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ENVIRONMENTAL SENSITIVITY INDEX FOR OIL SPILLS IN COLOMBIAN RIVERS (ESI-R): APPLICATION FOR THE MAGDALENA RIVER

INDICE DE SENSIBILIDAD AMBIENTAL (ESI-R) PARA DERRAMES DE HIDROCARBUROS EN LOS RÍOS COLOMBIANOS: APLICACIÓN PARA EL RÍO MAGDALENA

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ABSTRACT

The Environmental Sensitivity Index (ESI) mapping has been used globally for oil spill planning and response purposes in coastal areas since its development in the 1970s. However, application to riverine habitats has been limited. Following US National Oceanic and Atmospheric Administration (NOAA) formats and adapting them in working sessions held by a multidisciplinary team and in special sessions with experts and consultants in Colombia, this paper describes the development and application of the sensitivity index to develop maps for the conditions of the middle Magdalena River in Colombia. The index developed (ESI-R) is useful for application in other major rivers in Colombia and areas with similar characteristics. The use of the index to develop maps for smaller rivers and streams is likely to require further development.

RESUMEN

Los mapas basados en los índices de sensibilidad ambiental (ESI) han sido utilizados para la planeación y respuesta a derrames de hidrocarburos en áreas costeras desde los años 70. Sin embargo, su aplicación para ambientes fluviales ha sido limitada. Este artículo describe el desarrollo y aplicación de mapas de sensibilidad ambiental para las condiciones de la cuenca media del Río Magdalena, basándose en los formatos adoptados por la NOAA (US National Oceanic and Atmospheric Administration) y desarrollados en talleres del equipo de trabajo y en sesiones de consultas con expertos para su adaptación específica para el caso colombiano. El desarrollo del índice (ESI-R) es aplicable a otros ríos mayores en Colombia y áreas con características similares. Su uso en ríos pequeños y quebradas seguramente requerirá desarrollos posteriores.

KEYWORDS / PALABRAS CLAVE

Environmental sensitivity mapping | Oil spills |Contingency planning in rivers.
Mapas de sensibilidad ambiental | Derrames de hidrocarburos | Contingencias fluviales.

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1 INTRODUCTION

Since the late 1970´s, sensitivity maps based on the Environmental Sensitivity Index (ESI) have played an important role in contingency and response planning for oil spill emergencies [1],[2]. These maps were first developed for marine and coastal environments for planning response to large oil spills that were occurring in the 1970s[3]. Sensitivity maps are a technical and management tool for decision-making during emergency response to oil spills [4] and represent the sensitivity of coastal and riverine habitats on a scale of 1 (least sensitive) to 10 (most sensitive), based on physical aspects, complemented by biotic and socio-economic data [5].

In terms of overall preparedness, sensitive mapping is one the criteria to be evaluated in a robust oil spill preparedness and response program [6] and an important evaluation criterion in the RETOS™ (Readiness Evaluation Tool for Oil Spills) program developed by ARPEL [7]. Therefore, the development of sensitivity maps constitutes an important step in building a strong response capacity for the oil industry and government agencies.

One of the first cases of study and application of the ESI method in rivers dates from 1984 when The Office of Federal Coastal Programs, through the Energy Impact Program and Research Planning Inc. (USA), generated the Coastal Sensitivity Atlas – Apalachicola River System, based on premises used for the construction of marine and coastal sensitivity mapping, but adapting them to large river specific environments [8].

Some of the methods used to determine sensitivity in large rivers cannot be applied for evaluating oil spills in smaller rivers and streams [9]. Hence, the US Environmental Protection Agency (US-EPA) in association with NOAA and Research Planning Inc., developed in 1994 the Reach Sensitivity Index (RSI) applicable to these environments [10]. It was successfully tested in the Leaf River, Mississippi [11],[12] and again implemented by NOAA while development regional environmental sensitivity atlases in Louisiana [12] and Puerto Rico [1]. This shows the importance of adapting the Index to the specific conditions of the region where it will be applied [13], which is one key aim of this paper.

