Landscape changes in the Anavilhanas Archipelago during peaks of flood and drought in the Rio Negro, Central Amazônia, Brazil

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Abstract. The Anavilhanas constitutes the second largest group of freshwater islands in the world, comprising a complex pattern of islands, channels, lagoons, swamps, beaches and sandbanks, which dramatically changes during the seasonal periods of high and low waters of the Negro River ("Rio Negro"), affecting the rich biota of the archipelago, which is refuge of a diversified fauna and flora. The study estimates for the first time the extent of the changes in the landscape of the Anavlhanas during the second highest flood (2009) and the most severe drought events ever recorded in the Rio Negro (2010). Images from three different sensor systems were used in the study: Landsat-TM (high water), ALOS-PALSAR (high water), and Resourcesat-LISS-3 (low water). TM and LISS-3 scenes were converted into three endmember fraction images (vegetation, soil, and water), used to map four different land cover classes: deep water, vegetated island, sandbanks, and upland forest. Resulta showed that a water surface of approximately 2,000 km^2 mapped during the flooding was reduced by about 58% during the low-water, allowing the emergence of more than 700 km^2 of beaches, sandbanks, and shallow submerged sandbanks. In addition, the area of vegetated islands of the archipelago increased by 66%, accounting for more than 500 km^2. An unsupervised deterministic classifier algorithm that combines textural and radiometric information was applied on the ALOS-PALSAR radar scene to map flooded forests, which are not identified in TM and LISS-3 fraction images. Resulted showed that about 45% of the vegetated islands mapped in the TM fraction images constitute in fact flooded forests.

Palavras-chave: Arquipélago das Anavilhanas, imagens de satélites, classificação automática.

1. Introduction

The Anavilhanas Archipelago is on the Rio Negro, about 50 km from its confluence with the Solimões River, in the heart of the Amazonian rainforest. The second largest group of freshwater islands in the world, the Anavilhanas comprises an intricate pattern of islands, channels, lagoons, swamps, and partially submerged sandbanks, refuge for a diversified fauna and flora, protected by the Anavilhanas National Park.

From a geological point of view, the Anavilhanas Archipelago results from the neotectonic activity that prevails in the Central Amazônia, which derives from a compressional interplate stress regime caused by the Mid Atlantic Ridge spreading and the concurrent resistance from the Nazca and Caribbean plates (Mendiguren and Ritcher, 1978). This neotectonic activity was responsible for the local arrangement of fault blocks, which funnelled the river down into a passageway that constitutes the narrowest width of the lower Rio Negro (Almeida-Filho and Miranda, 2007). Partially blocked by this natural barrier, the river widens upstream, assuming the appearance of a lake (up to 20 km wide and 100 km long). Free space in a low energy environment has favoured the deposition of sediments (mainly clay and silt) to form the Anavilhanas Archipelago.

The landscape in the Anavilhanas Archipelago changes dramatically during the seasonal periods of high and low waters of the Rio Negro. Floods cause the total or partial drowning of many islands, which begin to emerge with the receding waters, forming beaches and sandbanks. The cycles of flood and drought constitute a dominant environmental factor affecting the rich biota of the region. They modify the landscape features and, consequently, the habitats in the area. Because it is a very remote region, remote sensing is the sole practical and effective way to map and estimate the extents of the landscape changes in the area. Thus, the aim of this study was to map and show the extents and the changes in the landscape features of the archipelago during pulses of rising and descending waters. To cope with this task, the study used satellite images acquired during the second highest flood ever recorded in the Rio Negro (2009), and the most severe drought ever recorded in the Amazônia (2010). The difference in the water levels between these two events was 16.14 m, which is roughly equivalent to the height of a five-story building.

