ENVIRONMENTAL SENSITIVITY INDEX (ESI) MAPPING OF OIL SPILL IN THE AMAZON COASTAL ZONE: THE PIATAM MAR PROJECT

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ABSTRACT. The importance of environmental monitoring is clear from the many oil spills that have occurred over the past three decades. This has encouraged both companies and the public sector involved in the prevention and response to these accidents to develop efficient procedures to minimize the damage caused by accidents involving oil spill. This study reviews the history of oil spill accidents in Brazil and examines how these events have contributed to the development of technological research through partnerships involving oil companies, government, universities and research institutes, with the emphasis on the Amazon coastal zone. As a result, environmental sensitivity indexes (ESIs) for oil spill have been developed specifically for the Amazon coast, where fluvial and marine processes take place in the estuary of the world's largest river system. Perspectives on research and emergency response procedures are presented, with the primary objective of conserving the social-environmental diversity of the planet's most important tropical region.

Keywords: environmental sensitivity index, ESI, remote sensing, oil spill, Amazon coastal zone.

RESUMO. A importância do monitoramento ambiental é medida pelos vários casos de derramamentos de óleo ocorridos no mundo durante as últimas três décadas. Isto tem incentivado as empresas e órgãos do governo envolvidos na prevenção e combate a estes acidentes a aperfeiçoarem cada vez mais os métodos, tanto preventivos como corretivos, para a minimização dos danos gerados por acidentes com derramamento de óleo. Este trabalho objetiva contextualizar de forma histórica como os acidentes com derramamento de óleo propiciaram o desenvolvimento de pesquisa tecnológica a partir de parcerias entre empresas de petróleo, agências de governo, universidades e institutos de pesquisa no Brasil, em especial na zona costeira Amazônica. Como resultado, índices de sensibilidade ambiental ao derramamento de óleo (ISA) foram definidos especialmente para a Amazônia costeira, onde processos fluviais e marinhos se encontram na foz do maior rio do mundo, o rio Amazonas. Perspectivas de pesquisa e respostas de emergência a acidentes são apresentadas, a fim de se conservar a diversidade socioambiental da mais importante região tropical do planeta.

Palavras-chave: índice de sensibilidade ambiental, ISA, sensoriamento remoto, derramamento de óleo, zona costeira da Amazônia.

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INTRODUCTION

The importance of environmental monitoring has been emphasized by numerous oil spills that have occurred along the Brazilian coast over the past few years. These accidents have encouraged the oil companies and public sector to develop increasingly efficient procedures, both preventive and emergence response, in order to minimize the damage caused by such events.

In 2000, more than 1300 m^3 of fuel oil leaked from the rupture of one of the transfer pipelines at the Duque de Caxias refinery (REDUC) into Rio de Janeiro, Guanabara Bay (Bentz & Miranda, 2001). In July of the same year, a Petrobras pipeline fractured at the Presidente Getúlio Vargas refinery in Paraná state, causing the spill of 3.7 million liters of crude oil into the Barigue river (Carvalho, 2003). In 2001, the tanker "Miss Rondônia", loaded with approximately 1900 tons of type A1 oil, sank in the Pará river near the Port of Vila do Conde, in the state of Pará (Berredo et al., 2001).

These accidents have provoked fundamental changes in the safety and environmental policies of Brazilian petroleum companies, in particular Petrobras, as a response to both their social responsibility, and the heavy fines and compensation costs imposed by the courts, in response to these episodes. This shift in perspective has resulted in increasing investment in measures aimed at reducing emissions, residues, and effluents, in addition to improvements in the procedures for prevention and control. This has brought the objectives of the petroleum companies increasingly in line with the Public anxieties and demands for socially and environmentally responsible actions. This change in attitude was consolidated by the production of maps of environmental sensitivity to oil spill for a number of different sectors of the Brazilian coast, including that of the Amazon region (Araújo et al., 2006). A fundamentally important publication was the "Basic Manual for the Elaboration of Maps of Environmental Sensitivity to Oil Spills in the Petrobras System: Coastal and Estuarine Environments" (Araújo et al., 2002).

In 2004, a project named PIATAM Mar was established to evaluate the "Potential Environmental Impacts of the Transportation of Petroleum and its Derivatives in the Amazon Coastal Zone" (Sales et al., 2004). The objective of the first phase of this project (2004-2005) was the compilation of existing environmental and social data, covering themes related to geology, oceanography, fisheries, biology, tropical diseases, and socio-economic parameters. The second phase of the project (2006-2008) has concentrated on the development of a social and environmental diagnosis of the areas surrounding ports where oil terminals are located, as well as adjacent areas under their indirect influence, represented by conservation units (protected areas).

The production of Environmental Sensitivity Index (ESI) charts must take into consideration the juxtaposition of the hydrological cycles of the rivers of the Amazon basin with the configuration of local tides. The combination of these factors results in at least 64 different scenarios, which must be considered in the development of the environmental sensitivity maps which will provide support for the development of contingency plans for the Amazon coastal zone. The aim of the present paper is to review the level of scientific and technological development that has gone into the production of the ESI charts for the Amazon coastal zone, providing the reader with a historical perspective of the stages in the scientific development of this topic, which is so important for the exploration and conservation of the coastal zone.

THE PAST

In the mid nineteen-seventies, scientists from the National Oceanic and Atmospheric Administration (NOAA) and the American Coast Guard began to study and classify the sensitivity of coastal environments to oil spill. This classification was based initially on the index of vulnerability to oil spills proposed by Gundlach & Hayes (1978), which was determined by the physical and geological characteristics of the coastal pipeline (ARPEL, 1997). Based on a study of five oil spills, the coastal environments were classified according to a 10-item scale of sensitivity, from which a hierarchy of 1 to 10 was defined, referring to increasing vulnerability according to the type of coastline (Gundlach & Hayes, 1978).

This Vulnerability Index became the standard for coastal management, planning and research into 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).

From this moment onwards, ESI charts have been an integral component of response and contingency planning for oil spills. The first ESI chart was produced in a matter of days, in 1979, in response to the advance and impending coastal landing of the oil slick resulting from the blowout of the IXTOC 1 well in the Gulf of Mexico (NOAA, 2002).

In the nineteen-eighties, ARPEL (Asociación Regional de Empresas de Petróleo y Gas Natural en Latinoamérica y el Caribe) 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

(ARPEL, 1997). Prior to 1989, these atlases were, however, a two-dimensional representation of a three-dimensional world, with all the information printed in color on paper maps, which had a limited distribution due to high production costs. Obviously, these maps were not only difficult to produce, but in particular to update, especially in comparison with the digital maps available in the present day. Given this, the ESI atlas has been generated from digital data bases by a Geographic Information System (GIS) since 1989.

In Brazil, the first ESI chart was produced only in 1993, by Petrobras. It covered the company's exploration and production areas in the Campos Basin. In 1996, ARPEL promoted a workshop, during which it recommended the use of a standard system for the production of ESI chart by the different petroleum companies (Araújo et al., 2002). The ESI scale adopted during this workshop was modified from the NOAA proposal, based on Gundlach & Hayes (1978), to include both biological and social parameters, and the adaptation of these parameters to the reality of local conditions (Michel et al., 1978).

