GENERATION OF OIL SENSITIVITY INDEX INFORMATION IN WESTERN AMAZONIA, BRAZIL, USING DUAL SEASON SAR IMAGE MOSAICS OF THE GLOBAL RAIN FOREST MAPPING PROJECT

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Abstract. This study focuses on improving information about oil spill environmental sensitivity in Western Amazonia, Brazil, by incorporating: (1) results of semivariogram textural classification (USTC) of dual season SAR image mosaics of the Global Rain Forest Mapping (GRFM) project in order to identify flooded forest and flooded vegetation; these cover types correspond to the most oil-sensitive habitat in the region; (2) manipulation of a pair of multiseasonal JERS-1 SAR mosaics using GIS technology to extract information about landscape modifications within half hydrological cycle. The sensitivity index information derived from JERS-1 SAR data is straightforward to interpret. Environmental risk assessment using this methodology is carried out along the Urucu-Coari pipeline, along the planned pipeline between Coari and Manaus and along the Solimões River transportation route. Results demonstrate that pipelines constitute an environmentally saver option for oil transportation in the region.

Keywords: SAR, textural classification, flooded vegetation, Amazonia.

1. Introduction

Habitat sensitivity to oil spills is a function of several factors, including (1) degree of exposure to natural removal processes, (2) biological productivity and ability to recover following oil exposure, (3) human use of the habitat, and (4) ease of oil removal (NOAA and API, 1994). These factors are used to rank the overall sensitivity of natural habitats to spilled oil as part of the Environmental Sensitivity Index (ESI). Following this approach, ten or more types of environments are identified, each having varying degrees of sensitivity to spilled oil and distinct recommendations for emergency response and clean up. The use of Environmental Sensitivity Index (ESI) is fundamental for oil spill contingency planning and for site definition in early stages of pipeline project design. Such environmental sensitivity information may seem too straightforward at first; this simplicity, however, enables rapid, effective decisions to be made in the event of an oil spill.

The global, continuous, frequent, weather-independent coverage provided by the Synthetic Aperture Radar (SAR) system onboard the JERS-1 satellite enable end users to monitor rapidly changing conditions in cloud-covered, rain forest regions. Potential applications for pipeline engineering and environmental protection in Amazonia include understanding and management of flood hazards.

The Japanese Earth Resources Satellite (JERS-1) was launched on February 11, 1992; the mission ended on October 11, 1998. Such a satellite included a SAR system with a 75-km wide strip of L-band, HH polarization image data to be acquired at a resolution of 18 meters (NASDA *et al.*, 2000). The recurrence cycle was 44 days; observations were made with a look angle of 35 degrees.

Schmullius and Evans (1997) pointed out that L-band and HH polarization are optimal SAR parameters for monitoring flooded forests. Therefore, JERS-1 SAR can be considered a prime tool for flood mapping in Amazonia. In addition, the orbital configuration also made JERS-1 particularly suiTable for continuous mapping of the hydrological cycle in the Amazon River basin, as data were acquired with adjacent passes on consecutive days. This acquisition manner yielded temporally homogeneous data over large areas. As a result, JERS-1 SAR images have been extensively used to mapping the spatial and temporal distribution of flooding in this rain forest region (Forsberg *et. al.* 2000).

The Global Rain Forest Mapping (GRFM) project is an international cooperation effort led by the National Space Development Agency of Japan (NASDA), with the aim of producing spatially and temporally contiguous JERS-1 SAR data sets over the tropical belt of the Earth. The GRFM data set is organized in semi-continental, 100 m resolution, image mosaics that are provided free of charge to the international science community for research and educational purposes.

All mosaics generated within the GRFM project are available in CD-ROM format (NASDA *et al.*, 2000). Due to the large sizes of the 100 m data files derived from full-resolution JERS-1 SAR images, it was considered necessary to divide them into smaller mosaics, or tiles, typically embracing a 5° by 5° region. This procedure has been carried out in order to ensure that users with relatively limited computer capacity can display and work with the data.

2. Research Objective

The objective of this paper is to extract sensitivity index information in regional scale directly from dual season GRFM SAR image mosaics using the Unsupervised Semivariogram Textural Classifier (USTC). Mapped oil-sensitive environments are subsequently inserted in a Geographic Information System (GIS) for environmental risk assessment along pipelines and along the Solimões River oil transportation route, Western Amazonia, Brazil.

