PRELIMINARY INTERPRETATIONS OF AQUATIC RESOURCES IN THE CENTRAL AMAZON BASIN USING LANDSAT MULTISPECTRAL IMAGERY

(2 tables, 1 figure)

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ABSTRACT

Images corresponding to high and low water on the R. Solimões-Amazonas near Manaus were analysed using the I-100 system. Training in areas with good "ground truth" information produced indistinct signatures for "white water", "black water", clarified/mixed water", emergent aquatic macrophytes, urban areas and three types of cleared ground. In spite of sufficient ground truth data, it was not possible to distinguish dense, inundated and non-inundated forest.

A series of strips 17 km wide covering the Solimões-Amazonas flood-plain were drawn up to aid in statistitical comparisons. A good log/log correlation between inundated area (less black water and forest) and aquatic macrophytes was obtained. However, the latter cannot be predicted because the variables are not completely independent. A less accurate correlation was obtained between "clarified/mixed water" area and aquatic macrophyte area (r = .746, d.f.8) which can be legitimately used for prediction.

Total area inundated at high water (less flooded forest) was significantly correlated (r = .807, d.f.8) to water area when the level was 8.6 m lower.

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Possibilities of extending this survey to other parts of the basin with the help of the RADAMBRASIL project, and its application to fisheries evaluation are discussed.

BRIEF DESCRIPTION OF STUDY AREA

This account is limited to the area influenced by the Rivers Solimões-Amazonas and Negro near Manaus. Upstream and downstream of the former river, the biotopes differ quantitatively rather than qualitatively.

The sediment-rich "white waters" of the Solimões-Amazonas have been instrumental in forming a floodplain of varying width, bounded by a pedeplain of Tertiary sediments which are not flooded. The annual flooding cycle involves an average amplitude of 10 m near Manaus. The invading "white waters" clear on sedimentation and mix with "black waters" rich in humic acids transported by many small streams (and rivers such as the Negro) along the periphery of the floodplain. The floodplain or *várzea* therefore consists of different water types which vary seasonally in extent and proportion. The combination of these effects with the substrate control the biological production of the system.

The vegetation consists of forest, some of which is regularly inundated, emergent aquatic macrophytes, and terrestrial grasses and shrubs on cleared areas. Jute and *malva* are the most extensive crops.

The morphology of the *várzea* is dominated by the levées, terraces, lagoons, ox-bow lakes and connecting channels. Permanent flooded valleys penetrate the Tertiary pedeplain bordering the floodplain proper.

More detailed descriptions can be found in the RADAM surveys and Sioli (1968, 1975).

METHODOLOGY

A preliminary analysis of areas best known near to Manaus was made at INPE using an image (orb 346 pt 14) corresponding to high water (27.85 m at Manaus) on 31st July 1977. The initial classification contained a large number (24%) of unclassified pixels. Using a print-out of alternate pixels, one of the authors obtained further ground truth information at a similar water level in July 1978. It was found that emergent aquatic macrophytes and some cleared, terrestrial areas had not been classified. In addition, better areas of "black water flooded forest" *(igapó)* and "white water flooded forest" *(floresta da várzea)* were identified for subsequent training and comparison with non-flooded, *terra firme* forest. Other terrestrial types such as *campina* were not investigated because they are not closely associated with the aquatic environment in the region studied.

With the assistance of improved ground truth and a set of aerial photographs (scale 1:50,000 from LASA survey 0-235), retraining of known features with the I-100 system was attempted. It was soon found that Single Cell and Multicell methods of signature discrimination were unsatisfactory due to small scale heterogeneity of the environment and the close similarity between some signatures. A maximum likelihood algorithm, MAXVER gave satisfactory results when signatures from terrestrial biotopes adjoining the eaquatic ones were included. A tolerance of five standard deviations on the frequency distributions was employed.

In order to investigate the degree of flooding from low to high water and the variability of this and other features for different stretches of the river, a series of statistical quadrats 17 km wide with sufficient north-south extension to cover the flood plain were drawn up (Fig. 1). New coordinates for the quadrats had to be calculated when changing images so that they corresponded to the same geographical areas, since the satellite cannot replicate precisely.

Similarly, light and atmospheric conditions cannot be replicated, and retraining on the low water image had to be performed before classification.

Classification was performed on all pixels within each quadrat. In most cases 512 pixels covered the width of the floodplain, allowing rapid classification.

RESULTS

1. High Water Image

The mean, annual maximum water level from 1968 to 1977 was 28.49 m. The level corresponding to the image analysed was 27.85 m, and was considered representative of high water conditions. This level had in fact dropped from a maximum of 28.45 m in that year (1977). Training resulted in signatures for 11 types:

1) "white", turbid water
2) cleared white or mixed water
3) "black" water
4) emergent aquatic macrophytes (free-floating or rooted in substrate)
5) cleared areas type 1: short grasses-dry soil, generally on *terra firme*
6) cleared areas type 2: dense terrestrial grasses and shrubs on dry land
7) cleared areas type 3: terrestrial plants on damp soil, in particular in lowest parts of floodplain
8) urban areas
9) *Terra firme* forest

10) Flooded *igapó* forest

11) Flooded *várzea* forest

Types 5), 6) and 7) were distinguished to provide the most satisfactory discrimination from aquatic macrophytes.