THE PRESENT

On December 12th, 2001, the Brazilian National Environment Council (CONAMA) published its Resolution number 293, which defined the minimum parameters for individual emergency plans for dealing with oil pollution in ports, dockings or terminals, pipelines, platforms, and their respective support installations. This document provides specific instructions for the development of each plan considering, among others factors, the serious oil spill that have occurred in the country, and the urgent need for the establishment of guidelines and effective response procedures for incidents involving oil pollution. Given this, the resolution requires that, whenever possible, the analysis of vulnerability be based on the information available in ESI charts, produced according to the relevant technical norms and specifications. The localization of the vulnerable areas should be indicated clearly on diagrams and maps, drawn up on an appropriate scale, with clear labels.

Resolution 293 led to the acceleration of the production of ESI charts in the country, and an increasing demand for the establishment of specific methods for their development. In 2002, Petrobras published its "Basic Manual for the Elaboration of Maps of Environmental Sensitivity to Oil Spills in the Petrobras System" (Araújo et al., 2002). This publication is a benchmark for the production of ESI charts in Brazil, as well as for the development of research into the evaluation of the environmental sensitivity of the Brazilian coastline, which stretches from the Amazon

zone ($\sim$4°N) to the lagoons in the southernmost extreme of the country ($\sim$35°S).

In 2002, the Northern-Northeastern Cooperative Network for the Environmental Monitoring of Areas under the Influence of the Petroleum Industry (Rede 5 – PETROMAR, FINEP/CNPq/PETROBRAS; http://www.geopro.ufrn.br/rede05/), led by the Federal University of Rio Grande do Norte, was created through a FINEP (Studies and Projects Financier) research initiative. This cooperative network is arbitrated by Petrobras, through its Research and Development Center (CENPES), and its Exploration and Production Business Units in Rio Grande do Norte and Ceará (UN-RNCE), Bahia (UN-BA), and (at the time) Pará (UN-PA), in addition to its Northeastern Lubricants and Petroleum Derivatives Unit (LUBNOR). PETROMAR created an organizational structure for the exchange of information, knowledge and experts, training and scientific specialization, research, and the collection and divulgation of new findings, which allowed its participants to identify, evaluate, and eliminate or minimize the negative effects of the activities of the petroleum and natural gas industries in the Brazilian North and Northeast. PETRORISCO, one of the projects of the PETROMAR network, introduced the application of multitemporal ESI maps for areas under meso- and macrotide regime. This resulted in the production of ESI charts, with the collaboration of the PIATAM Mar project, for a number of sectors of the northern and northeastern coasts of Brazil.

In 2002, the Secretariat for Environmental Quality, Coastal and Marine Management of the Brazilian Environment Ministry (MMA) published its "Technical Specifications for the Elaboration of Environmental Sensitivity Charts for Oil Spills" with reference to the coastal and marine zones of the country (MMA, 2002). This publication was based on the manual of Araújo et al. (2002) and currently regulates the norms for the production and publication of ESI charts in Brazil. In 2004, it was published the ESI Atlas of Ceará and Potiguar maritime basin (MMA, 2004).

As of 2006, Petrobras had published 23 ESI charts, covering 19 coastal and two fluvial terminals, and its marine activities in Sergipe and Alagoas. This initiative was coordinated by CENPES and involved universities, research institutions and environmental organizations (Araújo et al., 2006). Some 150 researchers participated in the project, which covered the whole of the Brazilian coastline, from north to south, as well as two sectors of the Amazon basin. These publications are based on the NOAA methods, which according to the ARPEL manual, have been adopted in many different parts of the world. In 2007, MMA published the ESI Atlas of the Santos Maritime Basin (Gherardi & Cabral, 2007).

The PIATAM Mar project

Petrobras has long been working to comprehend the Amazonian environment as a whole. It has been investing in the development of technological tools and processes to support local monitoring and environmental management through the projects PIATAM (www.piatam.ufam.edu.br), Cognitus (www.cognitus.org), LABCOG (www.lamce.ufrj.br/grva/data/labcogsdk), PIATAM Mar (www.piatammar.ufpa.br), and PIATAM Oceano (www.igeo.uff.br/piatamoceano). This project focuses on the development of the infrastructure and it is led by the Federal University of Pará (UFPA), Federal University of Rio de Janeiro (UFRJ) and CENPES, and involves other nine Amazonian institutions. This initiative led to the consolidation of a network of researchers who are active in the Amazon coastal zone, developing important scientific studies in a number of different fields of expertise.

The implementation of Phase I of the PIATAM Mar project was characterized by the compilation of the environmental data and other information available on the Amazon coastal zone, which resulted in an integrated overview of current knowledge of this region. A total of 3014 references were obtained, all of which were catalogued in a bibliographic data base, which culminated in the publication of the book "Bibliography of the Amazon Coastal Zone: Brazil" (Souza Filho et al., 2005a). An additional result worth of comment was the development of a computational system for the management of the data base, built using the MYSQL language. This system permits a continuous feed of the social-environmental information in a rapid and secure fashion (Souza, 2005). This also allowed the generation of the conceptual bases necessary for the development of a geographic information system (SIGmar), which provides a data base for the production of ESI charts.

The PIATAM Mar project is based on an innovative scientific concept, in which remote sensing, GIS and cartography combine to form a three-way spatial reference (Fig. 1) for the physical (e.g. Physics, Chemistry, Geology), biological (e.g. Botany, Zoology), and social (Geography, Sociology and Anthropology) sciences (Jensen et al., 1998; Jensen, 2000). These different mapping procedures all use techniques or tools that represent practical applications of mathematical concepts. Remote sensing permits the extraction of information from digital images which contain data on the radiation reflected, emitted or backscattered by specific targets on the Earth's surface, using specially-developed algorithms (Fussel et al., 1986; Dahlberg & Jensen, 1986). This approach exists harmoniously alongside other techniques for the collection of orbital data, and other mapping science tools, such as GIS and cartography. The term GIS refers to computational systems used for the treatment of geographic data, which integrate alphanumeric data bases with the spatial representation of real world entities. In fact, GIS is a highly-specialized information system, which combines cartography and the digital processing of images for the spatial analysis of information (Burrough, 1986). As Fisher & Lindenberg (1989) have pointed out, these sub-disciplines of the mapping sciences not only provide a baseline for knowledge and intellectual activity, but also a spatial orientation tool for the analysis of physical, biological, and social data (Fig. 1).
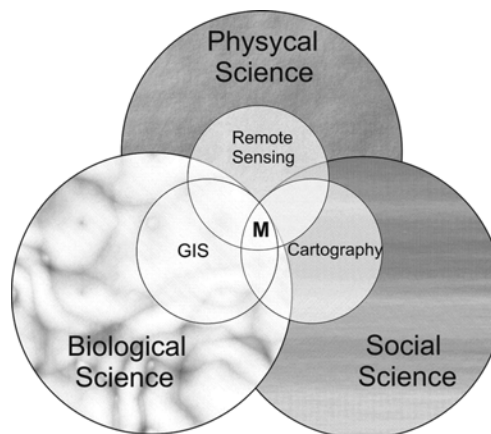
Figure 1 – Representation of the interaction among the remote sensing, GIS and cartographic approaches to mapping, and their relationships with the physical, biological and social sciences. M = Mathematics. Modified from Fisher & Lindenberg (1989) and Jensen (2000).

