

Multitemporal TM image analysis to assess the spatial and temporal dispersion of floating macrophytes in Brazilian hydroelectric reservoirs

Ivan Bergier Tavares de Lima¹

Evlyn Márcia Leão de Moraes Novo¹

Leonardo Bins¹

INPE - Instituto Nacional de Pesquisas Espaciais
Caixa Postal 515. 12227-010. São José dos Campos, SP, Brasil

Abstract. The focus on macrophyte community has increased due to their implications either on the electricity generation or on greenhouse gas production and emission. A TM/Landsat5 time series was used to assess the spatial-temporal variability of the area covered by floating macrophytes in Tucuruí dam, Pará State. The map produced by Boolean operation among classified historical images suggests that tributaries have suitable conditions for the retention of macrophyte stands. This fact may be assigned to the constant nutrient availability, to the lower hydrodynamic processes, and to the dead tree trunk effect producing a windless environment and a substrate to macrophytes in the tributaries.

Keywords: hydroelectric reservoirs, macrophyte, multitemporal analysis, methane.

Introduction

The conversion of riverine systems into reservoirs brings about the conditions for macrophyte infestation, such as the flooding of large terrestrial or forested areas, and the increasing of nutrient availability. Along the years, however, a nutrient concentration depletion in the water column tends to reduce the area of macrophytes within reservoirs (Junk e Mello, 1990). The major problems related to macrophytes are the formation of habitats suitable for nurturing vectors of endemic diseases, the disruption of navigation, the obstruction of the water flow into the turbines (Muller, 1995), and the production of greenhouse gases methane and carbon dioxide (Galy-Lacaux et al., 1997; Tavares de Lima et al., 1998).

The lack of information about the distribution and extent of floating macrophytes can be reduced using remote sensing techniques (Valeriano, 1984; Abdon and Meyer, 1990; Jensen et al., 1995; Lehmann and Lachavanne, 1997). Nonetheless, remote sensing mapping of submerged macrophytes has mostly been assessed for marine environments (Ackleson and Klemas, 1987; Ferguson and Korfmacher, 1997; Lehmann and Lachavanne, 1997). Recent studies (Malthus and George, 1997) showed that 4 meter deep submerged macrophytes could not be mapped with airborne images, even in clear waters. Spectroradiometric data, however, displayed differences between water spectra taken with and without submerged macrophytes.

Both the identification of submerged macrophytes and the assessment of the floating macrophyte dispersion through remote sensing images are difficult tasks. As an example, the lack of digital data in the rainy season inhibited studies of variation in the macrophyte stands seasonally.

Nowadays, the processing of synthetic aperture radar (SAR) images, which can be acquired under cloudy conditions, has provided satisfactory results, though image processing are quite difficult when compared to visible and infra-red images (Novo et al., unpublished data). Despite the limitation of remote sensing techniques, meaningful information about the macrophyte spread can be obtained through satellite images, associated to fieldwork. The main goal of this study is to apply remote sensing to detect spatial changes, and the distribution of floating macrophyte stands along time.

Methodology

Study area description

The Tucuruí reservoir is one of the most important man-made lakes in North Brazilian. Inaugurated in November 1984 in Pará state, it is a result of damming the Tocantins River, providing a total area of 2800 km² and having an installed power of 4000 MW (Figure 1).