Criteria used for the development and adaptation of the RSI include the natural sensitivity and vulnerability of the areas to the impact of oil, its intrinsic ability to recover from one of these events, the difficulty for contention, recovery or elimination of spilled oil by cleaning crews, and the ecological importance of the affected area or region. Maps produced in such manner are similar to those used in coastal areas, including information on biological resources and human use; however, river classification is different as it is divided into segments with similar biological and socio-economic potential impact, as well as having different spill response requirements [14].

ARPEL [15] published the guide for the Development of Environmental Sensitivity Maps for Oil Spill Planning and Response based on NOAA´s methods. In 2006, PETROBRAS adapted these methods to the Amazon River [16], being to date the most important oil spill sensitivity mapping project for rivers in Latin America.

In Colombia, an adaptation of NOAA´s methodology to prepare Environmental Sensitivity Mapping for marine and coastal areas was recently published [17]; however, it is estimated that over 70% of oil spills in Colombia impact riverine areas [18]. Therefore, it is crucial for the country to have tools to assist in emergency response actions in freshwater environments. The Index (ESI-R) presented in this paper is the first tool of this type designed for riverine environments in Colombia. ESI-R is the acronym used herein to refer to the riverine ESI for Colombia.

2. EXPERIMENTAL DEVELOPMENT

There are few examples of ESI applied to large rivers around the world. NOAA has developed specific cases in the United States since the 1980s (http://response.restoration.noaa.gov/maps-and-spatial-data/download-esi-maps-and-gis-data.html) while [16] adapted and applied this methodology in Brazil for the Amazon River. Based on these two experiences, and according to the recommendations of the International Petroleum Industry Environmental Conservation Association [2] and the Regional Association of Oil, Gas and Biofuels Sector Companies in Latin America and the Caribbean [15], a set of variables was considered to build the preliminary river-based ESI for Colombian conditions. The ESI-R includes variables common to other sensitivity maps for both rivers and coasts, such as physical characteristics and biological resources, but also include hydrologic and hydraulic features specifically related to rivers (**Table 1**).

Through workshops and consultation with experts, the characteristics of the different variables that make an environment more or less sensitive to potential oil spills (in terms of environmental impact and persistence of the impact over time) were established (**Table 1**). Participating experts included government officials (e.g. Ministry of Environment, National Environmental Licensing Agency), recognized researchers in natural sciences and professionals with vast experience in oil spill contingency preparedness and response from oil and gas companies (e.g. ECOPETROL, Shell, Anadarko), research institutions (e.g. INVEMAR, IAvH), among others.

For demonstration purposes, these variables and their characteristics were evaluated through satellite and aerial imagery as well as field trips for the Barrancabermeja (7° 3'33"N, 73°52'14"W) to La Gloria (8°37'19"N, 73°48'12"W) section of the Magdalena river, that consists of a high vulnerable areas in Colombia prone to oil spills due to presence of the largest oil refinery of the country and the heavy transit of barges that transport oil and refined products along the river from Barrancabermeja to the Caribbean coast.

Information gathered was presented once again to experts for their evaluation and determination of the ESI-R. As not all environment types were present in the area examined, the ESI-R for other areas was determined based on expert criteria.

As an example of the application of this methodology, 1:50.000 ESI-R Maps were created for the middle Magdalena River using official cartographic requirements of the Instituto Geográfico Agustín Codazzi (Colombian State cartographic data agency). Supplementary biological data was obtained from official sources such as the Ministry of Environment and Sustainable Development,

Table 1. Variables defined as part of the ESI-R and their characteristics (adapted from NOAA [13] and IPIECA [19])

