed, non-permeable shoreline with medium slope	Exposed rocky and shores with terraces		
3	Semi-permeable substrate with low abundance of infauna	Exposed sandy beaches with grain size fine to medium Exposed sandy, rocky and mixed scarps		
4	Permeable substrates with low abundance of biota	Protected fine and medium grain beaches Exposed beaches with coarse grain sand		
5	Medium permeability substrates with low abundance of biota	Mixed (sand with gravel) beaches		
6	High permeability substrates with low abundance of biota	Gravel beaches Rocky shorelines Wave breakers and ripraps		
7	Exposed tidal flats with semi-permeable substrate and abundant infauna	Exposed muddy and sandy tidal flats		
8	Protected rocky shorelines with crevices and abundant biota	Protected scarps Protected shorelines with rubble Protected artificial structures		

Table 4. Levels of sensitivity to oil spills of different Colombian coastline types. (Cont.)

ESI	Coastline description	Coastline type	Photographic reference	
9	Protected tidal flats with semi-permeable substrate and high abundance of biota	Protected muddy and sandy tidal flats		
10	Wetlands with abundant vegetation and related biota	Mangroves River deltas with abundant vegetation		

Coastlines with ESI 1 and 2 correspond to rocky shores or shorelines composed of cliffs with compact rocks, clay or other impermeable materials that prevent oil from penetrating the substrate, high slope ($>30^\circ$), high wave exposure and biota represented mainly by organisms capable of withstanding the force of waves breaking into the coast. The action of high wave energy into the coastline prevents oil from reaching the shoreline or when it does arrive, it helps to quickly remove it from the substrate (weeks). Also, low biological diversity of these areas and its high natural recoverability makes ecological impact smaller. Intervention of cleaning crews in these areas is minimal due to the low impact and difficulties and risk to the personnel.

ESIs 3 through 6 correspond to sand, gravel or mixed beaches as well as coastlines with ripraps with a slope of less than 30° , usually exposed to wave energy. These kinds of coastlines have mid to high permeability and biological communities are present in low densities, so the potential ecological impact remains low, but the natural recovery happens at a lower rate (months to years) than in ESIs 1 and 2 (IPIECA, 2000; Lubick, 2010). Cleaning actions for these areas include flushing sediments, or their partial or total removal.

ESIs 7 and 8 belong to coastlines with a higher biological diversity, mainly infauna that live in mudflats created by tides and in protected environments with hard substrates with crevices, including artificial substrates. These areas are difficult to access and clean, and cleaning actions can cause further damage to the environment, reason why it is important to prevent or minimize the arrival of oil to these areas.

Finally, higher ESIs (9 and 10) are reserved for areas with high sensitivity, mainly because they are home to a high biodiversity. These areas are mainly vegetated river mouths, coastal lagoons and mangroves, areas of high ecological importance with low wave energy where natural recovery from oil impacts can take years to decades. Cleaning oil from these areas might usually cause additional damage to the environment, which is why it is important to protect these environments from oil exposures. Ecosystems like coral reefs are not represented by the index since they are submerged, except in the case of coral crest or fringing reefs located very close to the water surface.

4. DISCUSSION

For more than 30 years, different countries around the world have created or adapted methodologies to classify coastline sensitivity to oil spills as a tool for the prevention and response against oil spills (Jensen *et al.*, 1998).

In Colombia, the only prior case of constructing an ESM was attempted by Tejada and Afanador (2003); nonetheless, these authors used the same ESI classification used by NOAA instead of adapting it to local ecosystems and conditions, as recommended by IPIECA (2011) and other organizations.

Most of the basic concepts of this work were extracted from methodologies used by Petersen *et al.* (2002) and the Ministry of Environment of Brazil (SQA/MMA, 2004), which are the most developed methods

for ESI. However, workshops with experts were fundamental for construction of an ESI for Colombia that can be applied to the entire country and that can be used for the creation of ESM or other oil spill contingency tools (Figure 3). Also, the participation of experts from different areas (industry, academia, government) in the ESI construction legitimize the process and results and guarantee its application and acceptance by different stakeholders. Results of the ESI for Colombia has coincidences with ESIs from NOAA and the Ministry of Environment of Brazil, especially in the lower and higher ends of the index; nonetheless, differences are evident in the intermediate levels, since the classification is influenced by factors such as the coastline accessibility and response characteristics. The most noticeable difference is found in index 8, where protected artificial structures were included by the expert panel mainly due to the social and economic impacts that an oil spill might produce.