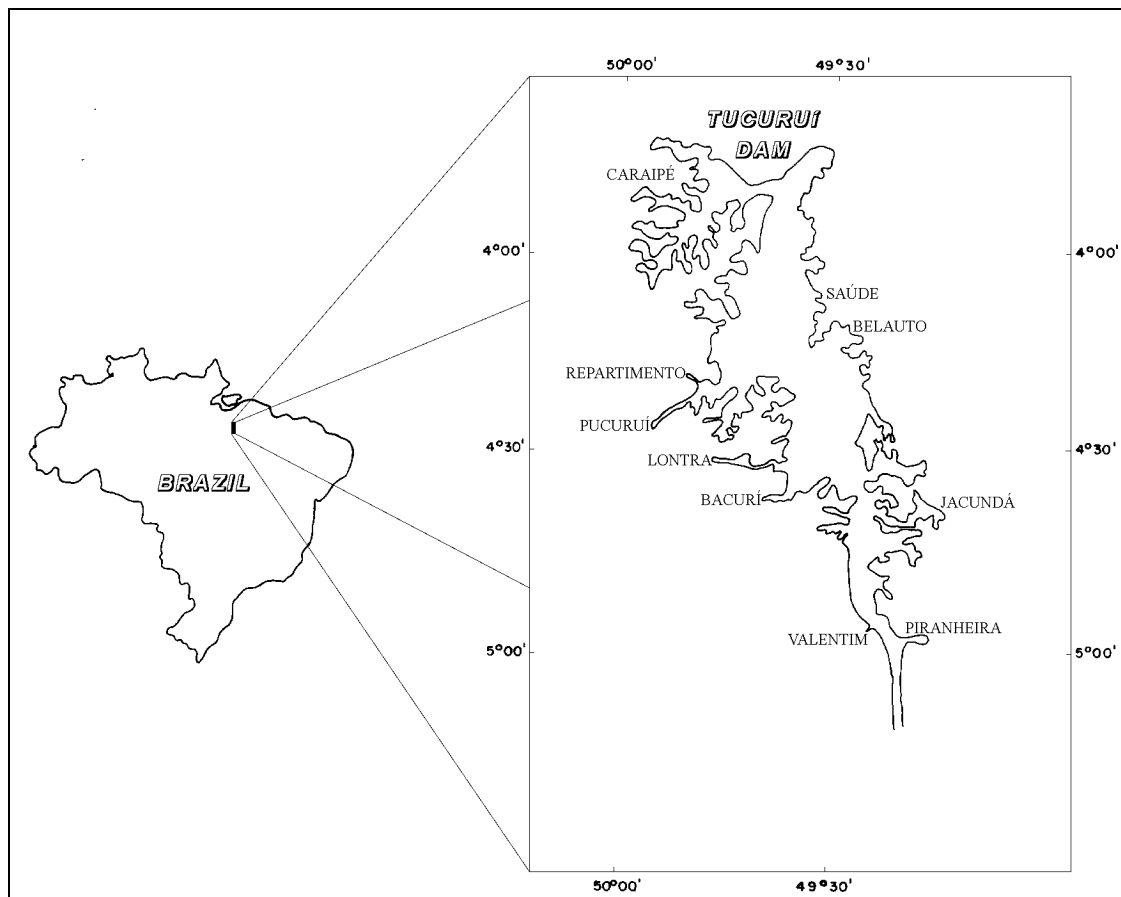


Figure 1. Location of the Tucuruí reservoir.

The main channel can reach up to 70 m in depth, whereas the average depth in the tributaries is around 10 m. Except for 400 km² in the Caraiapé tributary, the Terra Firme Forest was totally flooded, which corresponds to $1,90\text{--}2,34 \times 10^4$ tC.km⁻² in the reservoir (Revilla, 1984).

Due to the high respiration rates in tropical aquatic ecosystems (Richey et al., 1988), most of the labile portion of the inundated vegetation was quickly decomposed. As a result, part of the Carbon was released to the atmosphere mainly in methane and carbon dioxide compounds — two of the most important greenhouse gases (Rosa and Schaeffer, 1996; Galy-Lacaux et al., 1997). The refractory portion is still being decomposed in small rates, therefore, dead trunks are a constant scenario in the entire reservoir, and it might be necessary much time to mineralize it all.

Digital data processing

The water level regulates seasonally the area occupied by macrophyte stands. When the level rises the extent of macrophyte community increases as well. Inversely, when it depresses, considerable portion of individual plants starts a senescent process (Junk, 1980; Junk e Mello, 1990). TM/Landsat images in tropical rainforest are available mostly from June to August (dry season). Along this period, the reservoir is kept in its normal operation level, around 72 m, exactly when macrophyte stands are at their higher development. Therefore, in order to assess the spatial distribution of macrophytes in Tucuruí along the years, five TM images were selected: June/86, August/88, July/90, June/92, and July/94. Figure 2 provides an overview of the data set preprocessing and processing.