Variable	Characteristic	Sensitivity	
		More sensitive	Less sensitive
TYPE OF SUBSTRATE	Unconsolidated granular substrates that enable the filtration of hydrocarbons into the ground.	Sand, mud, gravel	Rock
SUBSTRATE PERMEABILITY	Permeable substrates enabling percolation and burying of hydrocarbons into the ground and persistence in deeper layers.	High	Low
SHORE SLOPE	River sections with low slopes enabling larger and longer resident distribution of hydrocarbon spills compared with high-slope areas.	Low	High
WATER FLOW	Strong water flow contributing to natural elimination of hydrocarbons from the area.	Low	High
VEGETATION COVER	Areas with vegetation fostering high biodiversity that can be affected by spilled oil and likely to hold hydrocarbons for a longer time.	Present	Absent
ASSOCIATED BIOTA	Areas with high biodiversity are more sensitive to oil spills than those with low associated biota.	High	Low

the Corporación Autónoma Regional del Río Grande de la Magdalena (CORMAGDALENA) and the Alexander von Humboldt Research Institute, among others, as well as during field visits. The Corine Land Cover methodology was used according to IDEAM et al. [20] and IDEAM [21]. Socioeconomic information was obtained mainly from local authorities and during field visits. NOAA toolbox (Accessed March 2014) (http://response.restoration.noaa.gov/maps-and-spatial-data/environmental-sensitivity-index-esi-maps.html) and ARPEL [14] recommendations were followed to produce the maps.

3. RESULTS

Using the variables and characteristics defined during the reference review and the criteria obtained from workshops and meetings with experts, added to *in-situ* observations, an Environmental Sensitivity Index for Rivers (ESI-R) for Colombia was created (Table 2).

Each ESI-R category is described below.

Figure 1. ESI-R for certain areas of the Magdalena River. (a) ESI-R 1; (b) ESI-R 3; (c) ESI-R 4; (d) ESI-R 6.

Table 2. Environmental Sensitivity Index for Riverine Shorelines (ESI-R) in Colombia