2. The Rio Negro hydrological cycle

The hydrological cycle of the Rio Negro features a period of high-water between May and July, and a period of low-water between October and November. Figure 1 shows a historical time series of highest and lowest water levels for the Rio Negro, recorded in the port of Manaus (ANA, 2012). The data show that over a period of 110 years the average difference in elevation of the water levels between the periods of high and low waters was 10.23 m. However, during the recent flood of 2012 and the drought of 2010, the Rio Negro broke its own historical records for peaks and troughs. Between May 29^{tht} and June 1st the level of the river reached 29.97 m. This record was 20cm higher than the flood of July 2009, which was used in this study. Subsequently, on October 2010 the river reached its ever recorded low-water level of 13.63 m.

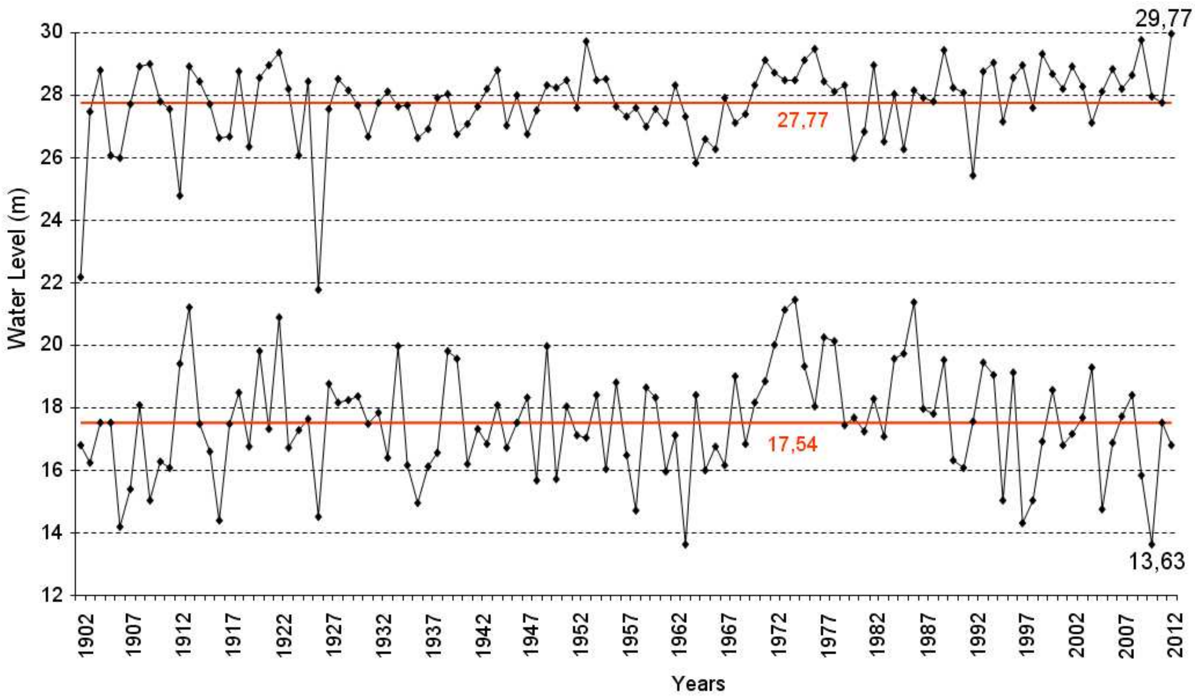

Figure 1. Historical time series of high and low water levels for the Rio Negro recorded in the port of Manaus from 1902 to 2012. The flood of July 2009 (29.77 m) was the second highest so far recorded in the Rio Negro, which was supplanted only by the flood recorded in May 2012 (29.97 m). The drought in October 2010 (13.63 m) is considered the most severe ever registered in Amazônia. Red lines indicate means of high and low waters (data source: ANA, 2012).