3. Study Area

PETROBRAS transports 6 million cubic meters of natural gas per day from the Urucu River region to a terminal in the vicinities of Coari, a city located in the right margin of the Solimões River (**Figures 1 and 2**). The 280 km long Urucu-Coari pipeline is solely used nowadays to transport 60 thousands barrels of oil per day from the Urucu oil and gas province to the Solimões terminal (TESOL). This oil is then shipped to another terminal in Manaus (TEMAN).

At the city of Coari, water level changes between dry and wet seasons attained a difference of 14 meters (**Figure 3**). The strong seasonal character of the Amazonian climate gives rise to four distinct scenarios in the annual hydrological cycle: low water, high water, receding water, and rising water. These scenarios constitute the main reference for the definition of oil spill response planning by PETROBRAS in the region.

JERS-1 SAR data depicted in dual season GRFM SAR image mosaics are used in this study to monitor seasonal inundation phenomena, in order to highlight flooded areas sensitive to oil spills (**Figures 1 and 2**). These mosaics are of semi-continental scale, with a pixel size of 100 meters and acquisition dates corresponding to subsequent periods of dry and wet climate (NASDA et al., 2000). SAR image tiles covering the study area are as follows: 112 and 113 (low flood; October, 1995); 312 and 313 (high flood; May, 1996).

4. Environmental Sensitivity Index (ESI) In Western Amazonia

The basis for the definition of a sensitivity index to oil spills in Western Amazonia is the relationship between physical and biological characteristics of the fluvial environment. Based on field surveys and previous studies, Araújo *et al.* (2002) distinguished different habitats in this region, as shown in **Table 1**. These habitats were used to rank the overall sensitivity of fluvial areas in Western Amazonia to spilled oil as part of the Environmental Sensitivity Index (ESI). The most sensitive fluvial environment to oil spills was given an index of 10b; the least sensitive, an index value of 1 (**Table 1**). Visual inspection of the high flood GRFM mosaic (**Figure 2**) indicates a widespread occurrence of double bounce reflections off flooded forests. Such a backscatter mechanism occurs when the JERS-1 SAR beam reflects off both the tree trunks and the smooth reflective surface of the water. JERS-1 SAR images therefore demonstrate that the study area was extensively by covered flooded forests in May 1996, which is the most oil-sensitive habitat described in Table 1 (ESI Ranking = 10b).

Table 1. Oil Spill Environmental Sensitivity Index (ESI) for fluvial regions of Amazonia. Source: Araújo *et al.* (2002).

ESI RANKING	HABITATS
1	Manmade structures
2	Exposed rocky platform or outcrop
3	Rapid / waterfall
4	Scarp / cliff
5	Exposed sand / gravel beach or bank
6	Sheltered sand / gravel beach or bank
7	Exposed mud beach or bank
8	Sheltered mud beach or bank
9	Confluence of rivers and lakes
10a	Aquatic vegetation bank (macrophytes)
10b	Flooded vegetation (igapós, várzea, chavascal, campo)

5. Image Processing

Reliance on spatial structure for remote sensing data classification is useful when the textural characteristics of an image are more important than its spectral information content. In the case of a single-frequency/single polarization spaceborne radar system such as the JERS-1 SAR (L-band/HH polarization), it is appropriate to choose a classifier that considers a pixel value in the context of its nearest neighbors. One way to carry out this approach is to examine image texture using the semivariogram function.

The Unsupervised Semivariogram Textural Classifier USTC is a deterministic classifier, which provides the option of combining both textural and radiometric information (Miranda et al., 1997). Radiometric information is conveyed by the despeckled digital number

(DN_{dsp}) value. Textural information is described by the shape and value of the circular semivariogram function, which has the following form:

$$\gamma (x_0, h) = (1/2n) \sum^{2\pi}_{\theta=0} (DN(x_0+r) - \mu_H(x_0)), \text{ where:}$$

$\gamma (x_0,h)$ is the semivariogram function at pixel location x_0 and radial lag distance of h pixels; $DN(x_0+r)$ is the digital number value at radial lag distance r from x_0 (radius h, angle θ); $\mu_H(x_0)$ is the mean value of a circular neighborhood of radius H, center x_0; H is the maximum radial lag distance (in pixels) suiTable to describe the data; n is the number of pixel neighbors at radial lag distance h. Textural information is also described by the digital number variance in a circular neighborhood of radius H around the pixel x_0 ($\sigma^2_H(x_0)$). The DN variance is included in the classification procedure because it reflects the value of the semivariogram function for a very large lag distance (greater than H).