The general aim of PIATAM Mar is to generate ESI charts as an operational alternative for the monitoring and mapping of the Amazon coastal zone. These charts have been developed through a Geographic Information System, called SIGmar. The results of this initiative will provide guidelines for the use of the InfoPAE (Computerized Emergency Action Plan Support) System on the Amazon coast. For this, a number of specific aims must be fulfilled, as described below:

1. Develop and implement a geographic information system (SIGmar), linked to a social-environmental data base;

2. Produce ESI charts of the study areas at strategic (1:250,000), tactical (1:50,000), and operational (1:10,000) scales;

3. Conduct a spatial analysis of the available data and studies from the areas of oceanographic geology, chemistry and physics, social-environmental studies, biology (birds and vegetation), archeology, and tropical diseases (malaria);

4. Evaluate and test methodological protocols for the collection and systematic analysis of social-environmental data,

effective for the monitoring of the Amazon coastal zone;

5. Generate possible scenarios of oil dispersion for the northern coast of Brazil;

6. Store the social-environmental data collected during these excursions in the geographical data base of the PIATAM Mar project (SIGmar).

The Amazon coastal zone setting

The coastal zone of the Brazilian Amazon is located between Tubarão Point in the state of Maranhão (4°S, 43°W) and Cape Orange, in Amapá (5°N, 51°W), encompassing the entire coastline of the states of Amapá and Pará, and the western half of that of Maranhão (Fig. 2). Overall, this zone extends along some 2250 km, measured on a 1:2,500,000 scale map, not counting the many inlets, islands and small estuaries, which punctuate the coastline (Souza Filho et al., 2005b). This coastal plain, characterized by flat sandy estuaries and extensive mudflats, is limited to the east by the aeolian deposits of the Lençóis Maranhenses dune system (Floriani et al., 2004), and extends north and west through the Guyanas to the Orinoco delta in Venezuela (Gonthier et al., 2002).

As part of the Coastal Ecosystem biome (Arruda, 2001), this region is considered to be important for the conservation of the Brazilian coastline biodiversity, and is characterized by an acute lack of information and by the intensity of anthropogenic pressures from human occupation (Fundação BIO-RIO, 2002). In any discussion of the marine or coastal processes of the Amazon Coastal Zone (ACZ), it is necessary to place its principal hydrographic basins into their proper perspective. These include the Amazon, the Araguaia-Tocantins, and the smaller coastal rivers, which together drain an area of approximately 8,127,000 km^2, and carry sediments, nutrients and all kinds of organic material (dissolved, particulate and organisms) into the ACZ. This means that the ACZ is the final destination of millions of tons of sediments and nutrients each year, carried by millions of cubic meters of water draining from an area the size of Australia (Souza Filho et al., 2005a).

The ACZ is located in a meso- to macrotidal area, in which tide amplitudes vary from 2 to 8 meters. The region is also characterized by the largest continuous tract of mangrove forest found anywhere in the world. It is located in a low-lying area, characterized by a high density of drainage and active processes of erosion, sedimentation and neotectonics (Souza Filho, 2005). Where macrotides are present, the area of flooded mangrove – an environment extremely sensitive to oil spills – may extend for up to 30 km inland, and the estuaries themselves as much as 80 km (Souza Filho, 2005). All of these characteristics contribute to the unique nature of the ACZ, and emphasize the need for adequate research to guarantee its conservation both in the present and far into the future.

ESI charts as oil spill guidelines for the Amazon coastal zone

The combination of the hydrological cycle of the Amazonian rivers, with local tide cycles, results in at least 64 distinct environmental scenarios for the development of the ESI charts necessary for the implementation of effective contingency plans for the coastal zone. The temporal variation in these tidal and fluvial processes is illustrated in Figure 3.

The estimated long-term average freshwater discharge of the Amazon river is of the order of 134,000 m^3/s (68% of Brazilian drainage basin), while that of the Araguaia-Tocantins system is 11,000 m^3/s. A large part of this discharge – 71,527 m^3/s – originates in the countries neighboring Brazil (ANA, 2002). Its mean annual discharge of 6.3 trillion m^3 represents approximately 16% of all the freshwater deposited in the world's oceans (Oltman, 1968). Peak discharge, with a mean of approximately 220 thousand m^3/s (Fig. 3), normally occurs in May, whereas the minimum, of around 100 thousand m^3/s is usually in November (Richey et al., 1986; Nittrouer et al., 1995). Therefore, the ACZ is strongly influenced by Amazon river processes.

The different tidal scenarios, varying from meso- (amplitude of 2–4 m) to macrotidal (amplitude > 4 m) are represented by the 16 combinations described below, and illustrated in Figure 4:

