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Remote Sensing and Environmental Sensitivity for Oil Spill in the Amazon, Brazil

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1. Introduction

The use of remote sensing has become a fundamental tool for the identification and analysis of different types of risks in coastal zones. The numerous and, in some cases, recent incidents of oil spills have encouraged companies and government agencies to improve methods, both anticipatory and corrective, to minimize damages. The term 'risk' denotes the possibility that adverse effects may occur as a result of natural events or human activities (Kates et al., 1985). Risk is defined as an association between the hazard´s characteristics (e.g. frequency, magnitude and location) and the vulnerability of affected human populations, environment and infrastructure (Wisner et al., 2004). Risk can be classified by their origin, such as natural, social, or technological (Renn, 2008). Oil spills are an example of the last category, and the coastal areas are one of the most impacted. Environmental sensitivity to oil impacts can be defined through the coastal Environmental Sensitivity Index (ESI), which considers: (i) the geomorphologic aspects such as type and slope of coastline and the degree of exposure to the energy of waves and tides; (ii) oil sensitive biological resources; and (iii) the socio-economic activities that can be affected by oil spills (Gundlach & Hayes, 1978; Dutrieux et al., 2000).

In Brazil, environmental sensitivity mapping has been carried out under the law 9966/2000, which gave the Ministry of the Environment (Climate Change and Environmental Quality Secretary) responsibility to identify, locate and define the boundaries of ecologically sensitive areas with respect to the spill of oil and other dangerous substances in waters within national jurisdiction. This way, based on PETROBRAS (2002) and NOAA (2002), the specifications and technical standards for preparing environmental sensitivity maps for oil spills in coastal and marine zones was elaborated upon (MMA, 2002). Such environmental sensitivity maps provide information in an easy format being useful to determine priorities to impact protection and mitigation. Identification and mapping is developed at three levels: (i) Strategic (1:500,000 for the entire area of a hydrographical basin); (ii) Tactical (1:150,000 for the entire coastline mapped); and (iii) Operational (up to 1:50,000 for a high-risk/sensitivity areas). Each of these mapping scales uses specific tools for remote sensing and GIS tools.

The Amazonian coastal zone extends along ~2250 km, not including the several inlets, islands and small estuaries, which punctuate the coastline (Souza Filho et al., 2005a). This coastal zone is placed in the context of the tropical humid regions, in a low-lying area with active processes of erosion, sedimentation and neotectonics. Also, it is marked by a great hydrologic influence; in a meso- to macrotidal area (Souza Filho, 2005). It is a high-density drainage network, in which the Amazon River discharges a volume of water of 6.3 trillion m^3/year and of sediment estimated at 1.2 billion tons/year (Meade et al., 1985).

Such environmental characteristics are responsible for the development of an extensive mud plain and mangrove area which is located in three States (Amapá, Pará and Maranhão), is approximately 8,386 km^2 wide, and contains 80% of all mangroves in Brazil (Herz, 1991). Where macrotides are present, the area of a flooded mangrove may extend for up to 30 km inland, and the estuaries themselves as much as 80 km (Souza Filho, 2005) (Figure 1). These extensive mud and mangroves plains are considered to be one of the most sensitive areas to oil spills. Also, these mangroves are along national and international ships routes. Transportation and storage are mainly responsible for oil spills in Amazonian coastal zone, since there is no expressive exploration. In 2001, in the state of Pará, approximately 1900 tons of oil sank near the Port of Vila do Conde (Berredo et al., 2001).

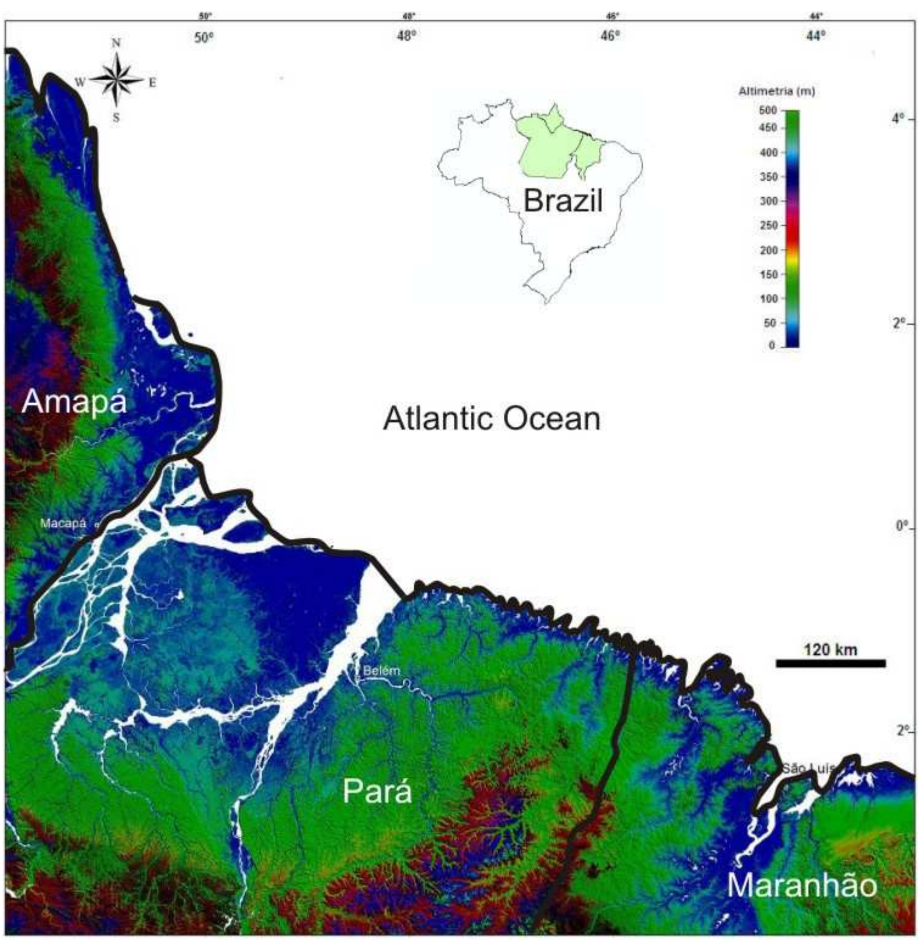

Fig. 1. Amazonian coastal zone in radar SRTM representation (source: modified from Souza Filho et al., 2005a)