Bitmaps (masks) have been used in classification systems to detect temporal changes in the macrophyte community in hydroreservoirs (Valeriano, 1984) and wetlands (Jensen et al., 1993). This approach reduces the confusion between pixels outside and within the mask. Classified images can thus be processed together to produce a change detection map. The accuracy of this method is dependent upon i) the quality of the geometric registration of each date in the dataset, and ii) the accurate classification of each image. Both limitations are strongly influenced by the spatial resolution of the system employed in spatial-temporal analysis (Jensen et al., 1993).

For TM/Landsat5, the pixel positioning on the ground is often shifted between dates, resulting in different representations of land-macrophyte, land-water, and macrophyte-water boundaries. TM spatial resolution also limits the detection of macrophyte beds smaller than 30 x 30 m. Difficulties concerning the geometric rectification and the classification accuracy are therefore expected. Thus, it might be difficult to measure the precise area covered by macrophytes for each date. Despite these limitations, TM information can be useful to study the relative variation of the area covered by floating macrophytes among dates, and allows the determination of the macrophyte stand ages. Moreover, TM images provide a synoptic view of the reservoir, and contribute to prepare ground sample missions.

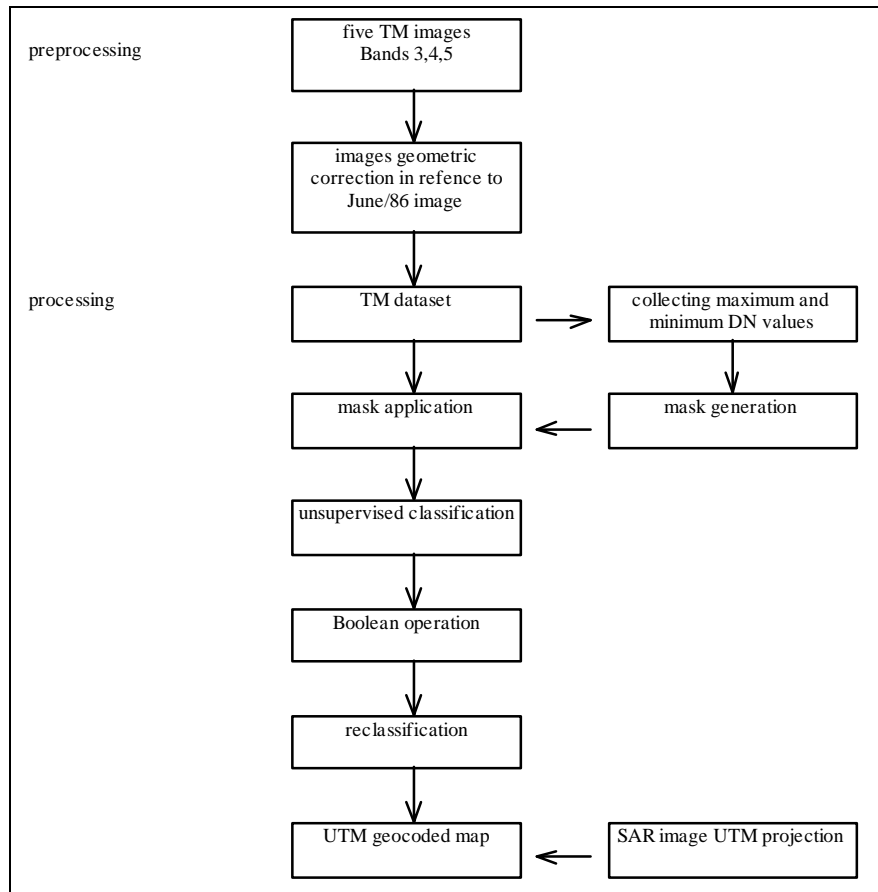


Figure 2. TM images preprocessing and processing.