3. Satellite images and processing

Images from three different sensor systems were used: Thematic Mapper (TM), Linear Imaging Self-Scanning Sensor-3 (LISS-3), and Phased Array L-band Synthetic Aperture Radar (PALSAR). The Landsat-TM images were acquired on July 24th, 2009, when the water level was 0.48 m below the peak reached during the flood of the Rio Negro (29.77 m). The PALSAR scene was also acquired during the high water period, on June 22nd, 2009. On that day, the water level was only 0.12m below the peak recorded during the flood. The LISS-3 images were acquired on October 17th, 2010, when the water level was 0.91 m above the minimum recorded level (13.63 m).

Before processing, LISS–3 and PALSAR images were resampled to 30 m using nearest-neighbor interpolation to fit to the same spatial resolution of the Landsat-TM. Then, all the scenes were converted to the Universal Transverse Mercator (UTM) coordinate system, with scene-to-scene registration yielding accuracies of 1.6 pixels. TM and LISS-3 were converted into three endmember fraction images (Adams et al., 1995): green vegetation, soil, and water. Represented by different proportions of vegetation, soil, and free-water within each pixel, the fraction images showed that the selected endmembers described the full range of natural variability of the ground features. This was attested by the very low values for the residual bands (the difference between measured and modelled spectral values in each band), and by fraction values that were neither less than 0 nor greater than 1.

Based on the analysis of false colour composites of the fraction images with soil (R), vegetation (G), and water (B), four classes of land cover were elected to be mapped: deep water, vegetated island, sandbanks, and upland forest. This was done using a classification approach discussed in Almeida-Filho and Shimabukuro (2002) that combines segmentation, non-supervised per-region classification, and editing techniques applied over endmember fraction images. The editing technique is performed in order to minimize the omission and commission errors in the digital classification. It is done by overlaying the thematic classification over a RGB colour composite of the original TM or LISS-3 images based on visual interpretation procedures. Therefore the proposed method produces classification maps with accuracy similar to those obtained by visual interpretation.

During the high water period for the Amazonian rivers, vast areas of dense forest are flooded, but these areas are not detected by optical systems like TM and LISS–3. However, radar images, especially those in the L-band frequency with increased capability to penetrate the vegetation canopy, allow the detection of these flooded forest areas. Four dominant land cover classes were visually identified in the ScanSAR image over the Anavilhanas Archipelago: deep water, vegetated islands, upland forest, and flooded forests. Areas of deep water appears dark, due to the specular reflection of the incident radar beam on the smooth surface of the river; upland forest appears in intermediate grey shades, due to the radar backscatter by the forest canopy; and flooded forest appears in bright grey shades, due to the double-bounce reflections between smooth water surfaces underneath the forest canopy and tree trunks (Hess et al., 1990).

The first step in the processing of the radar image was the application of an algorithm for antenna pattern correction, followed by a Frost filter (Frost *et al*., 1982) with a 3 x 3 window size to reduce the radar speckle. In addition, the scene was converted from amplitude data format to normalised radar cross section (σ^0), according to the equation (1) below (Rosenqvist *et al*., 2007):

$$\sigma^0 = 10 * \log_{10}(DN)^2 + CF, (1)$$

where CF = – 83.0 dB and DN is the Digital Number (Gray level)

To map and estimate the extent of these four land cover classes, an unsupervised deterministic classifier algorithm that combines both textural and radiometric information (Miranda *et al.*, 2004) was applied over the processed PALSAR image.

4. Results and discussions

Segmentation and region-classification of the fraction images allowed estimating for the first time the extent and the variation of the landscape features during high and low water periods in the Anavilhanas Archipelago. Figure 2 is a false-colour composite with soil (Red - R), vegetation (Green - G), and water (Blue - B) fraction images derived from the Landsat-TM scene and its corresponding land cover map. This map shows an area of deep water of about 1,718 km^2, and a complex array of narrow, elongated islands with dense vegetation, which together cover approximately 380 km^2.