In this sense, researches from Federal University of Pará have been working on several projects since 2001 aiming to study the Amazonian coastline and the impact of oil spills on the environment. Therefore, from 2004 to 2010, a large group of scientists were grouped in PIATAM-Mar project "Potential Environmental Impacts and Risks of the Oil and Gas Industry", financially supported by PETROBRAS[1], to map and analyse the vulnerability of the Amazonian coastline oil related disasters. Since 2012, the project "Elaboration of Environmental Sensitivity Maps (SAO maps) for oil spills in Pará-Maranhão and Barreirinhas Basins", founded by the National Research Council of Brazil (CNPQ) has been developed with similar objectives.

Remote sensing and GIS are principal tools aimed to enhance basic socio and environmental knowledge about Amazonian coast. Maps were prepared in strategic and tactical scales through the use of digital elevation models derived from the SRTM (Shuttle Radar Topographic Mission) and optical sensors data (Cohen & Lara, 2003; Souza Filho & El Robrini, 2000; Souza Filho, 2005; Szlafsztein & Sterr, 2007; Silva et al., 2009), synthetic aperture radar (SAR) data (Souza Filho & Paradella, 2002 and 2005; Costa 2004; Souza Filho et al., 2005b; Silva et al., 2009), and the combination of some of them (Souza Filho & Paradella, 2005; Gonçalves et al., 2009; Rodrigues & Souza Filho, 2011).

Oil spill environmental sensitivity maps, adapted to the peculiarities of the Amazonian region (Souza Filho et al., 2004) were drawn at tactical scales through the use of Radarsat and Landsat sensors (Gonçalves et al., 2009; Teixeira & Souza Filho 2009; Boulhosa & Souza Filho, 2009), and operational scale through the use of High Resolution remote sensing (Andrade et al., 2010; Rodrigues & Szlafsztein 2010; Andrade et al., 2009). Over the past decade were reached advances in identification and assessment of sensitivity through spatial maps, the impacts to oil spill analyses, and oil spill risk in Amazonian coastal. The goal of this book chapter is to present a review of the oil spills environmental sensitivity mapping activities using remote sensing and GIS tools in the Amazonian coastal zone of Brazil.

2. Remote sensing and coastal environmental sensitivity for oil spill

2.1 Remote sensing

Remote sensing tools are essential for the construction of maps. These tools help in the precise delimitation of coastlines and specific landforms. The selection of appropriate remote sensing data and applicable digital image processing techniques involves a compromise between costs and mapping capabilities, including coverage area, and spatial resolution (Green, 2000).

For risk maps, remote sensing are fundamental. Risk appears in a broader context in humans transform of the natural into a cultural environment, with the aim of improving living conditions and serving human wants and needs (Turner et al., 1990). There are several sources of hazards to the environment and to society, some of them originated in human activities (Smith & Petley, 2008).

Oil spills are an example of this technological risk. Information and detection about oil spills can be collected through remote sensing tools for prevention planning, as well as river/ocean pollution monitoring and restoration. Some reviews of the use of remote sensing and oil spills including Brekke & Solberg (2005) and Fingas & Brown (2000).

[1] PETROBRAS is the large oil company in Brazil

For a coastal environment, remote sensors can provide information about the physical characteristics of the shoreline, coastal ecosystems dynamics, water quality, and land use/occupation. This information could be mapped at different scales generating cartographic products using all types of sensors and specific digital image processing (Jensen, 1996). Sensors can provide timely and valuable information about oil spills, including the location and extent, thickness distribution, and oil type in order to estimate environmental damage, take appropriate response activities, and to assist in clean-up operations for oil spill contingency planning (Grüner, 1991).

The most common sensors utilized to detect oil spills and to map coastal environments are: optical (visible, infrared sensors and ultraviolet sensors) or radar. Both types of sensor may be acquired at terrestrial, sub-orbital or orbital levels. At terrestrial level, both still and video cameras are commonly used. At the sub-orbital level (or airborne remote sensing), airplanes is the most commonly utilized platform. At the orbital level, satellites are usually used as a platform for sensors. Satellite differs from airborne remote sensing due to timing and frequency of the data collection, the demand of good climate conditions and the time required for processing the dataset (Jha et al., 2008). Aiming to compare sensors, a brief description is given in Table 1.

2.1.1 Optical

Optical sensors can be composed by three bands in the electromagnetic spectrum. These sensors are usually composed by multispectral bands in visible and infrared intervals from the electromagnetic spectrum. In the visible region (350 to 750 nm), oil has a higher surface reflectance than water, but also shows limited nonspecific absorption tendencies (Jha et al., 2008). Instruments such as cameras, films and spectrometers are optical techniques for remote sensing with the benefit of low cost. Normally, visible sensors cannot operate at night as they depend on the reflectance of sunlight, but, in the case of oil spills they can be used to create environmental and logistic maps of the coast to subsidize field trips and first risk management decisions. The infrared sensors are at the 0,7-14 µm intervals in the electromagnetic spectrum. Solar radiation is partially absorbed and emitted as thermal energy by oil. This is thermal energy concentrated in the thermal infrared region with a distinct spectral signature; water has a higher emissivity (Salisbury et al., 1993). Infrared sensors can provide information about the relative thickness of oil slicks, but these sensors are unable to detect emulsions of oil in water when oil is diluted to 70% water (Fingas & Brown, 1997). Infrared is reasonably inexpensive, but has limitations related to false positive results generated by weeds and shorelines (Fingas & Brown, 2000).

Ultraviolet sensor scanners capture ultraviolet radiation (0,003 – 0,38 µm) reflected by the sea surface for detecting oil spills. Oil is more reflective than water in the ultraviolet region. Limitations of this sensor are related to undetected information greater than 10 microns and false images produced by such hindrances as wind slicks, sun glints, and biogenic material (Grüner, 1991).