The ISODATA clustering algorithm is applied in order to carry out the unsupervised classification of this set of vectors. After the unsupervised classification, results obtained from the clustering program are merged together through interactive class aggregation (an aggregate is a grouping of one or more classes considered to be of thematic significance).

The Unsupervised Semivariogram Textural Classifier (USTC) was applied in this study to discriminate and map cover types associated to the following scattering mechanisms: (1) specular reflection (mostly open water, but also pasture, clear cuts and airstrips); (2) double bounce (mostly flooded forest, but also urban areas); (3) diffuse backscatter (upland forest); (4) predominantly forward scattering (flooded vegetation with low to intermediate values of biomass above water). Results for low and high flood GRFM SAR image mosaics are shown in **Figures 4 and 5**, respectively. Flooded forest and flooded vegetation correspond to the most oil-sensitive habitat described in **Table 1** (ESI Ranking = 10b) and are therefore submitted to further analysis in a GIS environment.

6. Manipulation of Environmental Sensitivity Index (ESI) Information Using a GIS

Probably the single most significant aspect of GIS is the ability to combine different spatial data together. The purpose of making such combinations is to identify and describe spatial associations present in the data, and to use models for analysis and prediction of spatial phenomena. In this study, we use a method of comparison and combination of USTC-classified images in pairs (low and high flood). When two USTC-classified mosaics are combined, the result is a newly derived image that can be visually inspected for spatial associations. Correlation of cover types representative of oil-sensitive habitats using a pair of multiseasonal JERS-1 SAR mosaics is certainly enlightening.

The method used in this study for combining image pairs is called matrix overlay. Each combination of cover types from the two input USTC-classified GRFM SAR mosaics is assigned an output class (**Figure 6**). The goal is to utilize knowledge about these change detection classes (from low to high flood) to extract information about landscape modifications within half hydrological cycle. The most remarkable landscape change is represented by class C15', which corresponds to upland forest in October 1995, to flooded forest in May 1996. It is important to point out that this class accounts for the 15,95% increase in area of the most oil-sensitive habitat in the ESI Ranking (10b).

The USTC-classified GRFM SAR mosaics are also combined to define a Seasonal Sensitivity Index Ranking (SSIR). First, we assign weights for each cover type mapped in **Figures 4 and 5**. Such weights qualitatively express how these remotely-sensed classes are impacted in the event of an oil spill. Furthermore, we calculate the sum of weights corresponding to the change detection classes defined in **Figure 6**. These values are subsequently grouped together to define five broad SSIR categories, as follows: very high (SSIR = 20), high (SSIR = 15), intermediate (SSIR = 10), low (SSIR = 5) and very low (SSIR = 0). These SSRI categories correspond to a new set of map classes.

Finally, we identified the spatial distribution of the SSIR map classes along pipelines and along the Solimões River oil transportation route, within a regional buffer 20 km wide. The buffer areas correspond to the Urucu-Coari pipeline, to the location of the planned pipeline between Coari and Manaus, and to the Solimões River transportation route between the Solimões (TESOL) and Manaus (TEMAN) terminals. In the Urucu-Coari pipeline, SSIR map classes associated with very high (SSIR = 20) to high (SSIR = 15) oil spill seasonal sensitivity comprises 10,9% of the 20-km buffer area (**Figure 7**). In the region embracing the planned pipeline between Coari and Manaus, SSIR map classes associated with very high (SSRI = 20) to high (SSIR = 15) oil spill seasonal sensitivity comprises 43,30% of the 20-km buffer area (**Figure 7**). This value is remarkably lower than the one observed along the Solimões River transportation route between TESOL and TEMAN (57.60%; see **Figure 7**). Such a result demonstrates that pipelines constitute an environmentally saver option for oil transportation between Coari and Manaus.

7. Conclusions

This study focuses on improving information about oil spill environmental sensitivity in Western Amazonia, Brazil, by incorporating: (1) results of USTC classification of dual season GRFM SAR image mosaics in order to identify flooded forest and flooded vegetation; these cover types correspond to the most oil-sensitive habitat in the region (ESI Ranking = 10b); (2) manipulation of a pair of multiseasonal JERS-1 SAR mosaics using GIS technology (matrix overlay method) to extract information about landscape modifications within half hydrological cycle. The sensitivity index information derived from JERS-1 SAR data is straightforward to interpret and constitutes a representation of the original ESI product conceived by PETROBRAS.