Figure 3 shows the ALOS-PALSAR scene and its corresponding land cover map. Although the level of the Rio Negro was 0.36 m higher than on the date of the Landsat-TM acquisition, the area of open water in the radar image was about 3.5% lower than that mapped in the TM fraction images. One possible reason for this small difference is the poorer spatial resolution of the radar image in defining terrain features as precisely as TM images do. About 54% (207 km^2) of the areas mapped as vegetated islands in the Landsat-TM fraction images were flooded forest in the radar scene, which covered about 415 km^2. However, the final extent of the area of flooded forest was certainly higher, considering that after the acquisition of the radar image the water level rose by over 0.12 m to the peak of the flood (such an increase is significant considering the flat topography of the area). Together, the flooded area (deep water plus flooded forest) covered more than 2,000 km^2, and certainly it was even larger during the peak of the flood on July 1st and 2nd. Finally, compared to the low water period, the flooded area was reduced by about 58%.

The extent of deep water substantially decreased in the scene acquired during the period of receding waters, and covers a surface of only approximately 53% of that during the flood period (849 km^2). The receding waters resulted in an increase of about 35% (from 380 km^2 to 515 km^2) in the areas of vegetated islands, compared to the period of high water. The drought also enabled the emergence of about 492 km^2 of beaches and sandbanks and about 242 km^2 of shallow submerged sandbanks. Despite occurring throughout the entire archipelago, shallow submerged sandbanks predominate in the central and downstream portions of the archipelago. However, part of them probably became exposed sandbanks or beaches, because the water level dropped 0.91 m in the week following the acquisition of the LISS-3 image, when it reached the minimum on October 24th. Figure 4 is a false-colour composite combining soil (R), vegetation (G), and water (B) fraction images derived from the LISS-3 image, and its corresponding land cover map.

Table 1 summarizes the extent of the land cover classes in the area of the Anavilhanas Archipelago, as observed in the satellite images acquired during the flood of 2009 (TM and PALSAR) and the drought of 2010 (LISS-3).

Table 1. Extent (km^2) of the land cover types during flooding and drought periods in the Rio Negro region.

		Deep-water	Vegetated islands	Sand-banks	Flooded forest	Upland Forest
TM	Flooding period	1,718	380	0	0	5,234
PALSAR		1,534	173	0	415	5,210
LISS-3	Drought period	849	515	734	0	5,234