Species or genus variability was not taken into account in this study. If it were, radiometric rectification among dates should have been applied to the dataset (Hall et al., 1991; Jensen et al, 1995) in order to provide normalized digital numbers (DN) for distinct targets. Hence, the main goal of this work is to assess the spread variability of the whole floating macrophyte community. For this purpose, the five historical images were geometrically corrected using as reference June/86 image (Figure 2). Each band of the June/86 image was statistically inspected to find out which one would be the best for generating the mask. Significant differences in DN were found in band 4, where open water and macrophyte stands showed lower DN values than the surrounding area of the reservoir. It was determined by pixel site sampling that DN ranging from 0 to 50 were mainly within the reservoir. This range was then sliced to DN=1 and the remaining DN to 0 values. After this process, some pixels of the mask containing DN=1 on the surrounding area were removed by creating nulls bitmaps over them, which were multiplied to the image. The resulting mask using this approach is shown in Figure 3.

The mask was applied to the entire TM dataset to select only the reservoir for digital classification. Probably due to water column variation among dates, mismatch geometric corrections, or shifting TM pixels, land boundaries in portions of the reservoir banks were not excluded. To solve this problem a median 3x3 filter was applied to the five images. Unsupervised classification with k means algorithm (PCI, 1993) was then performed for each image. The classification results are

presented in Figure 4. The next procedure was to determine the temporal changes in the macrophyte stands. An algorithm was developed to simulate Boolean operations among the classified images (Figure 5).

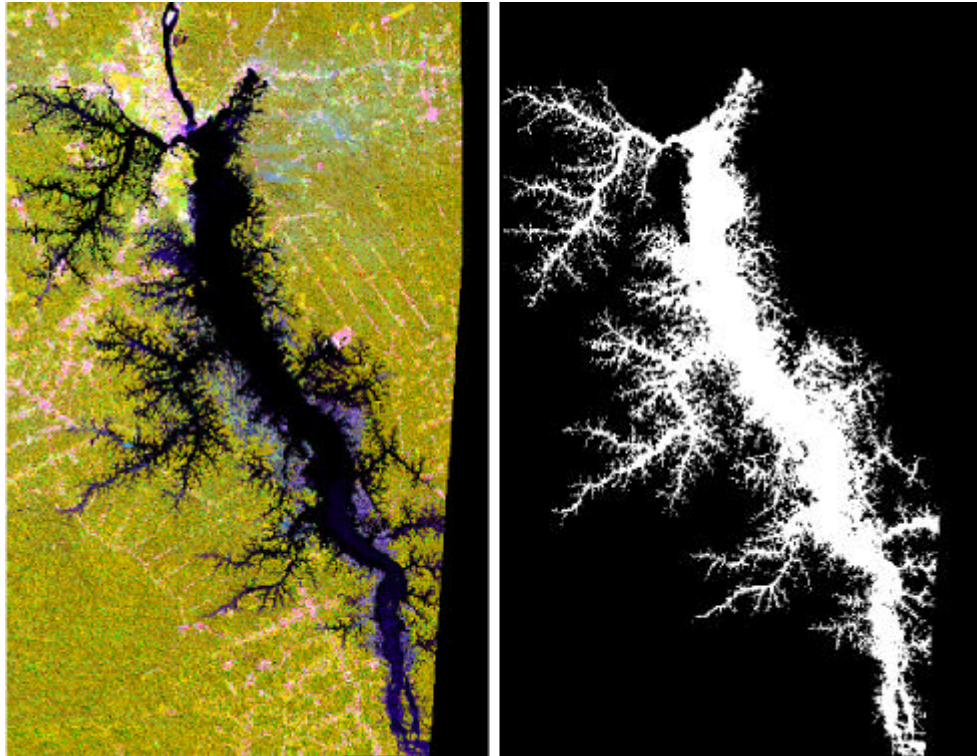


Figure 3. June/86 image bands 3,4,5 and the generated mask.