ESI-R	General description	Representative environments	Type of substrate	Substrate permeability	Substratum mobility	SLOPE	Exposure to water flow	Vegetation cover	Associated biota	Speed of natural remotion of hydrocarbons	Response / cleaning actions
1	Non-permeable shoreline with high slopes exposed to strong hydraulic flow	Rocky or artificial slopes exposed to water flow	Rock, cement, wood, metal	Non-permeable	Null	High (> 30°)	Exposed	Without vegetation	Low	Fast / short term (days to weeks)	Not required
2	Non-permeable shoreline with medium to low slope exposed to strong hydraulic flow	Non-permeable shoreline with medium to low slope exposed to strong hydraulic flow	Rock, cement, wood, metal	Non-permeable	Null	Medium to low (< 30°)	Exposed	Without vegetation	Low	Fast / short term (days to weeks)	Not required
3	Semi-permeable shoreline with high slope exposed to strong hydraulic flow and non-permeable shoreline exposed to low hydraulic flow	Exposed, eroded shorelines	Variable	Semipermeable	Medium-high	High (> 30°)	Exposed	Without vegetation	Low	Fast / short term (days to weeks)	Usually not required
		Shorelines with tall grasses	Variable	Semipermeable	Low	High (> 30°)	Exposed	With vegetation	Low	Medium (weeks to months)	Cleaning of free hydrocarbons; may require grass trimming
		Rocky or artificial slopes, non-exposed to strong currents	Rock, cement, wood, metal	Non-permeable	Null	High (> 30°)	Non-exposed	Without vegetation	Low	Medium (weeks to months)	Cleaning of free hydrocarbons
4	Medium-low permeability substrates exposed to variable water flows	Sand bars and beaches with variable exposure to water flow	Sand	Medium to low permeability	High	Medium to low (< 30°)	Variable	Without vegetation	Medium	Variable, depending on impact.	Variable cleaning efforts according to impact
5	Substrates with medium-high permeability, exposed to strong water flow	Bars and beaches of sand and gravel with variable exposure to water flow	Sand-gravel	Medium to high permeability	Medium-high	Medium to low (< 30°)	Variable	Without vegetation	Medium	Variable, depending on impact.	Variable cleaning efforts according to impact
6	Highly permeable substrates with low mobility, exposed to strong water flows	Bars and beaches of coarse gravel (> 64mm) exposed to water flow	Coarse gravel (>64mm)	High permeability	Low	Medium to low (< 30°)	Exposed	Without vegetation	Low	Medium (weeks to months)	Cleaning required
		Rip Raps exposed to water flow	Protecting rip raps (Concrete, rock)	High permeability	Low	Variable	Exposed	Without vegetation	Low	Medium (weeks to months)	Cleaning required
7	Highly permeable substrates with low and medium mobility, not exposed to strong water flows	Bars and beaches of coarse gravel of (larger than 256mm), not exposed to strong water flows	Coarse gravel (>64mm)	High permeability	Low	Medium to low (< 30°)	Non-exposed	Without vegetation	Low	Slow / long term (Months to years)	Cleaning required
		Non-exposed Ripraps	Protecting rip raps (Concrete, rock)	High permeability	Low	Medium to low (< 30°)	Non-exposed	Without vegetation	Low	Slow / long term (Months to years)	Cleaning required
8	Areas with aquatic vegetation and flooding areas	Macrophytes and emergent vegetation	Mud	Low permeability (by saturation)	High	Medium to low (< 30°)	Non-exposed	Macrophytes and emerging aquatic vegetation	High	Slow / long term (Months to years)	Protection, controlled removal of vegetation
		Low flooding areas with vegetation	Variable	Low permeability (by saturation)	Low	Medium to low (< 30°)	Non-exposed	Trees & bushes	High	Slow / long term (Months to years)	Protection and controlled cleaning
9	Protected muddy flats	Non-exposed muddy flats.	Mud	Low permeability (by saturation)	Medium-low	Low (< 10°)	Non-exposed	Without vegetation	High	Very Slow / long term (years)	Protection and non-intrusive cleaning
10	Low current vegetated channels and lentic (still water) environments	Swamps	Mud	Low permeability (by saturation)	Medium-low	Low (< 10°)	Non-exposed	Emergent vegetation	High	Very Slow / long term (years)	Protection and non-intrusive cleaning)
		Access channels to swamps.	Variable	N/A	N/A	Low (< 10°)	Non-exposed	Emergent vegetation	High	Very Slow / long term (years)	Protection and non-intrusive cleaning)

ESI-R 1: NON-PERMEABLE SHORELINE WITH HIGH SLOPES EXPOSED TO STRONG WATER FLOWS.

Areas with strong water flow, with slopes of non-permeable materials such as concrete or rock, generally with low biodiversity. Potential oil spills will generally keep away from the shoreline due to water flow reflection on the shoreline. If reaching the shoreline, oil will rapidly be removed by the action of the water flow (Figure 1a).

ESI-R 2: NON-PERMEABLE SHORELINE WITH MEDIUM TO LOW SLOPE EXPOSED TO STRONG WATER FLOWS.

Rocky shoreline areas with moderate and low slope (5-30°), usually with low related biota from the action of strong river flows. In general, these areas remain on the main stream; if reaching the shoreline during high waters, hydrocarbons may remain in the slope and some cleaning actions might be considered, mainly for aesthetic purposes.

ESI-R 3: SEMI-PERMEABLE SHORELINE WITH HIGH SLOPE EXPOSED TO STRONG WATER FLOWS AND NON-PERMEABLE SHORELINE EXPOSED TO LOW WATER FLOWS.

Different types of shorelines are included in this category:

- *Exposed, eroded shorelines:* Shorelines composed of medium consolidated sediments in a high slope (over 30°) with evidence of active erosion; occasionally, tall grasses are present. Potential oil spills can adhere to the slopes, but strong flow and erosion processes removes oil in short time, not requiring cleaning efforts (Figure 1b).

- *Shorelines with tall grasses:* Shorelines with medium or low slope (less than 30°) covered by grass and tall grasses usually with low associated biodiversity. Potential oil spills usually adhere to the grasses but do not penetrate the sediments. If necessary, oil can be washed out of the grasses; grass can be trimmed but not completely cut off as it can cause erosion processes.