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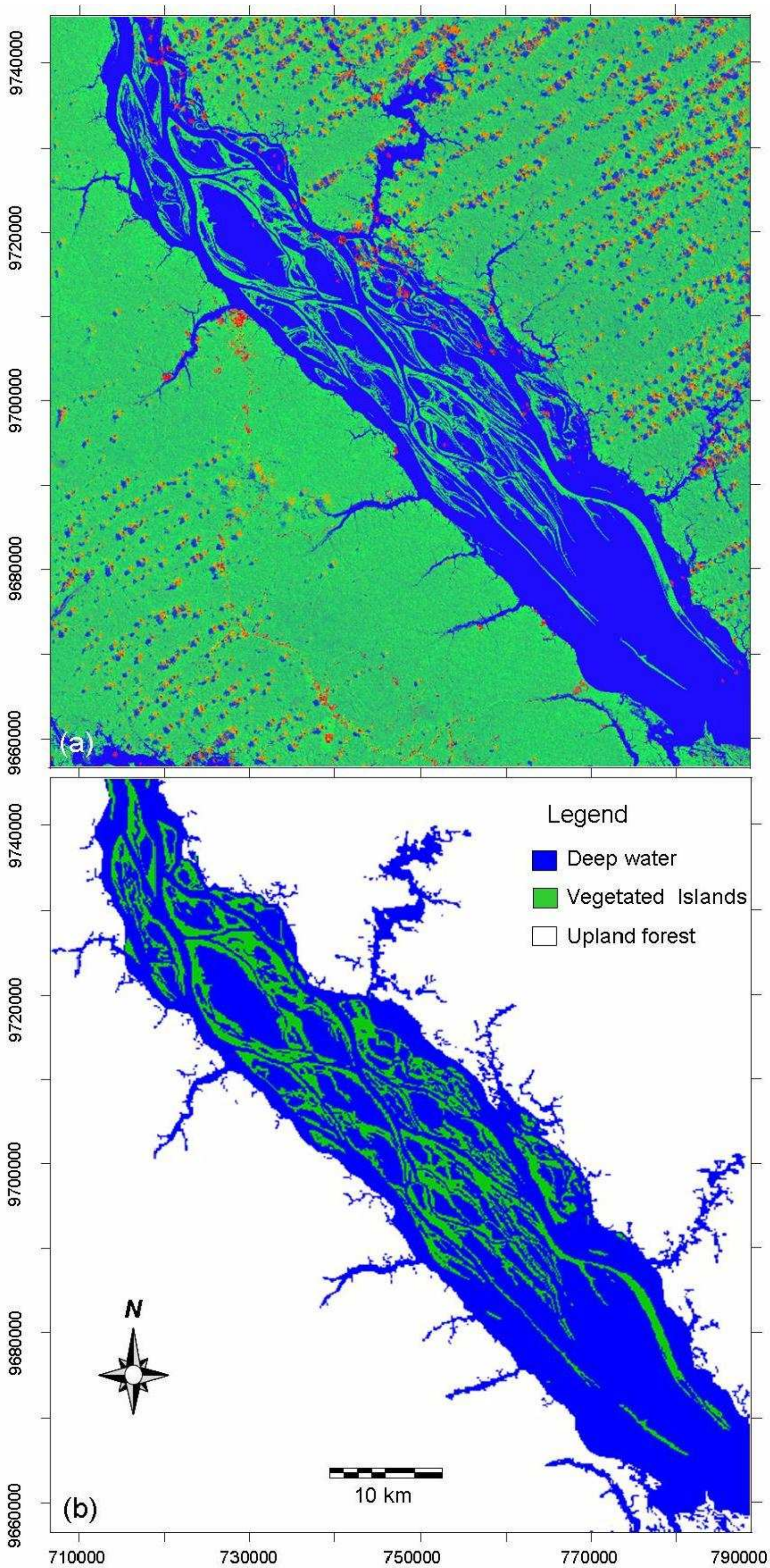

Figure 2. False-colour composite with soil (R), vegetation (G), and water (B) fraction images derived from the Landsat-TM scene (a) acquired during the 2009 flood period, and corresponding land cover map (b) of the Anavilhanas Archipelago. Coordinates are UTM/SAD 69, Zone 20. Some pixels labeled as soil (R) in Figure 2a are in fact associated with clouds, which were not considered in the final classification.