Each classified image was first binarized into 8-bit radiometric resolution for non-macrophyte (0) and macrophyte (1) areas. The algorithm takes all the five binarized images from June/86 to July/94 and generates a new image, where, in the vectorial space, the first bit of a pixel is related to the June/86 image, the second bit to the August/88, and so on. Thus, the resulting image presents all the possible combinations for presence or absence of macrophytes in the five images, i.e., 32 ND.

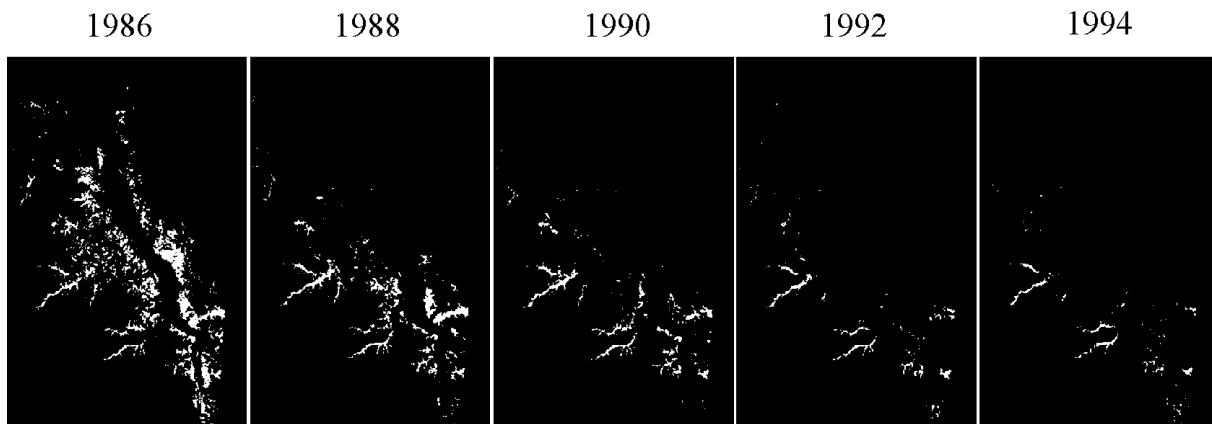


Figure 4. Macrophyte community in Tucuquí in each classified historical image.

To improve the multitemporal analysis and to determine the macrophyte stand ages, a reclassification procedure was carried out, transforming 32 DN into 4 DN, which allowed to distinguish areas i) never covered, ii) covered only in 1986, iii) temporarily covered, and iv) always covered by floating macrophytes (Figure 5).