The most remarkable landscape change in the study area is represented by the conversion of upland forest in October 1995, to flooded forest in May 1996. This change detection class accounts for the 15,95% increase in area of the most oil-sensitive habitat in the ESI Ranking (10b).

Sensitivity information from the dual season USTC-classified GRFM SAR mosaics is obtained within a 300 m buffer embracing the Urucu-Coari pipeline project design area. Results demonstrate that this pipeline is mostly situated in areas where oil spill environmental sensitivity is not high throughout the hydrological cycle.

The USTC-classified GRFM SAR mosaics are also combined to define a Seasonal Sensitivity Index Ranking (SSIR). Environmental risk assessment using SSIR is carried out along the Urucu-Coari pipeline, along the planned pipeline between Coari and Manaus, and along the Solimões River transportation route between TESOL and TEMAN. Results are as follows: (1) the Urucu-Coari pipeline is mostly situated in areas where oil spill environmental sensitivity is not high throughout the hydrological cycle; (2) pipelines constitute an environmentally saver option for oil transportation between Coari and Manaus.

8. Acknowledgments

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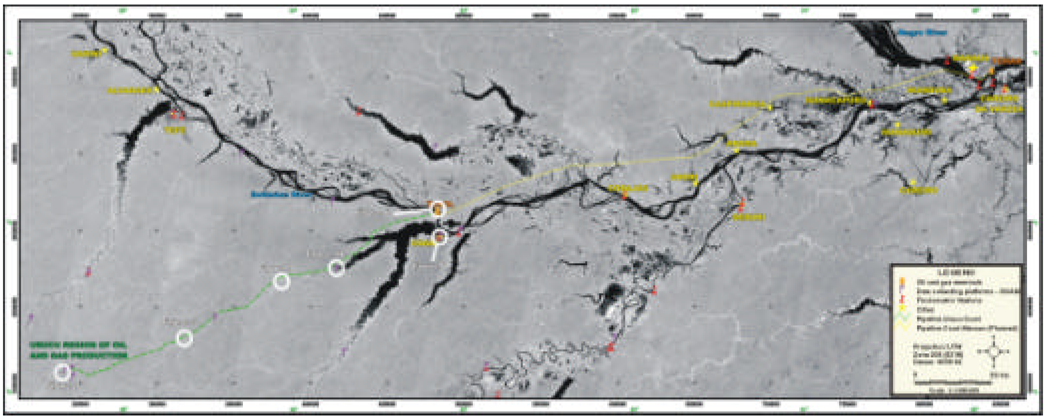

Figure 1. Low flood (October 1995) GRFM image mosaic (tiles 112 and 113).

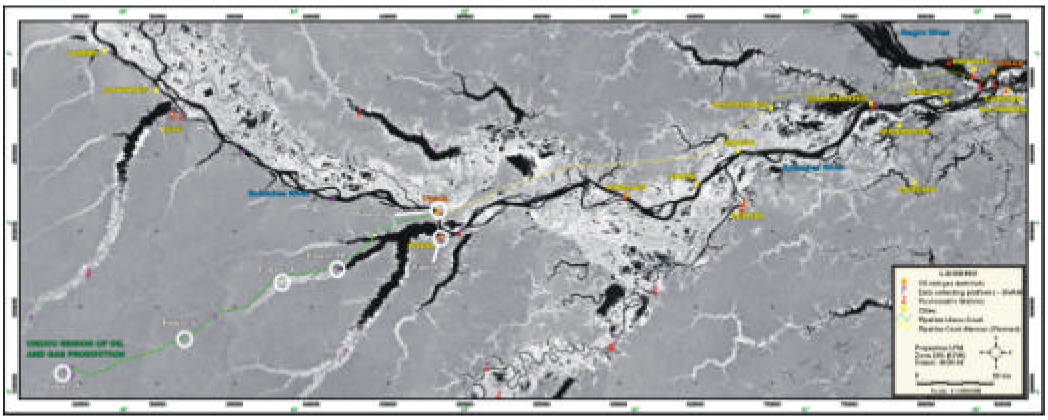

Figure 2. High flood (May 1996) GRFM image mosaic (tiles 312 and 313).