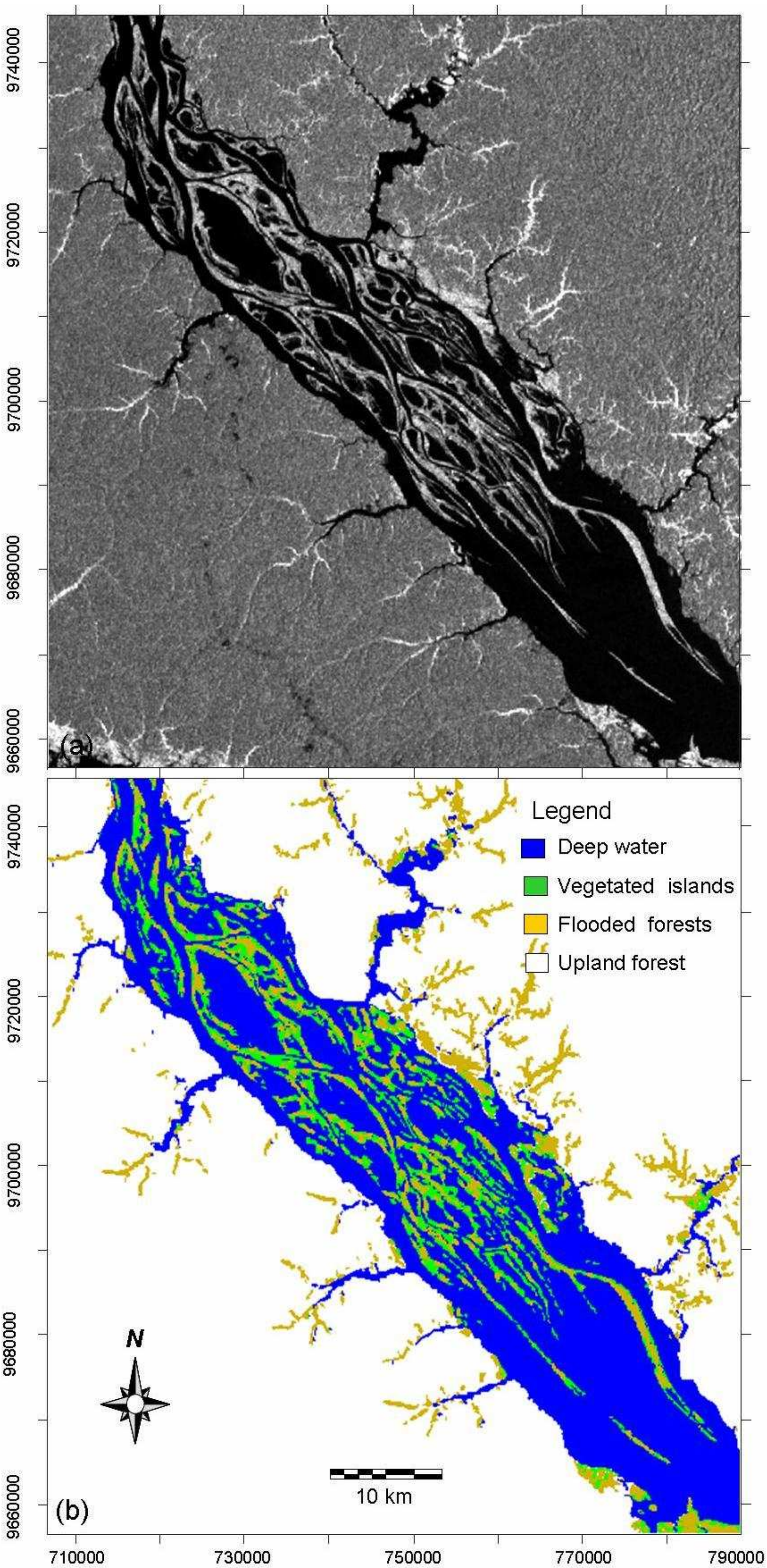

Figure 3. ALOS-PALSAR scene (a) acquired during the 2009 flood and corresponding land cover map (b) of the Anavilhanas Archipelago. Coordinates are UTM/SAD 69, Zone 20.