01. Equinox – Spring tide – low tide: March-April and September-October;

02. Equinox – Spring tide – flood tide: March-April and September-October;

03. Equinox – Spring tide – high tide: March-April and September-October;

04. Equinox – Spring tide – ebb tide: March-April and September-October;

05. Equinox – Neap tide – low tide: March-April and September-October;

06. Equinox – Neap tide – flood tide: March-April and September-October;

07. Equinox – Neap tide – high tide: March-April and September-October;
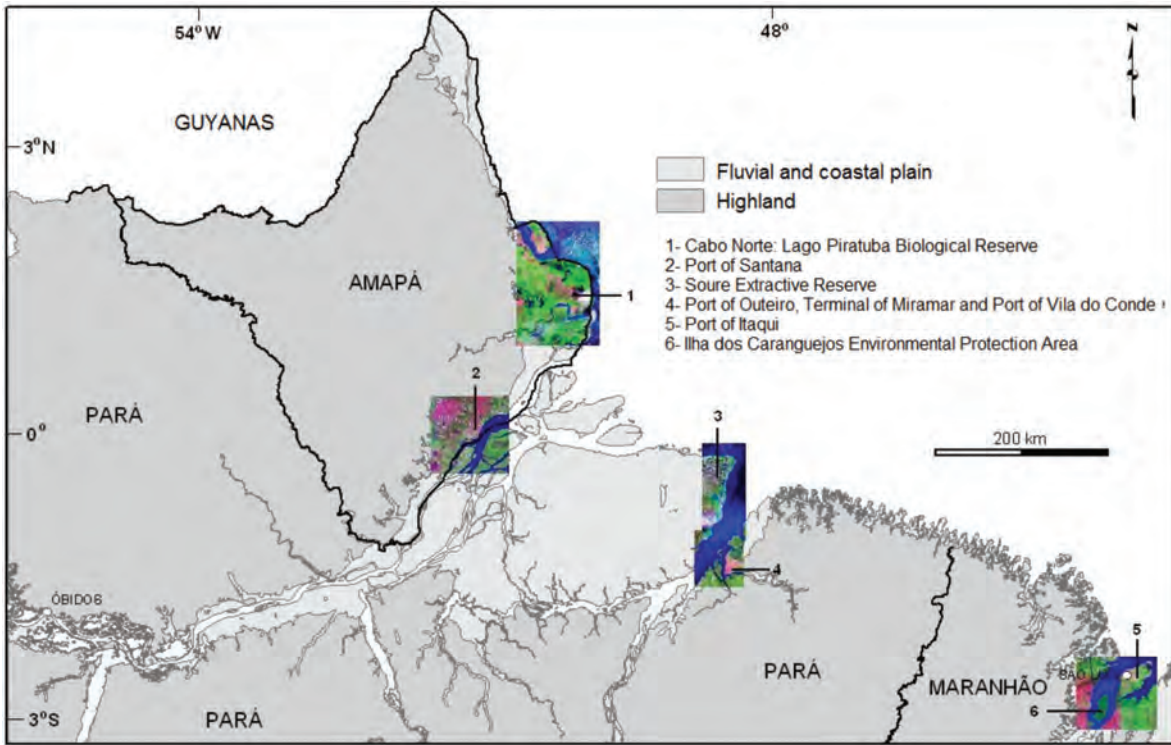
Figure 2 – Map of the study area, where will be produced ESI charts in 1:250,000 along the Amazon coast from Cabo Orange and Golfão Maranhense; ESI charts in 1:50,000 in the protected areas (Ilha dos Caranguejos – MA, Soure – PA, and Cabo Norte – AP); and ESI charts in 1:10,000 in the port and terminal areas (Itaqui, in Maranhão, Sotave-Miramar-Vila do Conde, in Pará, and Santana, in Amapá).
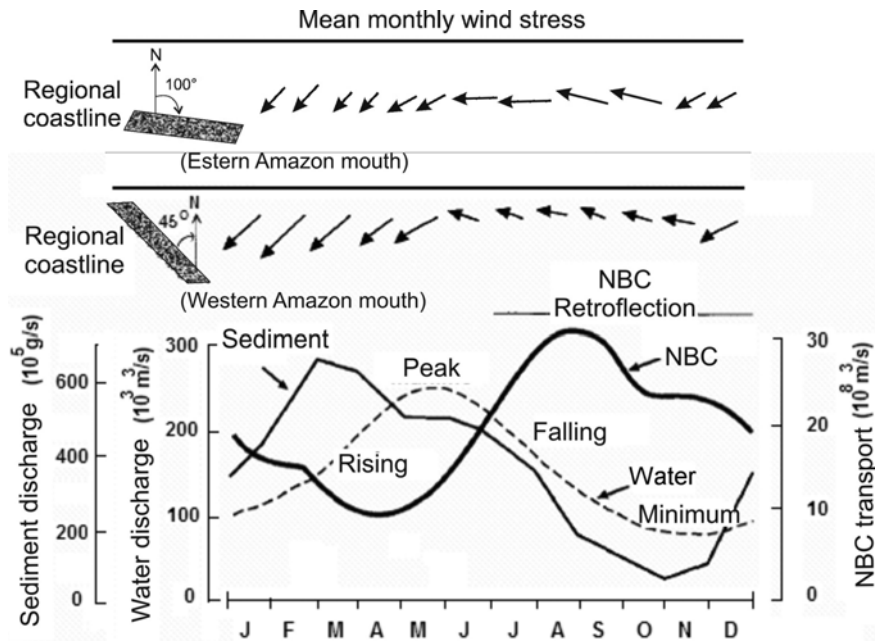
Figure 3 – Seasonal variation in the factors that affect sedimentation patterns on the Amazon coast (modified from Nittrouer et al., 1995). NBC = Northern Brazilian Current.

08. Equinox – Neap tide – ebb tide: March-April and September-October;

09. Solstice – Spring tide – low tide: June-July and December-January;

10. Solstice – Spring tide – flood tide: June-July and December-January;

11. Solstice – Spring tide – high tide: June-July and December-January;

12. Solstice – Spring tide – ebb tide: June-July and December-January;

13. Solstice – Neap tide – low tide: June-July and December-January;

14. Solstice – Neap tide – flood tide: June-July and December-January;

15. Solstice – Neap tide – high tide: June-July and December-January;

16. Solstice – Neap tide – ebb tide: June-July and December-January.

Note: Spring – new and full moon. Neap – half crescent.

The combination of these four fluvial scenarios with the 16 tidal phases results in a total of 64 simplified environmental scenarios for the Amazon coastal zone, all of which must be analyzed in the construction of the ESI charts. In addition to the fluvial discharge and tides, the local climate is affected primarily by the Inter-tropical Convergence Zone (ITCZ), the position of which fluctuates considerably between seasons. In August-September, the ITCZ is typically located at 14°N (Fig. 5), whereas by March-April, it migrates southward to 2°S, defining the dry and wet seasons, respectively. Secondarily, other factors control the precipitation in the region (REF). Furthermore, El-Niño and La-Niña cycles are responsible, in part, by changes in the precipitation in the Amazon region. Normally, almost 73% of the region's annual precipitation falls between January and April, whereas at the peak of the dry season, between September and November, rainfall can be almost negligible.

Human occupation of the Amazon coastal zone

Brazil presents considerable demographic disparities (Fig. 6), characterized by a major contrast between the Amazon region and the rest of the country. In addition, in both the Amazon and all other regions, coastal areas tend to be more densely populated than those further inland (Mello, 2002; Kampel, 2004; Jayme Jr. & Crocco, 2005).

Even in coastal regions, however, considerable gaps can be observed. On the Amazon coast, there is a close relationship between the distribution of the population, and the transport network, which is the principal conduit of human colonization in the region (Jayme Jr. & Crocco, 2005).

Overall, population density in Brazil tends to decline from east to west. This reflects the general pattern of colonization that begun on the coast, and progressed landward (Melo, 2002). Densities are very low – between 0.09 and 15 inhabitants per km^2 – throughout most of the Amazon basin, except for the major urban centers (Manaus, Belém and São Luís), where it rises to 11–35 inhabitants per km^2 (www.ibge.gov.br/censo).

The Amazon coastal zone is characterized mainly by municipalities with relatively small populations, most of which are between 10 and 25 thousand inhabitants (Fig. 7). In the coastal region of the state of Amapá, most municipalities have even smaller populations, of less than 10 thousand inhabitants. Only Belém and São Luís, capitals of the states of Pará and Maranhão, respectively, have populations of over one million inhabitants.

Operational risks of oil spills

The increasing operational safety applied to the exploration, production, and transportation of petroleum and its products by the petroleum companies over the past few years has led to a considerable reduction in the risk of accidents. Despite this, however, some disasters have still occurred, and the damage sustained persists as a serious threat to coastal areas.

It has been estimated that at least 4.5 million tons of oil is spilled each year worldwide. The principal causes are tanker cleaning operations and accidents occurring during the transportation of fuel (ESA, 1998). The Amazon estuary is obviously at considerable risk from the latter phenomenon.