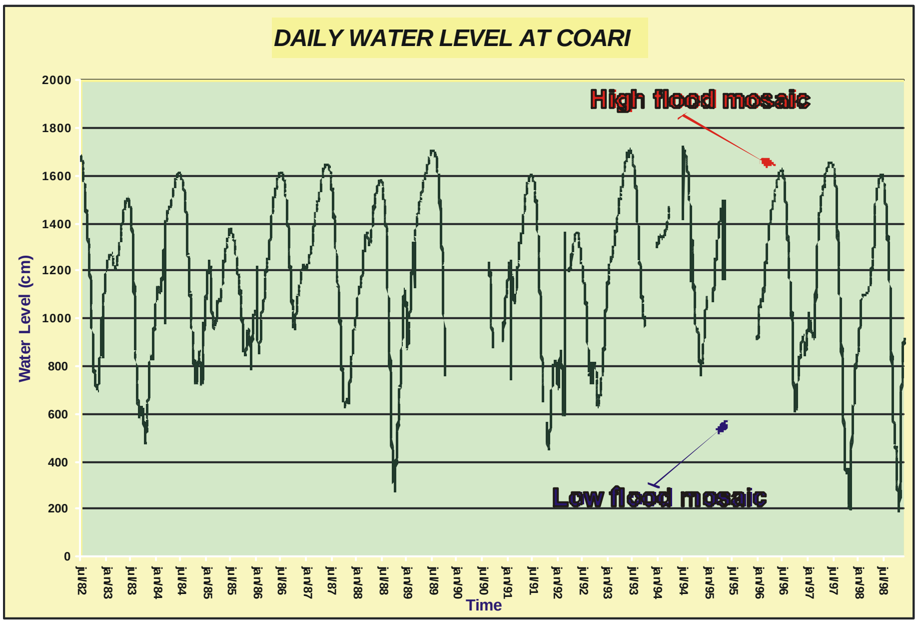

Figure 3. Daily stage height readings (cm) at Coari (July 1982 to December 1998). Source: National Agency of Electric Energy (ANEEL).

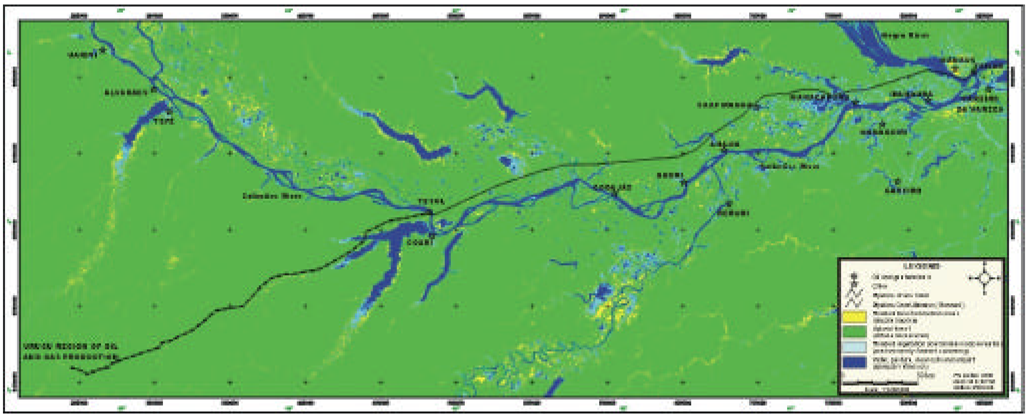

Figure 4. USTC-classified GRFM image mosaic (low flood).

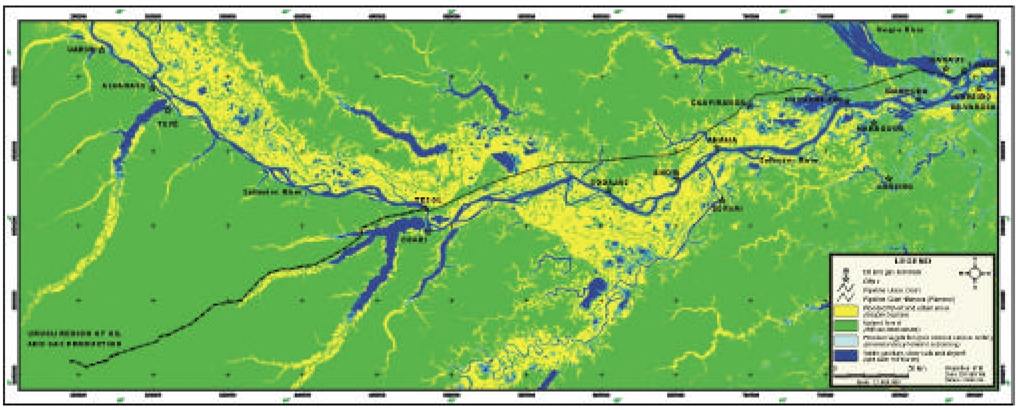

Figure 5. USTC-classified GRFM image mosaic (high flood).