2.1.2 Radar

Radar is an active sensor (not dependent on electromagnetic radiation from the sun) and operates in a radio wave region (1m – 10^4m). Radar sensors can have two principal

Sensors		Platform		Spatial resolution (m)	Over-pass Frequency (days)	Imagery area	Application
RADAR	SAR	Spaceborne	ERS-2	30	3, 35 and 176 days	100km	Identify large offshore spills and coastal environments – Strategic planning and monitoring
	SAR		RADARSAT-1	8-100	24 days	45-500km	
	SLAR	Airbone	Airplane	10-50	As required	60-80km	Detect and identify the polluter, the extent and type of oil spill and the cleaning necessity; Environmental mapping – Strategic and tactical planning
	SAR		Airplane	1-10	As required	-	
OPTICAL	MSS,TM, ETM, ETM +	Spaceborne	Landsat 5 Landsat 6 Landsat 7	15-120	16 days	183-185km	Detect oil spill if the weather conditions are good; can discriminate false positives; identify and mapping environments – Strategic and tactical planning
	HRV		Spot-2 Spot-3	10-20	26 days	60x60km /100km	
	CCD		Cbers-1; Cbers-2	20	26 days	113 km	Detect oil spill if the weather conditions are good; identify and mapping environments – Strategic and tactical planning
	IRMSS		Cbers-1; Cbers-2	80-160	26 days	120 km	Detect oil spill if the weather conditions are good; capable to detect thermal surface differentiations - Strategic and tactical planning
	WFI		Cbers-1; Cbers-2	260	5 days	890 km	Detect oil spill if the weather conditions are good; monitoring; identify and mapping environments – Strategic planning
	Video camera	Airbone	Airplane	Altitude Dependent	As required	-	Oil spill and coastal environmental documentation. The infrared sensor for measure the thickness of oil slicks – Operational planning
	Still camera		Airplane	Altitude Dependent	As required	-	

Table 1. Characteristics of some existing sensors for oil spill management applications.

instruments: Side-Looking Airborne Radar (SLAR) and Synthetic Aperture Radar (SAR). Radar is a very powerful and useful sensor for searching large areas, observing oceans at night, and capturing images during cloudy weather conditions. The presence of an oil spill can be detected without thickness estimation or oil type recognition. In the radar image, the leak appears as a dark area in contrast to the bright image of the ocean because radar waves are reflected by capillary waves on the ocean (Brown et al., 2003). For a coastal environment, mapping SAR is already considered to be a powerful tool for geomorphologic mapping, providing relevant information about the emergence and submergence of the coast (Souza Filho et al., 2009a).

SLAR is an old technology predominantly used for airborne remote sensing (Fingas & Brown, 2000). Airborne surveillance is limited by high costs and is less efficient for wide area observation due to its limited coverage. SAR has greater spatial range and resolution than the SLAR because it uses the forward motion of the aircraft to synthesize a very long antenna, thereby achieving very good spatial resolution, at the expense of sophisticated electronic processing (Mastin et al., 1994). SAR can be used to provide an initial warning because aircrafts are more suitable to identify the polluter, the extent, and the type of spill.

For large scale oil spill detection, satellite platforms, including ERS-1 and -2, Radarsat, and JERS-1, are commonly used for large scales oil spills (Fingas & Brown, 2005). Radar satellites, including ERS-1 and -2, Radarsat, and JERS-1, have been useful for mapping known large offshore spills (Biegert et al., 1997). On the other hand, optical satellite imagery does not offer much potential for oil spill detection (Fingas & Brown, 2000). However, to map coastal environments, geomorphology and its sensitivity, multi-sensor data fusion such as optical and radar has proved to be a successful tool (Souza Filho et al., 2009b).

2.2 Coastal environmental sensitivity to oil spills

The inter-relationships involving natural resources and human societies have led to a concentration of human activities, services and survival strategies in the coastal environment (Viles & Spencer, 1995; Muehe & Neves, 1995; Pernetta & Elder, 1992). The unique natural geodynamics, the highly productive and extremely diverse biological systems extending from coastal lands to deep water regions (Malthus & Mumby, 2003), the growing land use changes and the pressure on natural resources (MEA, 2005) transform the coastal zone into a conflict area. Oil exploration, transportation and storage have increased the technological risk in this zone.

Areas neighboring major ports (environmental and human populated) may be affected by oil transportation, tank cleaning and oil storage procedures in a port area (Noernberg & Lana, 2002). One of the initial concerns about oil spills result in a necessity for the construction of maps that indicate which type of environment and human resources will be affected. In the mid 1970s, scientists from the National Oceanic and Atmospheric Administration (NOAA) and the American Coast Guard of the United States began to study and classify the sensitivity of coastal environments to oil spill.

This classification was based, initially, on the vulnerability index to oil spills proposed by Gundlach & Hayes (1978). Coastal area is segmented considering environmental and geomorphologic characteristics and then classified using the Vulnerability Index, scaled from 1 (low) to 10 (high). This Vulnerability Index became the standard for coastal management, planning and research about the effects of oil spills on different types of coastline. Over time, this index evolved and was modified, leading eventually to the development of the Environmental Sensitivity Index (ESI).

The ESI should be represented cartographically as maps in different scales for different goals. The first ESI map was produced in 1979, in response to the advance toward the coast of oil resulting from the blowout of the IXTOC 1 oil-well in the Gulf of Mexico. In the 1980s, ARPEL produced an innovative ESI atlas for the whole coast of the United States, including Alaska and the Great Lakes, to be used for the planning of contingency measures in response to oil spills (NOAA, 2002). From this moment on, ESI maps have been an integral component of response and contingency planning for oil spills, looking for the protection of life, the reduction of environmental impacts, and facilitation of the response efforts. These atlases were integrated by color printed maps on a two dimensional representation of a three-dimensional world and high production costs.