- *Rocky or artificial slopes, non-exposed to strong currents:* Shoreline with high slopes (more than 30°), non-permeable substrates (rock, concrete, wood, etc.) in areas without strong water flows including piers, port facilities, among others. Hydrocarbons can adhere to these structures forming a distinctive line above water level that can persist over time due to the low water flow. Cleaning is recommended to avoid further water pollution, being careful not to discharge waste into the water stream.

ESI-R 4: MEDIUM-LOW PERMEABILITY SUBSTRATES EXPOSED TO VARIABLE WATER FLOWS.

Sand bars and beaches with low or moderate slope (less than 30°) with relatively high mobility sediments. Areas usually visited by birds and other important fauna. Deposit of oil spill residues can occur along the high-water mark and may spread depending on the changes in water level. Oil residues can penetrate into the sediment up to 25 cm, possibly affecting subsurface organisms. Natural removal of hydrocarbons is relatively efficient, as residues are washed out by water flow. Cleaning efforts should concentrate on the removal of high oil concentrations using manual techniques to avoid sediment removal and prevent further damage (Figure 1c).

ESI-R 5: SUBSTRATES WITH MEDIUM-HIGH PERMEABILITY, EXPOSED TO STRONG WATER FLOW.

Sand bars and beaches with low or moderate slope (less than 30°) with sediments composed of a mix of gravel and sand that enables the penetration of hydrocarbons more than 50 cm into the sediment. Under these conditions, hydrocarbons can remain for years mainly when strong water flow is not permanent. Although biodiversity in these areas is usually low, fish, birds and mammals can be present. Cleaning efforts are recommended to remove persistence of oil and high concentrations of oil and contaminated debris. Cleaning using water at low pressure is also recommended to remove oil residues; water at high pressure should be avoided to prevent pushing pollution into deeper sediments.

ESI-R 6: HIGHLY PERMEABLE SUBSTRATES WITH LOW MOBILITY, EXPOSED TO STRONG WATER FLOWS

- *Coarse gravel bars and beaches (larger than 256 mm), exposed to strong water flow:* Coarse gravel allows deep penetration of hydrocarbons that can remain buried for a long time. Depending on changes in water level or other factors, chronic iridescence, the formation of pavements and/or tars can remain in for a long time. As regards cleaning, it is recommended to use water at low pressure to refloat oil residues and then remove such residues with adsorbent material and skimmers.

-*Exposed Riprap.* Made up of different-size rocks or concrete blocks used to protect river shores, piers, ports, and others. Biota are usually scarce. Hydrocarbons penetrate deep into the crevices and spaces, adhering to the surface of rocks and concrete, which can be slowly released again into the water when water level changes, possibly creating chronic iridescence and other impacts. Cleaning techniques may include high water pressure to remove oil residues and, in more severe cases, it may include scraping and use of hot water (Figure 1d).

ESI-R 7: HIGHLY PERMEABLE SUBSTRATES WITH LOW AND MEDIUM MOBILITY, NOT EXPOSED TO STRONG WATER FLOWS.

- *Coarse gravel bars and beaches (larger than 256mm), not exposed to strong water flow:* Gravel size allows for penetration of oil and oil products that can remain for a long time due to the lack of strong water flow. Chronic iridescence and formation of tars and pavements can be a long-term consequence in these areas. Manual removal of oil and contaminated material is required, as well as the use of pressurized water to refloat the contaminant for recapturing, using skimmers or adsorbent material.

-*Non-exposed Riprap:* Made up of different size rocks or concrete blocks used to protect river shores, piers, ports, and others. Biota are usually scarce, but fish, birds and some mammals can be present. Hydrocarbons penetrate deep into the crevices and spaces, adhering to the surface of rocks and concrete, but are not naturally removed due to the lack of strong water flows. Cleaning techniques may include high water pressure to remove oil residues, scraping, and the use of hot water (Figure 2a).