The ports of the coastal states of the Amazon involved in the transportation and storage of petroleum and its derivatives represent the areas with the highest risk of such incidents, as the most likely locations of oil spills. These locations include the ports of Santana, in Amapá, and Itaqui, in Maranhão, as well as the Outeiro and Miramar terminals and the Vila do Conde port, all located in the state of Pará (Fig. 8). The protected areas adjacent to these ports (Fig. 2) are considered to be under their indirect influence. In the PIATAM Mar project, these conservation units are treated as control areas, given both their well-preserved conditions and their proximity to transportation routes (Fig. 9). These areas are the Lago Piratuba Biological Reserve in Amapá, the Soure Marine Sustainable Exploitation Reserve in Pará, and the Ilha dos Caranguejos Environmental Protection Area, in Maranhão (Fig. 2).
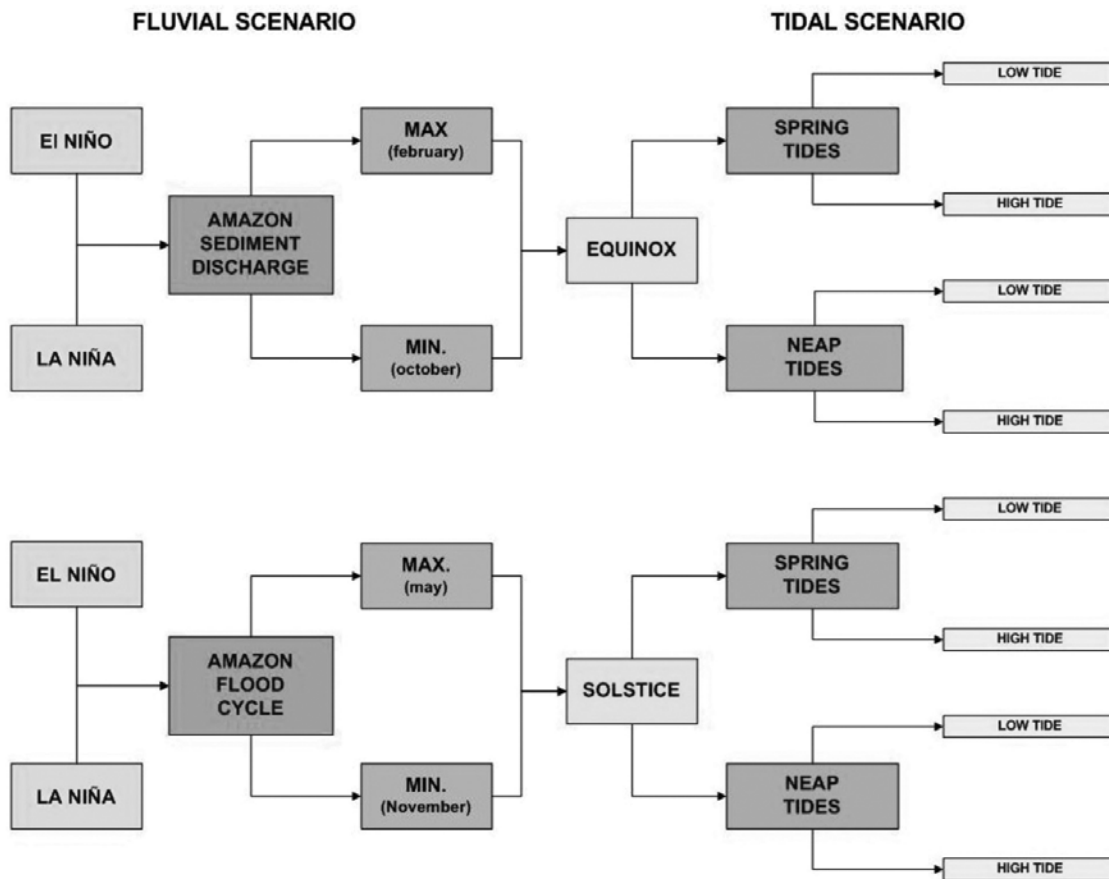
Figure 4 – Environmental scenarios for the development of oil spill contingency plans for the Amazon coastal zone (Almeida, 2008).
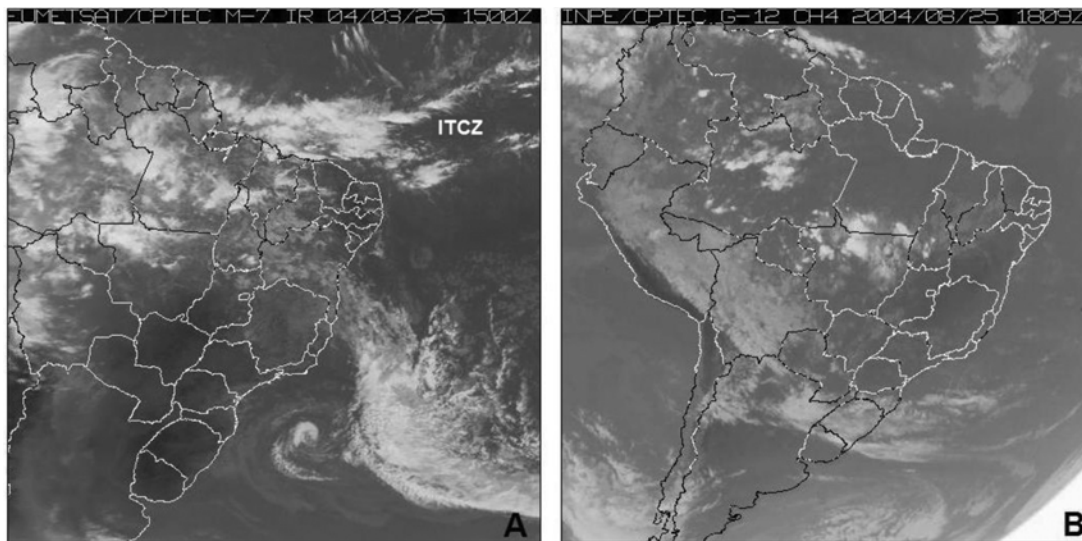