After the 1990's, NOAA (2002) standardized output formats and symbols for ESI maps construction. The basic necessary information is 1) shoreline classification; 2) biological resources; 3) human-use resources. The shoreline classification scheme is based on an understanding of the physical and biological characteristics of the shoreline environment. Relationships among physical processes, exposure to wave and tidal energy, slope, substrate type (i.e. grain size, mobility, penetration and/or burial, and mobility), and associated biota produce specific geomorphic/ecologic shoreline types. Shoreline classification helps to identify oil spill origin and impacts and the best cleanup methods for a specific shoreline type. The sensitivity ranking was developed for the estuarine settings and is slightly modified for lakes and rivers. The human use resources relate to specific, valuable specific areas because of their use, such as beaches, parks and protected marine areas, water intakes, fisheries, tourism, economic sectors, and archaeological sites. The biological resources include the study and maps of oil-sensitive biological and ecological resources.

3. Remote sensing and coastal environmental sensitivity in Brazil

Brazil has an expansive coastline through the equatorial region to the subtropical latitude of the south hemisphere. The length is approximately 8.500 km with 17 of the 26 states of the country lying on the coast of the Atlantic Ocean. The Brazilian coast is defined by the National Plan for Coastal Management (law 7661/1988), as the geographic space where there are air, sea and land interacts, which includes renewable and non-renewable resources along a maritime and terrestrial border.

A diversity of coastal environments and population densities are found along the Brazilian coast. Population is higher in state capitals than in the other coastal municipalities. Environments vary from very productive, such as mangroves, to rocky and artificial man-made structures. Man-made structures, such as ports are established along the entire coastline of Brazil (Figure 2).

Ports are high-risk areas, and oil spill monitoring is clearly important there. In 2000, two large oil spills occurred at Baía de Guanabara (Rio de Janeiro) and Paraná, both resulting from pipeline ruptures. After these accidents, fundamental changes have been made to

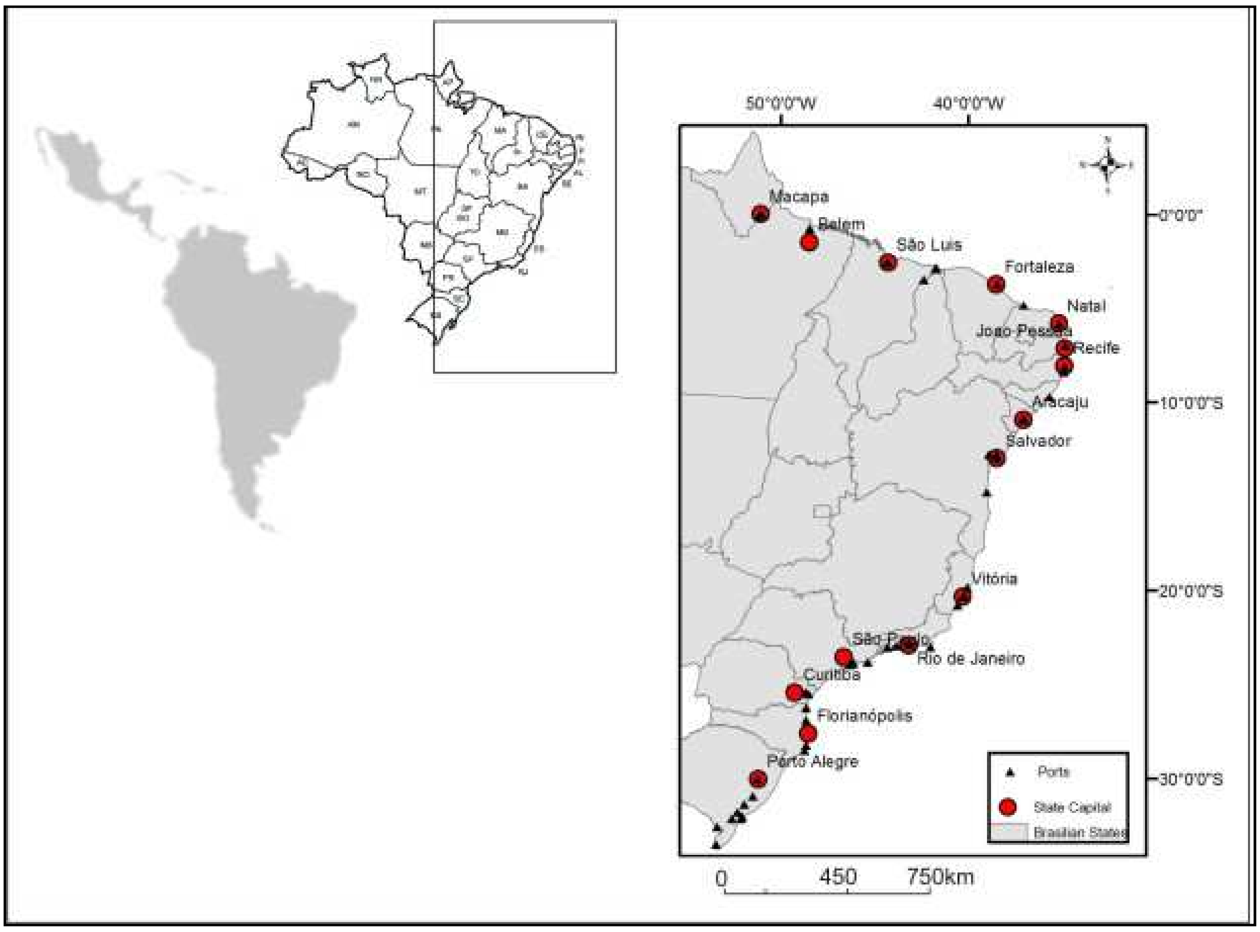

Fig. 2. Main ports of the Brazilian coast (IBAMA, 2011).

the environmental policies of Brazil and PETROBRAS (Souza Filho et al., 2009b), in order to give priority to prevention and mitigation activities.