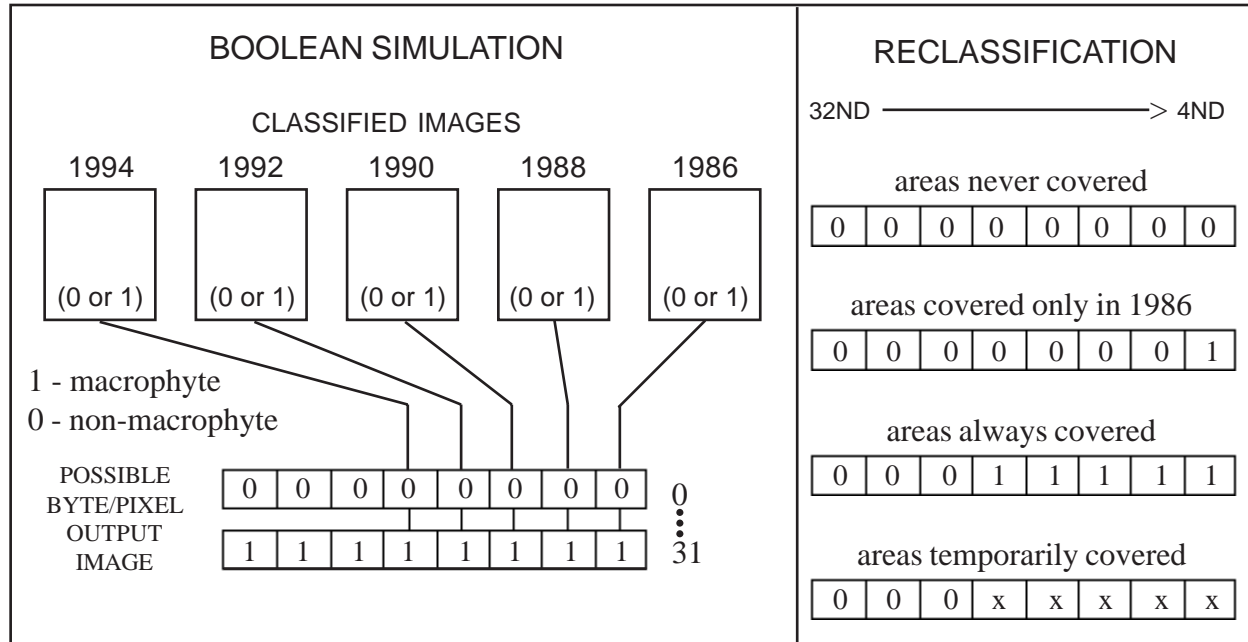


Figure 5. Conceptual framework of the Boolean simulation and reclassification procedure.

There are advantages and disadvantages in this bit altering procedure. The Boolean operation, which should be done sequentially every two images, is readily applied, gathering all five images and reducing the time processing for large datasets. On the other hand, it is applied only when two classes (binary system) are being considered. The change detection map geocodification to Universal Transverse Mercator projection (UTM) was realized using a previous UTM geocoded SAR RADARSAT image, the best cartographic base available of the study area. June/86 image was used to acquire control points for the map geometric rectification and geocodification.

Results and discussion

The map produced here is similar to that produced by Abdon and Meyer (1990) for the period between 1986 to 1989. Figure 6 presents the map used to assess the macrophyte community distribution in Tucuruí reservoir from 1986 through 1994. In 1986, the majority of the reservoir banks were covered by macrophytes. As it would be expected due to the nutrient depletion, a drastic decrease took place since 1986 in the extent of macrophyte beds, mainly in the reservoir main channel. In subsequent years, macrophyte community was particularly restricted to the majority of larger tributaries (temporarily and always covered classes in Figure 6). In relation to the percentage area coverage, always covered class presented 1,84%, temporarily covered 9,16%, only in 1986 14,0%, and never covered 75% of the reservoir area.

In a fieldwork carried out in August 1997 almost the entire reservoir was visited by boat. It was observed that such situation is quite similar and did not changed since 1994. The extension of the area covered by macrophytes is almost the same as the one in Figure 6. Of course some environmental factors determine such a distribution pattern of floating macrophytes. One circumstance that must be considered is the dead trunks in the reservoir (also called paliteiro).

Paliteiro areas are vastly covered by floating macrophytes, provided that nutrients are not limiting factors. However, when nutrient starts to decrease, only paliteiro tributaries, where nutrient availability is suitable, allowed their establishment.