Figure 5 – GOES satellite image showing the position of the ITCZ over South America on (A) March 3rd, 2004, and (B) August 25th, 2004. Source: CPTEC/INPE.
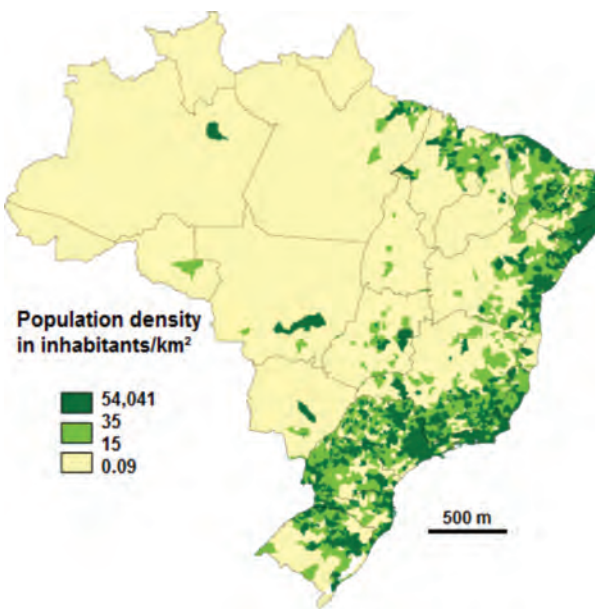
Figure 6 – Population density of Brazil (inhabitants per km^2). Source: www.ibge.gov.br/censo.
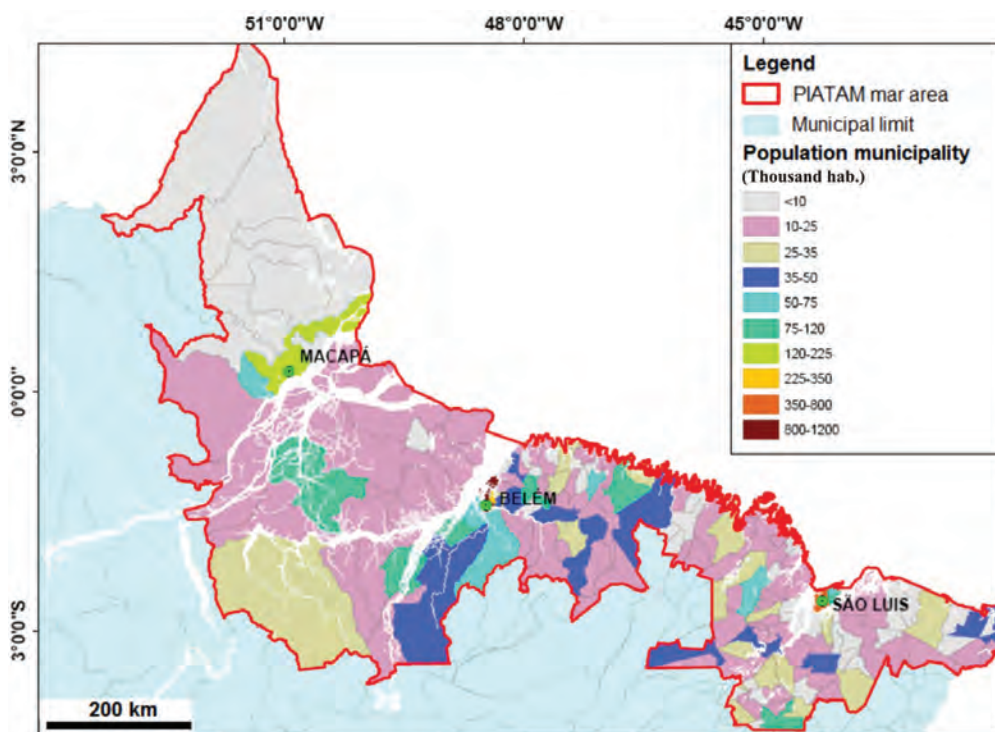

Figure 7 – Population density of the municipalities of the Amazon coastal zone. Source: www.ibge.gov.br/censo.

Production of ESI charts

Areas considered sensitive to oil spills are those with the greatest biological and social-environmental risks. In these areas, the adequate application of contingency measures results in a reduction in contamination, thereby mitigating impacts on the environment. In this scenario, ESI charts are essential for the most efficient application of the available response resources, making the clean-up operation more effective.
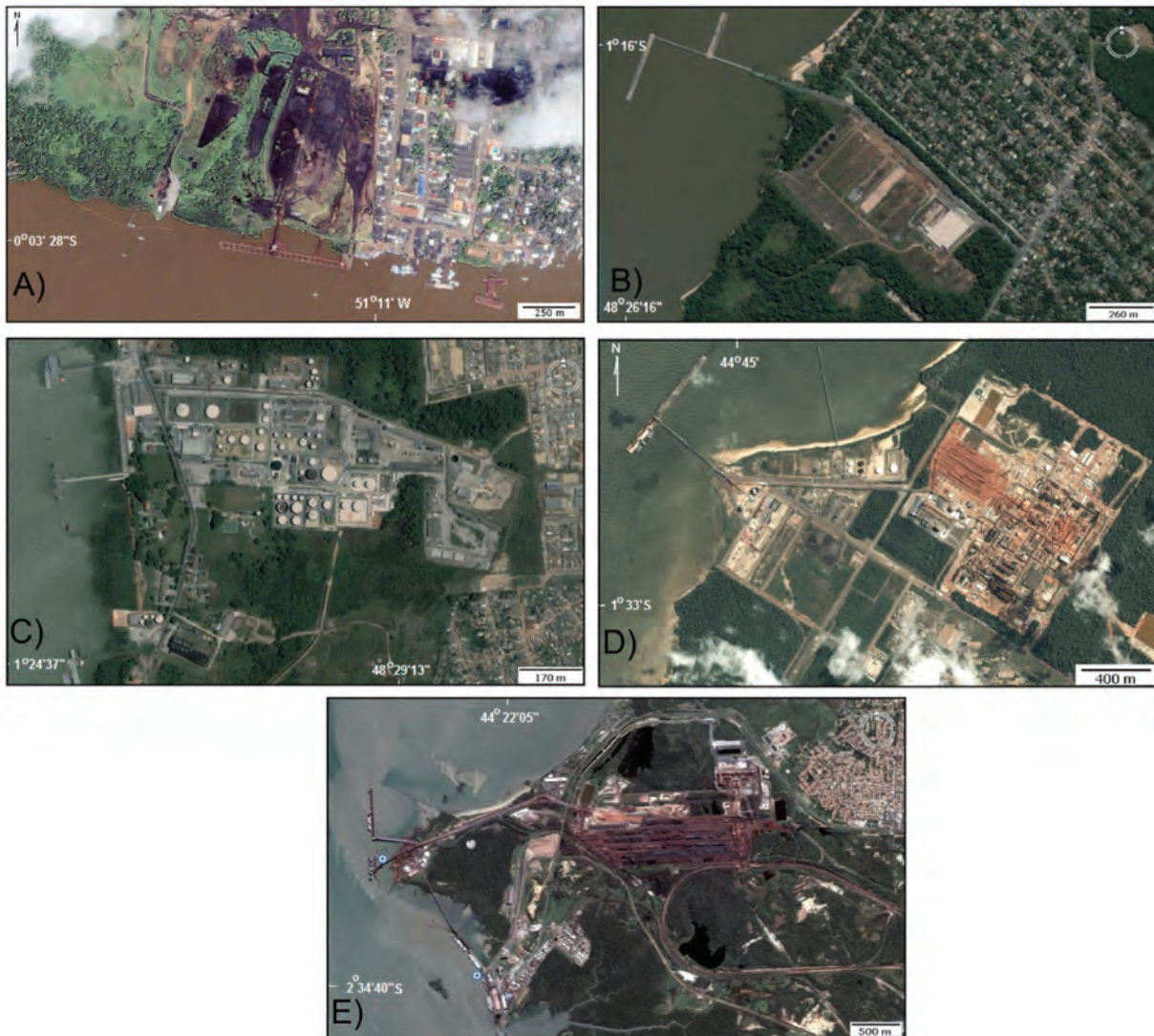
Figure 8 – Port areas surveyed during the PIATAM Mar project: (A) Port of Santana; (B) Outeiro Terminal; (C) Miramar Terminal; (D) Port of Vila do Conde; and (E) Port of Itaqui. For geographic location, see Figure 2. Based on Ikonos images acquired in 2007.

In the PIATAM Mar project, the ESI charts are produced according to NOAA (2002) procedures, with adaptations appropriate to the specific conditions of the Amazon coastal zone. The remote sensing products used in the creation of these documents are as follows:

- ESI charts in strategic scale (1:250,000) of the whole Amazon coastal zone based on the processing of RADAR-SAT-1 Wide 1 images and mosaics of JERS-1 SAR and SRTM images, with spatial resolution of 30 m, 90 m, and 90 m, respectively;

- ESI charts in tactical scale (1:50,000) of the protected areas based on the processing of RADARSAT-1 Wide 1, Landsat TM and ETM+, and CBERS-2 images, with spatial resolution of 30 m, 30 m, 15 m, and 20 m, respectively;

- ESI charts in tactical scale (1:10,000) of the port areas based on the processing of Ikonos images, with a spatial resolution of 1 m.