After these accidents, the prevention and mitigation oil spill impacts became a priority. The law 9966/2000 was established to regulate the activities of prevention, control and supervision of pollution caused by oil and other dangerous substances in Brazilian waters. The Ministry of the Environment has the responsibility of identifying, locating and defining the boundaries of the ecologically sensitive areas to oil spills. Ecologically sensitive areas are defined as regions where special attention is needed in order to protect and preserve the environment from pollution by regulatory and preventive measures (MMA, 2002). In this context, Araújo et al. (2002) published the document "Basic Manual for the Elaboration of Maps of Environmental Sensitivity to Oil Spills in the Petrobras System: Coastal and Estuarine Environments" edited by the Ministry of the Environment (Climate Change and Quality Environmental Secretary) and based on PETROBRAS (2002) and NOAA (2002).

This change in attitude was reflected in a large production of oil spill environmental sensitivity maps for the Brazilian coast (Araújo et al., 2006) (Table 2). These maps are produced in order to support environmental management and the elaboration and implementation of contingency plans. The ESI preparation was intensified through Decrees 4136/2002 and 4871/2003.

Author	Spatial Resolution	Sensor	Method	Scale	Case study (State)
Romero, et al. (2010)	High	Aerial photography	Literature review, Field data collection	Operational	Cananéia-Iguape Estuary (São Paulo)
Silva et al. (2010)	Low	SRTM, Radarsat	Highly precision field data collection with DGPS, Previous database research, visual classification	Tactical, Operational	Potiguar Sedimentary Basin (Rio Grande do Norte)
	Moderate	Landsat 7 ETM+, Cbers-2, Cbers-2B			
Cantagalo et al. (2008)	High	Aerial photography	Visual classification, field data collection	Tactical, Operational	Santos Estuary (São Paulo)
Carvalho & Gherardi (2008)	Moderate	Landsat 7 ETM	Automatic classification, visual interpretation, Field data collection	Tactical, Operational	Potiguar Sedimentary Basin (Ceará and Rio Grande do Norte)
Bellotto & Sarolli (2008)	Moderate	Landsat 7 ETM+	Visual interpretation, Previous database research, Field data collection	Operational	Municipality of Imbatuba (Santa Catarina)
Poletto & Batista (2008)	Moderate	Cbers	Visual interpretation, Previous database research, Field data collection	Tactical, Operational	Municipality of Ubatuba (São Paulo)
	High	Aerial photography			
Rocha-Oliveira et al. (2008)	Moderate	Landsat 7 TM+	Visual interpretation, Field data collection	Operational	Southeast and south area (Santa Catarina)
Silva et al. (2008)	Moderate	Landsat 7 TM+	Visual interpretation, field works, literature review	Operational	Santa Catarina Island and surrounding areas (Santa Catarina)
Araújo et al. (2007)	Moderate	Landsat 7 ETM+	Visual interpretation, Field data collection	Operational	Municipalities of Itapoa, Barra Vellha, Piçarras, Itajaí, Balneário Camboriú (Santa Catarina)
	High	Aerial photography			
Chacaltana (2007)	High	Ikonos	Visual interpretation, Field data collection	Operational	Vitória Bay (Espírito Santo)
Lima et al. (2008)	High	Aerial photography	Visual interpretation, Field data collection	Operational	São Sebastião Island (São Paulo)
Wieczorek et al. (2007)	High	Aerial photography	Visual interpretation, Field data collection	Operational	Cananéia-Iguape Estuary (São Paulo)

Author	Spatial Resolution	Sensor	Method	Scale	Case study (State)
Castro et al. (2006)	Moderate	Landsat 5 TM, Landsat 7 ETM+	Database development, geomorphology; hydrodynamic, waves energy, currents direction; slope and grain size of profile beach	Operational	São Bento, Galinho Municipalities (Rio Grande do Norte)
	High	Aerial photography			
Souto et al. (2006)	Moderate	Landsat 5 TM, Landsat 7 ETM+	Normalized Difference Vegetation Index, Automatic classification, Visual interpretation, Field data collection	Operational	Ponta Macau (Rio Grande do Norte)
	High	Aerial photography			
Souza, et al. (2005)	Moderate	Landsat 5 TM, Landsat 7 ETM+, SPOT, Cbers-2	Database utilization; visual interpretation, Field data collection	Tactical	Northern coast (Rio Grande do Norte)
	High	Ikonos			
Noernberg & Lana (2002)	Moderate	Landsat TM	Database access, digital processing	Operational	Paranaguá Estuary (Santa Catarina)

Table 2. Principal studies of oil spill coastal sensitivity using remote sensing techniques in order to generate ESI maps in Brazil organized by date (Amazon Region are not included).

In Brazil, the ESI maps were also developed in a cartographic plan at strategic, tactical and operational scale for the role country. As an initial step, the tools of remote sensing and GIS are necessary to ESI maps construction and to comprehend differential spread of the technological risk for the country's coasts. Mostly moderate and high resolution images were used to produce these maps.

Moderate resolution images (e.g. RADARSAT-1 and Landsat TM/ETM/ETM+) and SRTM derived digital elevation models have been used to map the Brazilian coastal zone at strategic and tactical scales. Studying an oil spill emergency due to a pipeline rupture in Guanabara Bay (Rio de Janeiro), Bentz and Miranda (2001) found that RADARSAT-1 provided suitable temporal coverage. Once cloud cover, haze and the eight-day revisit schedule (using both Landsat-5 and -7) prevented Landsat from being used systematically for oil spill monitoring. In the same case Thematic Mapper (TM) sensor was used to capture images after the oil spill emergency where a pipeline ruptured (Bentz & Miranda, 2001).

Carvalho & Gherardi (2008) used Landsat 7 ETM+ images to generate land use and land cover maps, as well as ESI maps in Northeast Brazil, aiming for oil spill contingency planning and emergency responses. A fusion of multispectral and panchromatic ETM images via IHS (Intensity-Hue-Saturation) transformation was used. Then socioeconomic information was inserted using automated and visual image interpretation.

High resolution images have mostly been used for operational ESI maps production in the states of São Paulo and Rio Grande do Norte using aerial photography and Ikonos. Visual interpretation, together with field data collection, has been the principal methodological procedure. Most areas have mangroves, conservation units and are surrounding by intensive technological activities.