Having a standardized ESI for Colombia paves the way for a fast and easy application of tools such as ESM, contingency plans, contingency maps, and others that are largely based in this index. It also allows different

companies and organizations to develop these kinds of tools for their particular area of interest that can be shared and used by other organizations or government entities.

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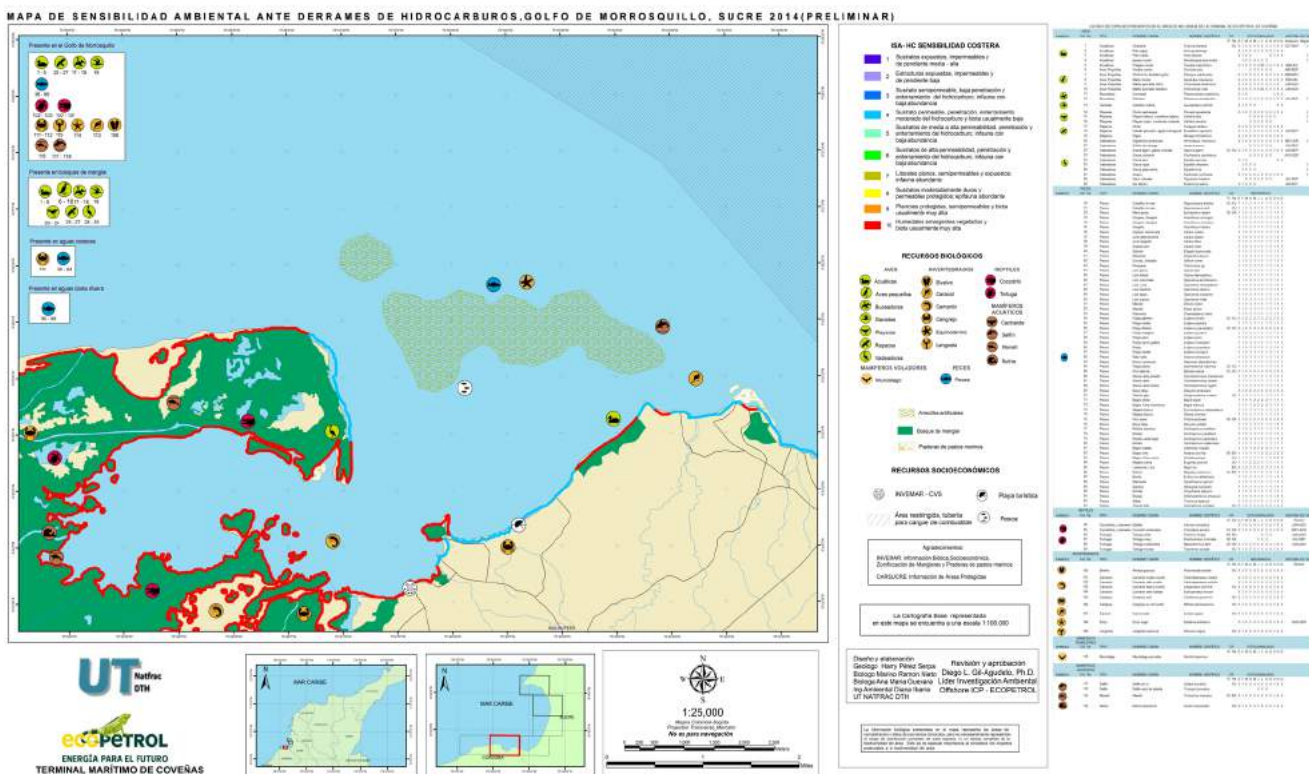


Figure 3. Application of Environmental Sensitivity Index (ESI) to Environmental Sensitivity Map (ESM) in an area of the Colombian Caribbean.

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