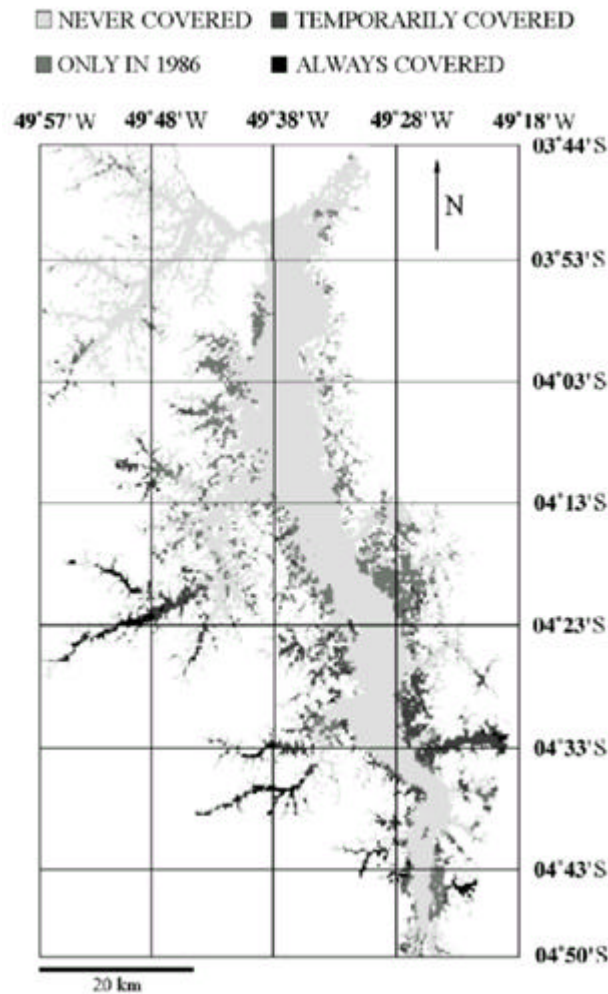


Figure 6. Spatial and temporal distribution of the floating macrophyte community in Tucuruí reservoir from 1986 to 1994.

This fact may be an outcome of the tributary ideal conditions for floating macrophytes, such as i) the constant nutrient availability from the anoxic sediment and the terrestrial runoff, ii) the windless effect on floating macrophytes caused by paliteiro, and iii) the lower hydrodynamic processes in these compartments.

Aquatic plants did not colonize Caraipé inlet since reservoir formation (Figure 1 and 6). As previously outlined, around 400 km² of this compartment was logged before flooding, promoting a non-paliteiro environment, which might contribute to the absence of macrophyte stands in this tributary. In fact, paliteiro is responsible for the windless effect, and moreover, fieldwork have

shown that dead trunks floating in the water surface serve as substrate to the development of different types of floating macrophytes, mainly the genus *Scirpus*.

Conclusion

According to the spreading of floating macrophytes in the Tucuruí reservoir, one can conclude that the occupation process starts by the damming and the increase of nutrient availability in the water column due to submerged rainforest decomposition. After that, dead trunks are used by macrophytes as substrate to their development (floating trunks) and as a macrophyte bed retainer (fixed trunks). When nutrients become a limiting factor, most of the covered areas disappear, and only areas that provide enough nitrogen and phosphorous compounds and an ideal hydrodynamic, such as the tributaries, remain covered by floating macrophytes.

From hydroelectric companies point of view, remote sensing multitemporal assessment offers a suitable manner to understand how engineering and political decisions have consequences, sometimes undesirable, on the environment and on the multiple use of hydroelectric reservoirs. In the case of Tucuruí dam, spatial flux variability of the greenhouse gas methane was studied, according to the map presented in the Figure 6. It was statistically estimated that tributaries often covered by macrophytes are responsible for the higher methane fluxes (Table 1), and that the macrophyte community might be considered an important source of organic matter into the reservoir to the methanogenesis process (Tavares de Lima, 1998). Probably, if tributary rainforests had been logged before flooding, as happened to Caraipé, such a retention of macrophyte beds would not have occurred, and methane production and emission would be decreasing along the years, as proposed by Rosa and Schaeffer (1996).

Table 1. Methane fluxes from Tucuruí reservoir in August 1997.

		always covered	temporarily covered	only in 1986	never covered
average		75,44 (36,59)	94,25 (79,90)	34,31 (16,91)	-
methane flux mgCH ₄ .m ⁻² .d ⁻¹	median	79,93	63,21	29,64	-
	min	18,69	14,76	20,53	-
	max	141,92	248,63	66,75	-
	n	14	12	6	-

() standard deviation

Although there are some limitations related to the use of remote sensing techniques for monitoring different types of macrophytes in hydroreservoirs, floating macrophyte multitemporal mapping through remote sensing is rather feasible. The evolution of the macrophyte distribution shown by the map in Figure 6, associated with the fieldwork was useful to understand the reasons of such dispersion pattern in Tucuruí reservoir. Therefore, this methodology can also be tested to other hydroelectric reservoirs in different Brazilian watersheds, improving the understanding of the relationship between macrophytes and dams.

Acknowledgments

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