The methodology, standards and technical specifications for determining coastal sensitivity follow Araújo et al. (2002). The principal steps for shoreline identification are: 1) Analysis of the available literature, aerial photographs, maps of the entire area; 2) Aerial reconnaissance of the entire area and selection of detailed study areas; 3) Mapping of major features in representative areas; 4) Collection of sediment from the intertidal zone and biologic floral and faunal groups samples; construction of beach topographic profile; 6) Analysis of the sediment sample sizes; 7) Data compilation and classification; and 8) Construction of detailed sensitivity maps.

Colors are used indicate the ESI and symbols to the human and biological resources. Each number is represented by a color index. Two environments may occur at the same coastal segment; in that case, both colors of the separated lines should be displayed, one inside and the other outside. In the case of intertidal zones, for example, the intertidal plain should display colors according to the differences of sediment sizes to the high tidal line and the low tidal line. Table 3 compares ESI specification defined by the Ministry of the Environment (MMA, 2002) with the original defined by NOAA (2002).

ESI number	Color	NOAA (2002)	MMA (2002)
1		Exposed rocky shores and man-made structures; rocky cliffs with boulder talus base	Exposed rocky shores; exposed rocky sedimentary cliffs; exposed solid man-made structures
2		Exposed wave-cut platforms in bedrock, scarps and steep slopes in clay	Exposed medium to high declivity rocky shores; exposed sandy substrate with medium declivity
3		Fine to medium grained sand beaches; Scarps and steep slopes in sand; Tundra cliffs	Fine to medium grained sand in dissipative beaches; continuous and multiple beach strings; Scarps and steep slopes in sand; exposed dune field
4		Coarse-grained sand beaches	Coarse-grained sand beaches; exposed; exposed fine to medium grained sand intermediary beaches; sheltered fine- to medium- grained sand beaches
5		Mixed sand and gravel beaches	Mixed sand and gravel beaches, coral reefs fragments; vegetated abrasion platform; sandy reefs

ESI number	Color	NOAA (2002)	MMA (2002)
6		Gravel beaches; Riprap gravel beaches (cobbles and boulders)	Gravel beaches; dendritic limestone coast; platform with lateritic concretion
7		Exposed tidal flats	Exposed sandy tidal flats; low tide platform
8		Sheltered: scarps in bedrock, mud or clay, rocky shores (impermeable/permeable), solid man-made structures, riprap, rocky rubble shores; Peat shoreline	Sheltered scarps in bedrock (permeable and non permeable); Scarps and steep slopes in sand; permeable sheltered man-made structures (riprap)
9		Sheltered tidal flats; Vegetated low banks; hypersaline tidal flats	Sand tidal flats; sheltered mud tidal flats; coral reefs
10		Salt and brackish water marshes; Freshwater marshes; Swamps; Scrub-shrub wetlands: mangroves; Inundated low-lying tundra	Delta and vegetated sand bars; sheltered wetlands; salt marshes saline wetlands; mangroves

Table 3. ESI comparison between NOAA (2002) and Ministry of the Environment (MMA, 2002) classification.

4. Remote sensing and coastal environmental sensitivity in Amazon

The coastal zone of the Brazilian Amazon is composed by tree states: Amapá, Pará and Maranhão. According to the IBGE (2011), the total population of Amapá State is 669,526 distributed in 16 municipalities; the state capital, Macapá, concentrates 59% of this population. The state of Pará has a total population of 7,581,051 distributed in 143 municipalities; Belém comprises 18%. Maranhão state has a total population of 6,574,789 distributed in 217 municipalities; São Luis comprises 15% of this population. The population density in capital cities is over 100 hab/km^2, while in other coastal municipalities vary from 10 to 50 hab/km^2.

Until 21st century most of the coastal zone of the north of Brazil had sectors virtually devoid of information, or where data was available, it was non-systematized and both temporally and spatially non-continuous. The most important environmental dataset is related to the large continuous and well-developed mangroves - *Rhizophora mangle*, *Avicennia germinans* and *Laguncularia racemosa* (Szlafsztein, 2000). The mangroves have ecological and socioeconomic importance due to communities' livelihoods, and they are considered a protected ecosystem. The main activities are fishing, collecting shrimp and crabs (Andrade et al., 2010; Andrade et al., 2009).

However, port complexes and industries have been established alongside residential, protected areas and fishing grounds. For example, in Piatam Mar context the principal ports chosen to develop oil mapping were "Santana" (State of Amapá); "Itaqui" (State of Maranhão); "Outeiro", "Miramar" and "Vila do Conde" (State of Pará). The biological information was intensively identified in “Lago Piratuba biological reserve” (Amapá); “Soure extractive reserve” (Pará) and “Ilha dos Caranguejos Environmental Protection Area” (Maranhão). According to Souza Filho et al., (2009a) these conservation units work as control areas, given both their well-preserved conditions and their proximity to transportation routes due to proximity to protected areas along the ports mentioned above (Figure 3).