ESI charts will be produced in the SIGmar geographic information system (Costa et al., 2005) and will be used in association with a social-environmental data base (Souza, 2005; Costa et al., 2005; Castro et al., 2006). This system was modeled in three modules, as follows:
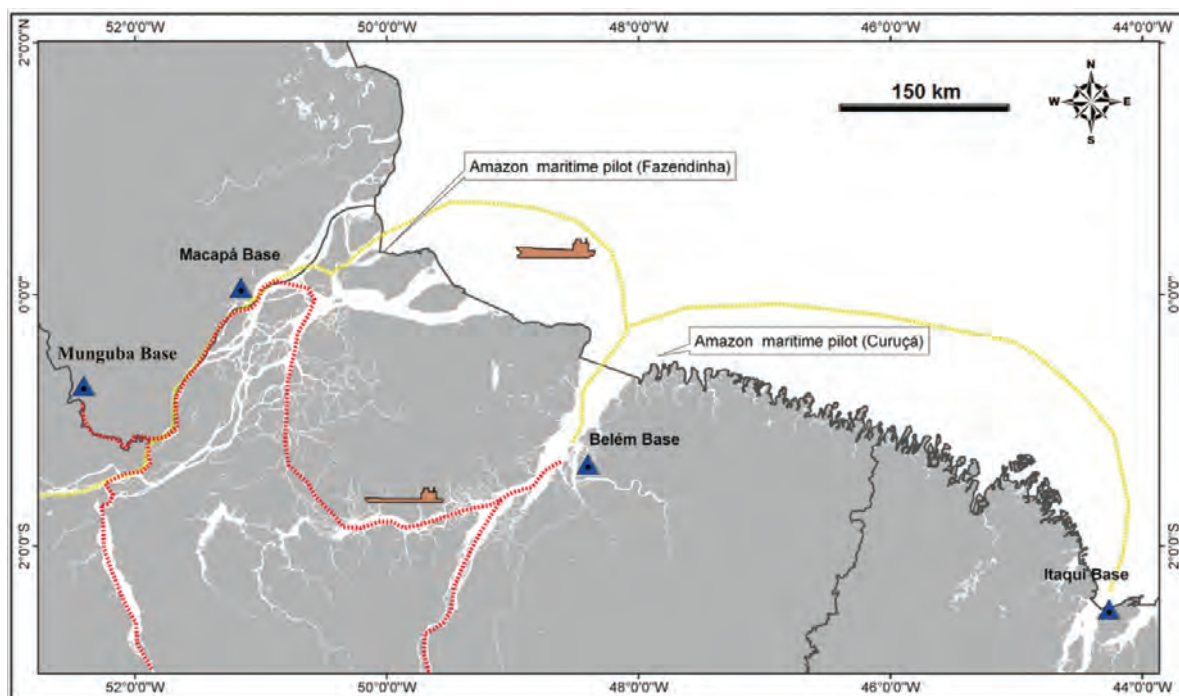
Figure 9 – Transportation routes for petroleum and its derivatives in the Amazon coastal zone. Transpetro supertankers in yellow; river tankers of the BR local distributor in red. Source: Petrobras.

- Monitoring Module: processing of Synthetic Aperture Radar (SAR) and optical images for the identification of possible oil spills, as well as the classification of the coastal environments, the construction of oceanographic models of the study areas to support the production of sensitivity maps, and the feeding of information into the data base via internet;

- Evaluation Module: identification of possible oil spills in the SAR images using PCI Geomatica 9.1 software tools to determine the exact geographic coordinates (latitude and longitude) of the possible spillage. A variety of thematic maps will be generated in ArcGIS 9.0 software to attend to the requirements of the system. These maps provide a more reliable assessment of risks and potential damage, on which the more efficient coordination of oil spill prevention operations can be based;

- Report Module: three classes of report are generated. Class A reports are very detailed, and are designed to provide the authorities responsible for clean-up operations with the information they need; the briefer class B reports are destined for the Media. By contrast, class C reports are provided to local organizations that may be affected by the oil spill.

ESI for the Amazon coastal zone

The ESI scale classifies coastal environments according to their relative sensitivity to oil spills, taking into consideration natural, physical and biological processes. This scale was developed on the basis of prior experience with actual oil spills, as well as fieldwork in each type of environment. The classification is thus based on a comprehensive understanding of the environment, including the relationships between physical processes and the substrate, which produce specific types of environment, and permit the prediction of the ways in which the spilt oil may behave and move (MMA, 2002).

In addition, the unique complexities of the Amazon basin, in terms of both the dynamics of environmental (sedimentary, geomorphological, oceanographic and biological) processes, and the importance and fragility of this rich ecosystem, demand the development of a specific approach, which takes the intricacy of local variations in account. From this perspective, Souza Filho et al. (2004) proposed an ESI classification for the Amazon coastal zone (Tab. 1) based on a modification of the proposals of NOAA (2002) and Araújo et al. (2002). Subsequently, Gonçalves (2005), Gonçalves et al. (2006), Teixeira (2006), Boulhosa (2006), Almeida (2008), Boulhosa & Souza Filho (2009) and Teixeira & Souza Filho (2009), followed this adaptation in order to map a

number of different sectors of the zone, and attribute indexes of environmental sensitivity to oil spill to each one.

Table 1 – ESI shoreline classification for the Amazon Coast (modified from Souza Filho et al., 2004).

ESI Ranking	Amazon Coastal Environments
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. Sheltered rocky shores (impermeable), Paleo-cliff.
8B	Sheltered, solid man-made structures.
8C	Sheltered riprap.
8D	Peat shorelines.
9A	Sheltered tidal flats mangrove scarp.
9B	Vegetated low banks and tidal flats.
9C	Hypersaline tidal flats or supratidal sandflats.
10A	Salt, and brackish- water marshes.
10B	Freshwater marshes with aquatic vegetation, flooded forest ("varzea") and intermitent lakes.
10C	Intertidal mangrove.
10D	Supratidal mangrove.

THE FUTURE

The principal objective of the PIATAM Mar project is the formation of a data base which organizes systematically all the social and environmental information available for the Amazon coastal zone. It is expected that these data can be mapped and cross-referenced in such a way as to generate new types of information for the production of ESI charts.

Social-environmental data will be collected during joint scientific expeditions, in which they will be integrated with the collection of abiotic (geology, chemistry, geomorphology and oceanography, physics), biological (birds, fish, benthic fauna, plankton), and tropical disease (malaria) data in order to achieve the best possible understanding of the environment as a whole. The mapping of these data will be essential, and to this end, the long-term availability and acquisition of remote sensing imagery will be fundamentally important.