Figure 2. . ESI-R for certain areas of the Magdalena River. (a) ESI-R 7; (b) ESI-R 8; (c) ESI-R 9; (d) ESI-R 10.

ESI-R 8: AREAS WITH AQUATIC VEGETATION AND FLOODING AREAS.

-*Macrophytes and floating vegetation:* Floating or emergent vegetation in areas that are not exposed to strong water flow. These areas are usually feeding grounds for fish, birds, amphibians, reptiles and mammals (i.e. manatees, otters, etc.). Hydrocarbons from oil spills are retained by vegetation possibly causing a high impact. Cleaning techniques include the extraction of oil using pumps and skimmers and, in some cases, the controlled removal of impregnated vegetation.

-Flooding areas with vegetation. Low flooding areas with trees, shrubs and other vegetation in contact with water. Flora and fauna are usually abundant and diverse with numerous species. During dry and low water seasons, the probability of impacts is low, but during high waters, these areas can be affected and oil can remain adhered to the vegetation, thus causing high impact; recovery is slow due to the permanence of oil residues in the area. Hydrocarbons can be removed using pumps, adsorbent materials and other techniques avoiding further damage to vegetation due to intervention with heavy machinery and massive stepping in the area (Figure 2b).

ESI-R 9: PROTECTED MUDDY FLATS.

-*Mud flats, low water flow:* Substrate primarily composed of mud material and sand and gravel to a lesser extent. Areas with low water flow usually related to swamps and river branches. Unconsolidated sediments will increase the difficulty of people and/or machinery transit. These areas are biodiverse, being important feeding and nesting grounds for fish and birds. Hydrocarbons usually deposit during high waters and, as waters recede, products accumulate on top of the sediments. Although oil and oil products rarely penetrate the sediment, they can reach lower layers through crevices and burrows created by animals, potentially causing severe damage to benthic organisms. Oil should be prevented from entering these areas using booms, skimmers and pumps because of the difficulty of cleaning the soft substrate. Some cleaning can be accomplished washing with water at low pressure and using adsorbent materials (Figure 2c).

ESI-R 10: LOW CURRENT VEGETATED CHANNELS AND LENTIC (STILL WATER) ENVIRONMENTS.

-*Swamps.* Wetlands with abundant vegetation; soils are variable, from sand and gravel to peat. The area is biologically diverse, being an important feeding and nesting ground for birds and fish. Hydrocarbons usually adhere to vegetation and can affect the entire biota. The arrival of hydrocarbons from oil spills should be avoided using booms, skimmers and pumps to prevent damage to the area. In case of arrival, the excess product might be recovered using pumps or adsorbent materials, but further cleaning must be avoided to prevent additional damage. Natural remediation should be considered as the best option. Some vegetation might be removed in cases other resources are at risk.

-*Access channels:* Water bodies connecting rivers to swamps with changing water levels depending on the season. Sediments usually have high content of clay and organic matter. They provide a habitat of high importance for biodiversity, as refuge, feeding source, and providing reproductive ground for numerous species. Highly susceptible to oil spills, particularly during high waters with oil penetration into organic sediments and burrows as the water recedes. Preventing oil from entering these areas is a priority. Booms, skimmers and pumps are the entrance of the channel are recommended to prevent damage to the area. Natural remediation should be considered as the best option, as other cleaning efforts might cause further damage (Figure 2d).

PREPARATION OF MAPS

1:50.000 maps were prepared using cartographic, biotic and socioeconomic data from official sources in the country as an exercise to understand and adjust the application of this methodology. The NOAA format (http://response.restoration.noaa.gov/maps-and-