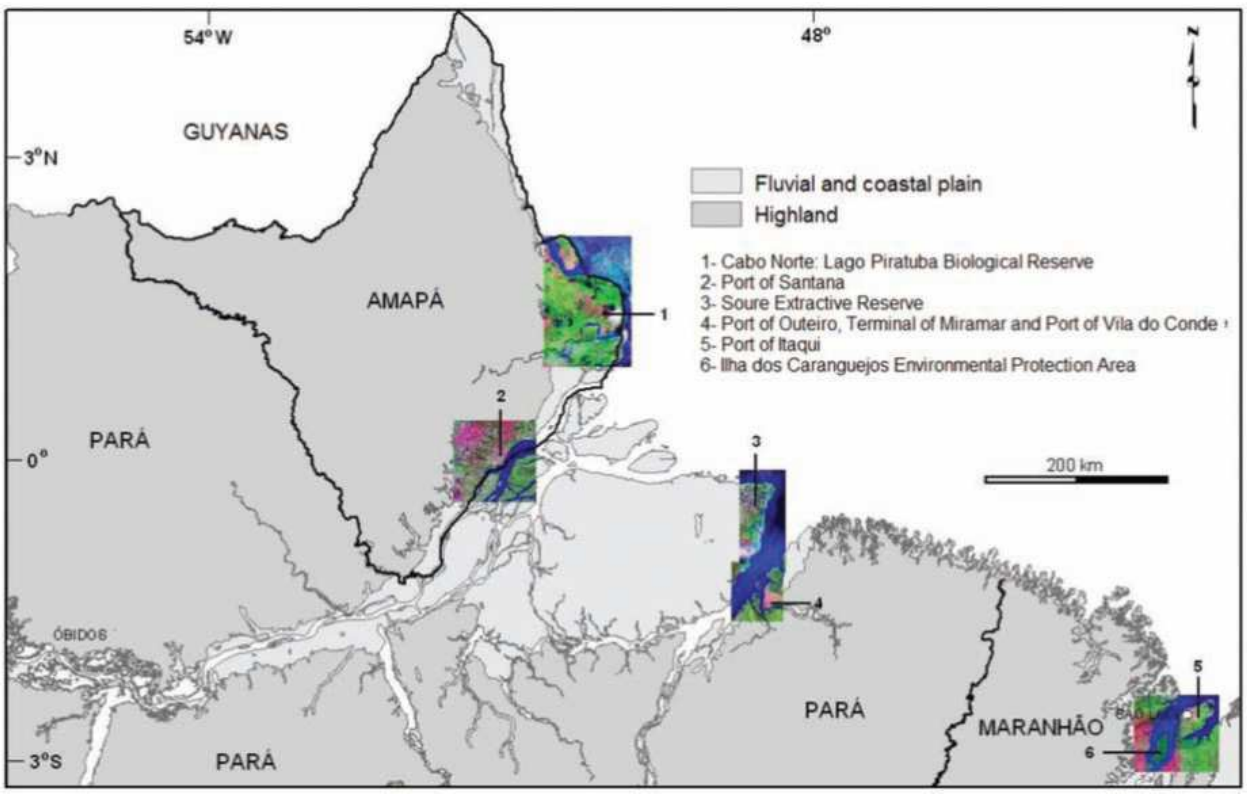

Fig. 3. Principal ports and environmental protected areas in the Amazon coast (source: Souza Filho et al., 2009a).

Oil spills are a potential risk around these port areas which can affect the environment, human population infrastructure and livelihood, resulting from the transportation process, as well as tank cleaning and oil storage procedures within the area of the port (Noernberg & Lana, 2002). To comprehend the oil impact, it is necessary to analyze the coastal Amazonian environment as a whole. PETROBRAS established and financed nine projects to deal with this subject, among them, the “Environmental Sensitivity Map to Oil Spill in Guajará Bay (PA)” (2001 – 2003), the “JERS-1, RADARSAT-1 and ALOS/PALSAR application in monitoring and mapping Amazon coastal environments: an approach for multi-temporal environmental sensitivity maps to oil spill” (2004 - 2006), PIATAM MAR (2004 - 2010) and currently “Elaboration of ESI maps for Pará-Maranhão and Barreirinhas basin” (2012 until 2014).

The PIATAM MAR project was implemented in Northern Brazil and was led by the Federal University of Pará, the Federal University of Rio de Janeiro and PETROBRAS. The general aims proposed are: the consolidation of a multidisciplinary researcher’s network that are active in the Amazonian coastal zone; the development of technological tools and infrastructure to support local monitoring and environmental management; and ESI maps construction (Souza Filho et al., 2009a).

Initially, the researchers of PIATAM MAR project compiled environmental data and other information available on the Amazon coastal zone. The results are integrated in the book, "Bibliography of the Amazon Coastal Zone: Brazil" (Souza Filho et al., 2005a). Meanwhile, a computational database system using the MYSQL language was developed and used as a basis for the development of a geographic information system called SIGmar.

All of these initial steps support the subsequent aim of PIATAM MAR: the construction of ESI maps. From 2006 to 2010 socio-economic and environmental data were integrated in ESI maps. These maps have been developed through the SIGmar and the extensive use of remote sensing. ESI maps create an operational alternative for the monitoring and mapping of the Amazonian coastal zone and provide guidelines for the use of the InfoPAE (Computerized Emergency Action Plan Support) System on the Amazonian coast (Souza Filho et al., 2009a).

Two considerations should be taken into account when mapping and monitoring oil spills in the Amazonian coastal environments. First, the unique complex environmental dynamics of the Amazon basin have demanded an adaptation of ESI classification with values from 1 (low) to 10 (high) sensitivity (Souza Filho et al., 2004) (Table 4). Second, the Amazonian coast is situated in the intertropical convergence zone (ITCZ) that is located near the equator and has a broad area of low atmospheric pressure. Therefore, there is a huge cloud cover between December and May which limits the use of some kinds of sensors.

Coastal ESI mapping for the Amazon uses remote sensing as an indispensable and very powerful tool. Oil spill and environmental sensitivity to oil spills in the Amazon were mostly mapped during the PIATAM MAR project. Table 5 shows the most important scientific results in this study area. The perspectives of the ESI adaptation proposed by Souza Filho et al. (2004) were extensively used.

The whole Amazon coastal zone was mapped with spatial resolution of 90 m based on the processing and images mosaics of SRTM images and 30 m of RADARSAT-1 Wide 1 images and mosaics of JERS-1 SAR. This sensor was chosen given the six months of unfavorable climatic conditions; radar sensors (Synthetic Aperture Radar – SAR) are used for strategic scale.

On a tactical scale, multi-sensor data fusion between microwaves sensors and optical sensors are considered to be the most important source of spatial data for geomorphologic recognition and basic coastline characteristics. The commons sensors fusion are made in general with low resolution data from RADARSAT-1 Wide 1 and JERS-1 SAR mosaic, together with moderate spatial resolution data (10–30 km) from Landsat series (MSS, TM and ETM+) and Cbers-2 images (20m). The multi-fusion of optical (Landsat 5 TM) and radar (RADARSAT-1) sensors had a particular emphasis on the evaluation of the new hybrid sensor product combining PCA (Principal Component Analysis) and IHS components. In areas with little or no data, this fusion method from multi sensors to orbital images, together with field data are economically efficient and provide a good environment sensitivity characterization (Rodrigues & Souza Filho, 2011).