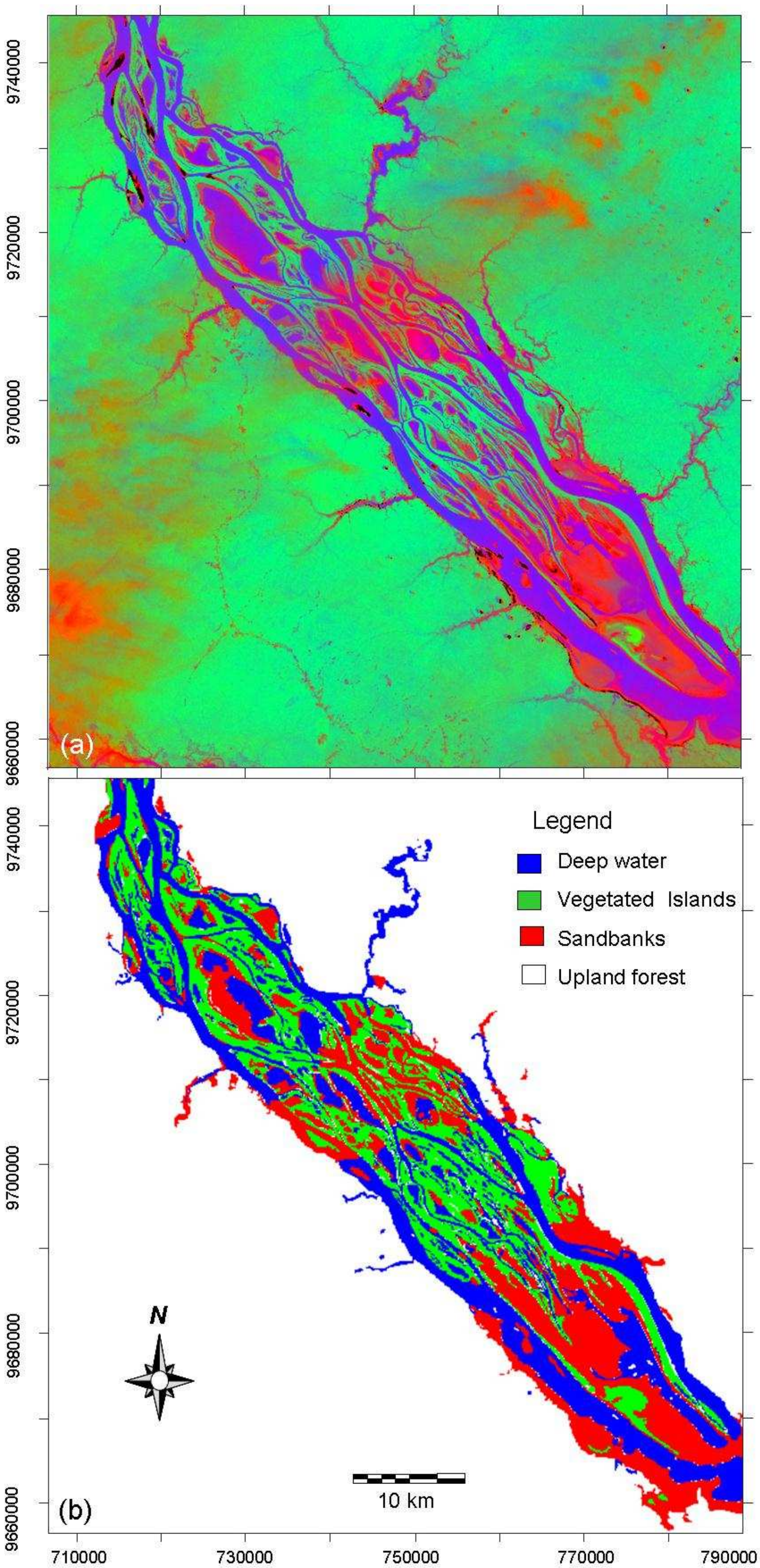

Figure 4. False-colour composite with soil (R), vegetation (G), and water (B) fraction images derived from the Resourcesat-LISS-3 scene (a) acquired during the 2010 drought, and corresponding land cover map (b) of the Anavilhanas Archipelago. Coordinates are UTM/SAD 69, Zone 20). Some pixels labeled as soil (R) in Figure 4a are in fact associated with clouds, which were not considered in the final classification

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5. Conclusion

Remote sensing images acquired by different satellites during the flood of 2009 and the maximum drought ever registered for the Rio Negro in 2010, allowed mapping for the first time the seasonal variation in the extent of the landscape features of the Anavilhanas Archipelago. Results showed that a surface of 1,718 km^2 entirely flooded during the high-water period is converted into 869 km^2 of vegetated islands, beaches, and shallow submerged sandbanks in the low-water period. These data can be an important source of information in the effort to better understanding aspects associated with the pulses of rising and receding waters, which are dominant environmental factors affecting the biota in the region.

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