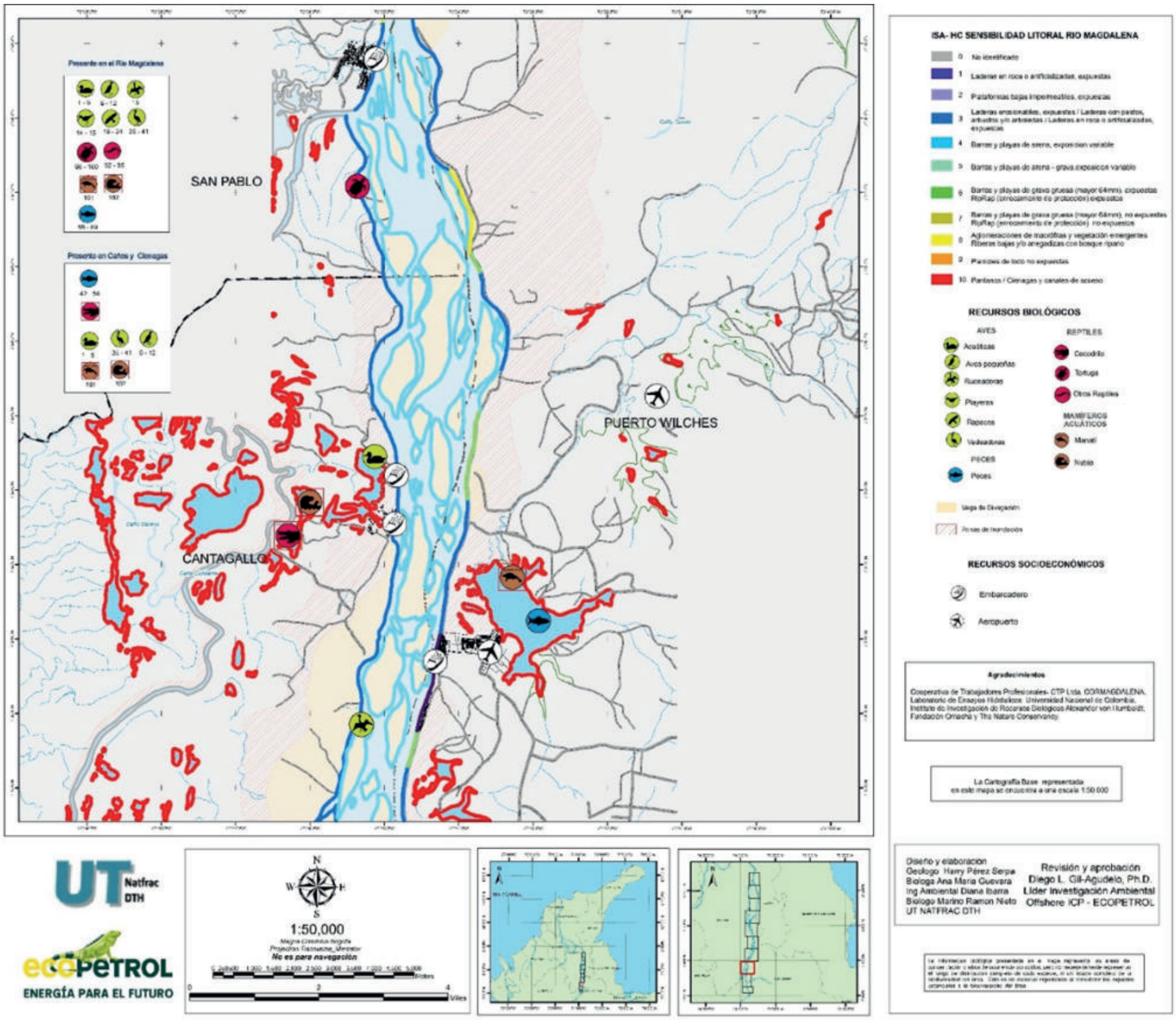

Figure 3. ESI-R sensitivity map of a section of the Magdalena River.

spatial-data/environmental-sensitivity-index-esi-maps.html) was used due to the widespread international acceptance and recognition by emergency response personnel (**Figure 3**).