Hydrological dynamics with flood area delimitation could be differentiated by the use of JERS-1, L band (Santos et al., 2009), which is important in a region dominated by different tidal regimes that can amplify the area affected by oil spills. Methods include visual and automatic classification leading to good results in identifying widespread occurrence of

ESI	Amazon Coastal Environment
1A	Exposed rocky shores
1B	Exposed, solid man-made structures
1C	Exposed rocky cliffs with boulder talus base
2	Exposed scarps and steep slopes in clay
3A	Fine to medium grained sand beaches
3B	Scarps and steep slopes in sand
4	Coarse-grained sand beaches
5	Mixed sand and gravel banks and beaches
6	Riprap
7	Exposed tidal flats
8A	Sheltered scarps in bedrock, mud, or clay
8B	Sheltered, solid man-made structures
8C	Sheltered riprap
8D	Peat shorelines
9A	Sheltered tidal flats
9B	Vegetated low banks
9C	Hypersaline tidal flats
10A	Salt, and brackish-water marshes
10B	Freshwater marches, aquatic vegetation
10C	Intertidal mangrove
10D	Supratidal mangrove

Table 4. ESI shoreline classification for the Amazon Coast, modified by Souza Filho et al. (2004) based on the proposals of NOAA (2002) and Araújo et al. (2002).

flooded mangrove forests. This environment is considered to be the most oil-sensitive habitat described in Table 4 - ESI Ranking specification = 10c and 10d (Souza Filho et al., 2005a).

High resolution images, such as Ikonos, were used for operational scale mapping. The resolution of 1 m provides a detailed geomorphic map, and it's also possible to map the potentially hazardous industrial structures stratified by type of hazard. However, the use of Ikonos images is limited when cloud cover is higher than 25%. As a result the images are mostly inadequate between March and June (Andrade et al., 2010). On the other hand, biological and socioeconomic resources, risk areas and oil spill hazard zones of storage and platform transportation can be better identified and delimitated (Rodrigues & Szlafsztein, 2010; Andrade et al., 2009). This location contributes to planning and management strategies and cleaning efforts.

Author	Map Type	Spatial Resolution	Sensor	Method	Scale	Study case
Andrade et al. (2010)	Oil spill Vulnerability	High	Ikonos	Visual interpretation, Field data collection	Operational	Municipality of São Luis (Maranhão)
Rodrigues & Szlafsztein (2010)	Oil spill risk	High	Ikonos	Visual interpretation, Field data collection	Operational	Municipality Barcarena (Pará)
Andrade et al. (2009)	Oil spill hazard representation and susceptible socioeconomic resources	High	Ikonos	Visual interpretation, Field data collection	Operational	Municipality of São Luis (Maranhão)
Boulhosa & Mendes (2009)	ESI	Moderate	Spot-5	Visual interpretation, Field data collection	Operational	Municipality of Barcarena (Pará)
Boulhosa & Souza Filho (2009)	ESI	Moderate	Landsat 7 ETM+, SRTM High, aerial photography	Automatic classification, multi-fusion sensors, Field data collection	Tactical	Municipalities of Maracanã, Santarém Novo, Salinópolis, Cuiarana, São João de PIrabas, Santa Luzia and Primavera (Pará)
Gonçalves et al. (2009)	ESI	Moderate	Landsat 7 ETM, Radarsat 1	Automatic classification, multi-sensor fusion, field data collection	Tactical	Municipality of Belém (Pará)
Souza Filho et al. (2009)	ESI	Moderate	Landsat 5 TM, Radarsat 1	Visual classification	Tactical	Municipality of Bragança (Pará)
Novaes et al. (2007)	ESI	Moderate	Landsat 5 TM	Visual interpretation, Field data collection	Operational	Municipality of São Luis, (Maranhão)

Table 5. Results published in a scientific paper related to remote sensing use and sensitivity environment to oil spill in Amazon coast.

5. Conclusions

Remote sensing techniques are used for risk identification, assessment and analysis. The technological risk of oil spills needs continuous planning and monitoring actions. The availability of airborne and satellite remote sensing provides a diversity of resolution and sensors required to construct environmental sensitivity maps, using basic information about socioeconomic and biological resources and geomorphic characteristics.

Remote sensing and ground confirmation provide accurate information about this basic information. In particular, the coastline is usually mapped in detail with both optical and radar sensors. The multi-sensor data fusion of an optical moderate sensor with radar has been extensively used in the Amazon region to provide basic information about coastal environments. Radar is a very powerful tool once it can operate in difficult weather conditions. It provides detailed information about shoreline irregularities and geomorphic units if the texture and the altitude of this type of images are precise. Optical sensors are used for environmental differentiation once land cover and land use have different spectral responses.

Studies in Brazil regarding oil spills have increased after 2000, and ESI maps have been generated at different scales for different areas along the coast. Remote sensing tools were essential to achieve initial and advanced cartographic information in a context of the diversity of the environment, information and cartographic background. Particularly in the Amazon, little background information about the coastline existed before the PIATAM MAR project. In the context of this project, the Amazon coast was previewed at strategic scale with the use of a moderate sensor. ESI maps were produced at the tactical and operational scales and it was possible to map the coastal environment and organize information about socioeconomic and biological resources. A large, extensive mangrove system coexists with industrial port areas on the Amazon coast with a high sensitivity to oil spills, which should to be continuously monitored with remote sensing techniques.

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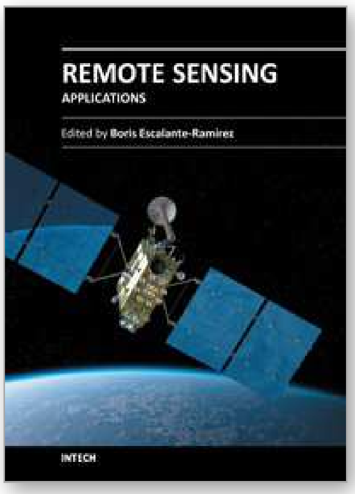

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