Perspectives of the new remote sensor data

Up to 1991, the available orbital remote sensing data with global coverage were of the multi-spectral electro-optical type (which operates in the visible electromagnetic and the infrared spectra) such as, for example, the NOAA (AVHRR) low spatial resolution (1.1 km) sensors, and the moderate spatial resolution (10–30 km) Landsat series (MSS, TM and ETM+), SPOT (HRV and HRVIR) and CBERS (CCD) sensors, which provide images that are extremely affected by the presence of cloud cover, which is almost always present in the equatorial region. During the nineteen-nineties, new microwave sensors (Synthetic Aperture Radar – SAR), e.g. ERS 1 and 2, JERS-1, and RADARSAT-1, were launched. Given their long wavelengths (5.6, 23, and 5.6 cm, respectively), these systems allow images to be acquired under unfavorable climatic conditions. It is important to remember here that all these types of sensor provide low to moderate spatial resolution. Electro-optical images from high spatial resolution (4 m or less) sensors such as Ikonos, Quickbird, and SPOT 5 (HRG), were only available commercially from 1999 onwards. Multi-spectral sensors of low to medium spatial resolution, such as the MODIS sensors on the TERRA and AQUA satellites, nevertheless provide imaging on an almost daily basis, which is extremely useful for the monitoring of the dynamics of the Amazon coastline.

Low to medium spatial resolution sensors have been used for the production of strategic scale (1:250,000) ESI charts, while those at a tactical scale (1:50,000) have been derived from imagery of moderate resolution. High resolution images are only necessary for the production of ESI charts at the operational level (scale of 1:10,000).

Given the electro-optical characteristics of the high resolution sensors, operational ESI charts can only be produced during the driest part of the year, which is June to November in the Amazon coastal zone. During the rest of the year, cloud cover is extensive, due to the positioning of the inter-tropical convergence zone (ITCZ). This limitation can nevertheless be overcome by the use of airborne sensors, such as CENSIPAM's SAR-R99B, although, like all airborne equipment, the operational logistics of this system is complex, and it is not always possible to acquire data during the required period. The use of SAR technology in the reconnaissance and mapping of coastal environments expanded considerably following the launches of the ALOS satellite (www.eorc.jaxa.jp/ALOS/) in 2006, and RADARSAT-2 (www.radarsat2.info/) and Terra-SAR (www.lsespace.com/missions/terrasar.php) in 2007. This promising orbital panorama was further diversified by the an-
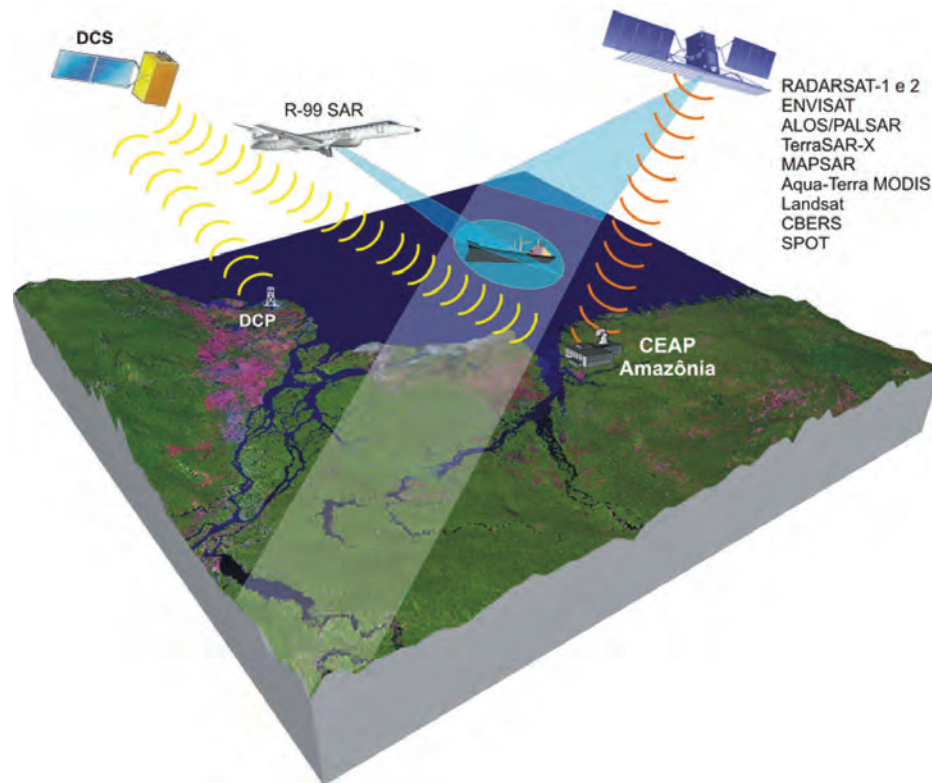
Figure 10 – Proposed observation system for the monitoring of the lower Amazon basin and the adjacent oceanic zone. DCP – Data Collection Platform, DCS – Orbital Data Collection System, R-99 SAR – airborne radar.

nouncement, in 2007, of the technical viability of the orbital Multi-Application Purpose Synthetic Aperture Radar (MAPSAR), to be constructed by a Brazilian-German consortium (Schröder et al., 2005).

Strategic partnerships between universities, research institutes and companies

The eventual integration of orbital imaging and field data will permit the implementation of an observation system for the monitoring of the lower Amazon basin and adjacent coastal zone, for which remote sensing can be considered to be the only source of data adequate for the systematic supply of information in multiple scales of time and space (Souza Filho et al., 2005b, 2006). The most effective path to the development of this system would appear to depend on the establishment of partnerships between universities, research institutions and companies, in alliance with the entities responsible for the social-environmental management of the region, as well as the productive sector, such as petroleum companies and port authorities.

In this context, Petrobras has fostered strategic institutional alliances with the following objectives:

(i)   systematic establishment of partnerships with universities, research institutions, governments, investors, economic agencies, social entities, communities and other groups of interest to the region's petroleum and natural gas sectors;

(ii) stimulation of scientific output and improvement of infrastructure in local universities and research institutions, as a basis for the training and fixing of human resources in the Amazon basin;

(iii) consolidation of strategic partnerships in the region, and

(iv) acquisition and analysis of social-environmental data essential for the development of studies of environmental impact in the Amazon Region.

These initiatives will encorage:

(i)   production of ESI maps for oil spills, with multi-temporal information;

(ii) expansion of the use of GIS technology in association with social-environmental data bases containing information from different seasons, and

(iii) mapping of environmental risk, vulnerability and sensitivity, and computer simulation of the potential social-environmental consequences of oil spills.

An illustrative scheme of the proposed observation system for Brazilian Amazonian is presented in Figure 10.

CONCLUDING REMARKS

The Amazon coastal zone presents a unique set of characteristics, including the estuary of the world's largest river system and its most ample tract of continuous mangrove forest, as well as a macrotidal system and annual rainfall in excess of 2500 mm. The combination of these factors results in a dramatically dynamic geomorphological scenario that encompasses a variety of temporal and spatial scales. Given this diversity, a single map of the vulnerability of local coastal environments to oil spill incidents would be inadequate. Clearly, it is necessary to update such maps on a regular – seasonal and yearly – basis, in accordance with the spatial dynamic of the region. The production of ESI charts for the Amazon coastal zone is thus a considerable challenge, which requires the systematic use of orbital remote sensing data, GIS data analysis, and field investigation of remote areas.

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