4. RESULTS ANALYSIS

Environmental sensitivity maps are extensively used around the world as a tool for planning and response actions associated with oil spills, but they are almost exclusively intended for marine and coastal environments. In contrast, the ESI for riverine environments is unusual and only a few countries such as the US and Brazil have continued their development. Some examples include the Columbia River (NOAA, 2004) and the Hudson River [22] in the United States, and the "Amazon Riverine Sensitivity", in Brazil [16].

Comparison between the various indexes developed (ESI, Amazon Riverine Sensitivity and the ESI-R in Colombia) show numerous similarities (**Table 3**). For example, in all cases non-permeable substrates, without vegetation and associated biota and high water flows are considered less sensitive, while more sensitive areas are those with high biodiversity (flora and fauna), permeable substrates, and low water flow. Differences are also present, such as the designation of cascades (water falls) in Brazil which is not present in the RSI or ESI-R. As regards the ESI-R, these types of environments are part of ESI-R where rocks and strong water flow are identified. Similarly, the RSI and the ESI-R include an index that describes vegetated flooded areas not present in the RSI, showing the importance of these areas both in Brazil and Colombia and their sensitivity in case of an oil spill, highlighting the importance of adapting these tools before using them locally.

The modification and adaptation of sensitivity maps to the specific circumstances of a country or region is common since the 1970s and will continue in the future. The development of ESI-R categories based on previous classifications, but specific to the major river systems of Colombia, follows that tradition. Applying the methodology further to smaller rivers and creeks in Colombia may require additional efforts and possibly the establishment of additional categories to develop appropriate maps.

Table 3. Comparison of different Environmental Sensitivity Indices for riverine environments.

ESI	NOAA ESI GUIDELINES 3.0 [1] COLUMBIA RIVER [19]* HUDSON RIVER [22]**	INDEX	AMAZON RIVERINE SENSITIVITY [16]	ESI-R	ENVIRONMENTAL SENSITIVITY INDEX FOR RIVERS (ESI-R) IN COLOMBIA
1a	Exposed rocky banks	1	Man-made structures	1	Non-permeable shoreline with high slopes exposed to strong hydraulic flow
1b	Exposed, solid man-made structures				
1c	Exposed rocky cliffs with boulder talus base				
2a	Exposed wave-cut platforms in bedrock*	2	Rocky shoals	2	Non-permeable shoreline with medium to low slope exposed to strong hydraulic flow
2b	Rocky shoals, bedrock ledges				
3a	Fine to medium-grained sand*	3	Rapids/waterfalls	3	Semi-permeable shoreline with high slope exposed to strong hydraulic flow and non-permeable shoreline exposed to low hydraulic flow
3b	Exposed, eroding banks in unconsolidated sediments/scarps & steep slopes in sand*				
4	Sandy bars and gently sloping banks	4	Scarps/high banks in unconsolidated sediment	4	Medium-low permeability substrates exposed to variable water flows
5	Mixed sand and gravel bars and gently sloping banks	5	Exposed beaches and sand/gravel bars	5	Substrates with medium-high permeability, exposed to strong water flow
6a	Gravel bars and gently sloping banks	6	Sheltered beaches and sand/gravel bars	6	Highly permeable substrates with low mobility, exposed to strong water flows
6b	Riprap				
7	Exposed tidal flats*	7	Exposed mud beaches and bars	7	Highly permeable substrates with low and medium mobility, not exposed to strong water flows
8a	Sheltered rocky shores*	8	Sheltered mud beaches and bars	8	Areas with aquatic vegetation and flooding areas
8b	Sheltered, solid man-made structures				
8c	Sheltered riprap				
8d	Sheltered gravel beaches**				
8f	Vegetated, steeply-sloping bluffs				
9a	Sheltered tidal flat*	9	Zones of confluence rivers and lakes	9	Protected muddy flats
9b	Sheltered vegetated low banks				
10a	Salt & Brackish water marshes*	10a	Aquatic macropyte bars	10	Low current vegetated channels and lentic (still water) environments
10b	Freshwater marshes				
10c	Swamps	10b	Scrub-shrub wetlands		
10d	Scrub-shrub wetlands				

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