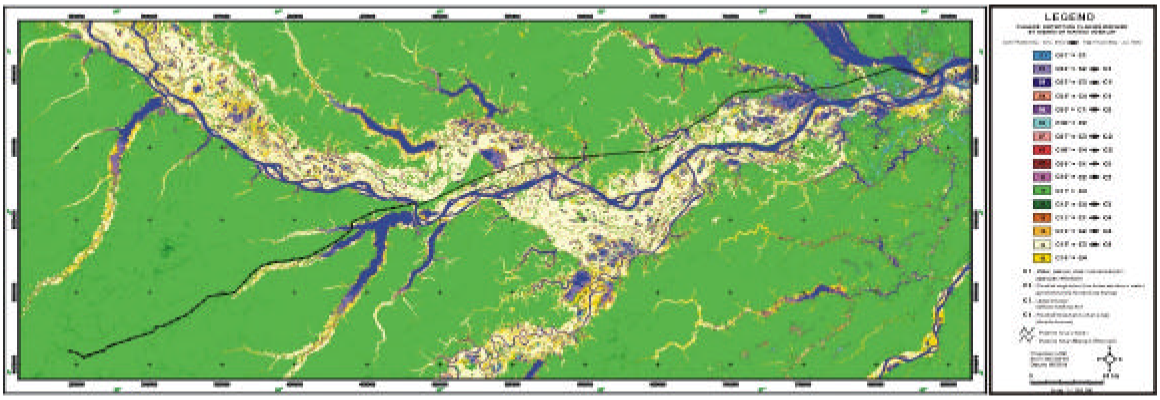

Figure 6. Map of change detection classes defined using matrix overlay (low to high flood).

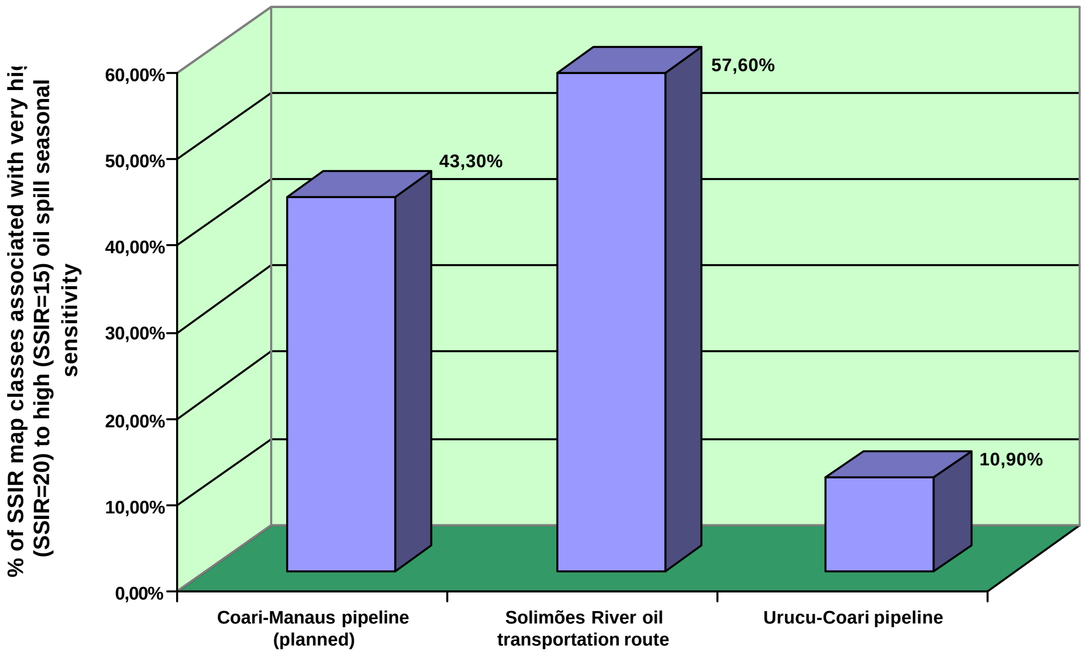

Figure 7. Assessment of oil spill seasonal sensitivity along pipelines and along the Solimões River oil transportation route (low to high flood).