The apparent distinctions between the signatures of 9), 10) and 11) did not always correspond to their descriptions when the classifications were observed. Type 10) and 11) were classified in areas which are never flooded and conversely, 9) was classified in areas known to be inundated at the time, even within parts of those used for training 10) and 11). It became evident that there was insufficient radiation through the forest canopy to influence the signatures. Their histograms were very similar, and the slight differences may be due to different tree densities, or different combinations of foliage types. However, within all three biotopes there is a large species diversity on a small scale which probably masks any radiation differences due to dominant species groups.

The results of the first four aquatic types are shown in Table 1. The values shown are proportional to total areas within each quadrat. They are provisional, as some corrections have to be made for unclassified pixels which varied between 2% and 8%. The large percentages were mostly due to magnetic tape imperfections, and the remainder were identified as "hybrid" or borderline pixels, in particular those between water/forest, water/aquatic macrophytes and uncleared white/black waters. Also the totals for the high water image underestimate the total area flooded because of the difficulty distinguishing between flooded and non-flooded forest mentioned above.

Table 1 indicates a large variability in area, even when area per kilometer of main channel (equivalent to effective width of floodplain) is computed. Biologically, it would be expected that the total area (less flooded forest and nutrient-poor black waters) per kilometer would be positively related to aquatic macrophyte biomass accumulated at high water, when the latter reaches a maximum. Table 2 indicates a strong log/log correlation between aquatic macrophyte area per kilometer of main river channel and the area flooded as defined above. A weaker correlation resulted when clack water was included.

Unfortunately, these correlations cannot be used to predict macrophyte areas on the basis of area flooded, because the latter included the former, and cannot be measured independently. However, a significant log/log correlation was found between cleared/ mixed water and aquatic macrophyte (Table 2) allowing the latter to be predicted, allbeit with rather wide confidence limits.

These correlations with aquatic macrophytes were attempted (see also below) since training and discrimination of this feature is time-consuming, and requires accurate ground truth data, whereas water types are relatively easier. Another possible approach is suggested in the last section.

2. Low Water Image

An excellent imagem taken on 9th December 1976 corresponded to a level of 19.23 m, the water having risen from a minimum of 18.05 m that year. The mean annual minimum for 1968-77 was 19.38 m.

Different features were evident at low water. Shallow, floodplain lagoons of relatively-clear water produced a different signature from deeper, cleared white or mixed water. Sandy beaches bordering the large rivers and islands were evident. Aquatic macrophytes can be regarded as occupying a negligible area at this water level. No attempt was made to distinguish between different forest types, which in any case are almost completely on dry land at this level.

Table 1 shown the results in corresponding quadrats, with the clear, shallow water values added to those of cleared white/ mixed water. It can be seen that water areas at high water (less flooded forest) are from 50% to 150% more than those when the level was 8.6 m lower. The increase depends on the low water area since a significant correlation was obtained (Table 2) between high and low water areas per kilometer of main channel.

The increased "black" water areas at high water cannot be accounted for by the limited increase in black water input. Some of the apparent increase is believed to be due to mixed water which has cleared but is deep enough to give a similar signature to that of permanently black water.

The black water areas at low water can be regarded as those which are permanently black. These areas are known to have limited flooding capacity in this region, because they are mostly contained in the steep-sided flooded valleys penetrating the *terra firme* pedeplain.

As would be expected from biological reasoning, the increase in total area flooded (less flooded forest) should be positively related to the accumulated aquatic macrophyte area at high water. A significant log/log correlation was obtained (Table 2) whose power was not significantly different from unity, suggesting a directly proportional relationship.

Although this and some of the above correlations have a biological basis, they can be criticized on statistical grounds since aquatic macrophyte area has to be included in the flooded area. Alternative approaches to assist in predicting the former are mentioned below.

APPLICATIONS AND FUTURE WORK

Degree of flooding is the single most important variable in controlling fish production in river-floodplain systems (Welcome, 1975). Conversely, degree of reduction in water area or volume has a marked effect on natural and fishing mortalities.

Most of the energy turnover and organic of the system is associated with the annual production and decay of emergent aquatic macrophytes. These are important for the pre-recruitment stages of commercial fishes, and a large proportion of the fish biomass depends directly on the derived detritus and associated microorganisms.

Those aspects of the resources should be quantified, and multispectral analysis of LANDSAT images provides the best and cheapest means.

The major limitation is the failure to distinguish between flooded and non-flooded forest. The former provides important feeding habitats for adults and sub-adults of many larger fish especies (M. Goulding pers, comm. and pers. observation, P.B.B.).

An attempt will be made to combine LANDSAT results with the more extensive RADAM survey in two interrelated ways. Firstly, RADAM field surveys have allowed large-scale mapping of forest types to be made. Estimates of maximum area flooded including and excluding flooded forest can be made, and the latter compared with LANDSAT results in the same quadrats. Satisfactory comparisons would help to verify the RADAM work, and subsequently estimates of maximum flooded forest areas could be obtained. Secondly, good correlations between areas of aquatic biotopes per kilometer of river from RADAM's geological maps would allow extrapolations or interpolations to be made with confidence limits. Cloud-free LANDSAT coverage in the Amazon is by no means complete, but high and low water images in the smallest and largest floodplain areas are available. Successful interpretations of these combined with interpolations in intermediate parts of the system with the help of RADAM maps would provide a satisfactory evaluation of aquatic resources and their dynamic characteristics. This in turn can be compared with fishery yields, for which good data has been collected.

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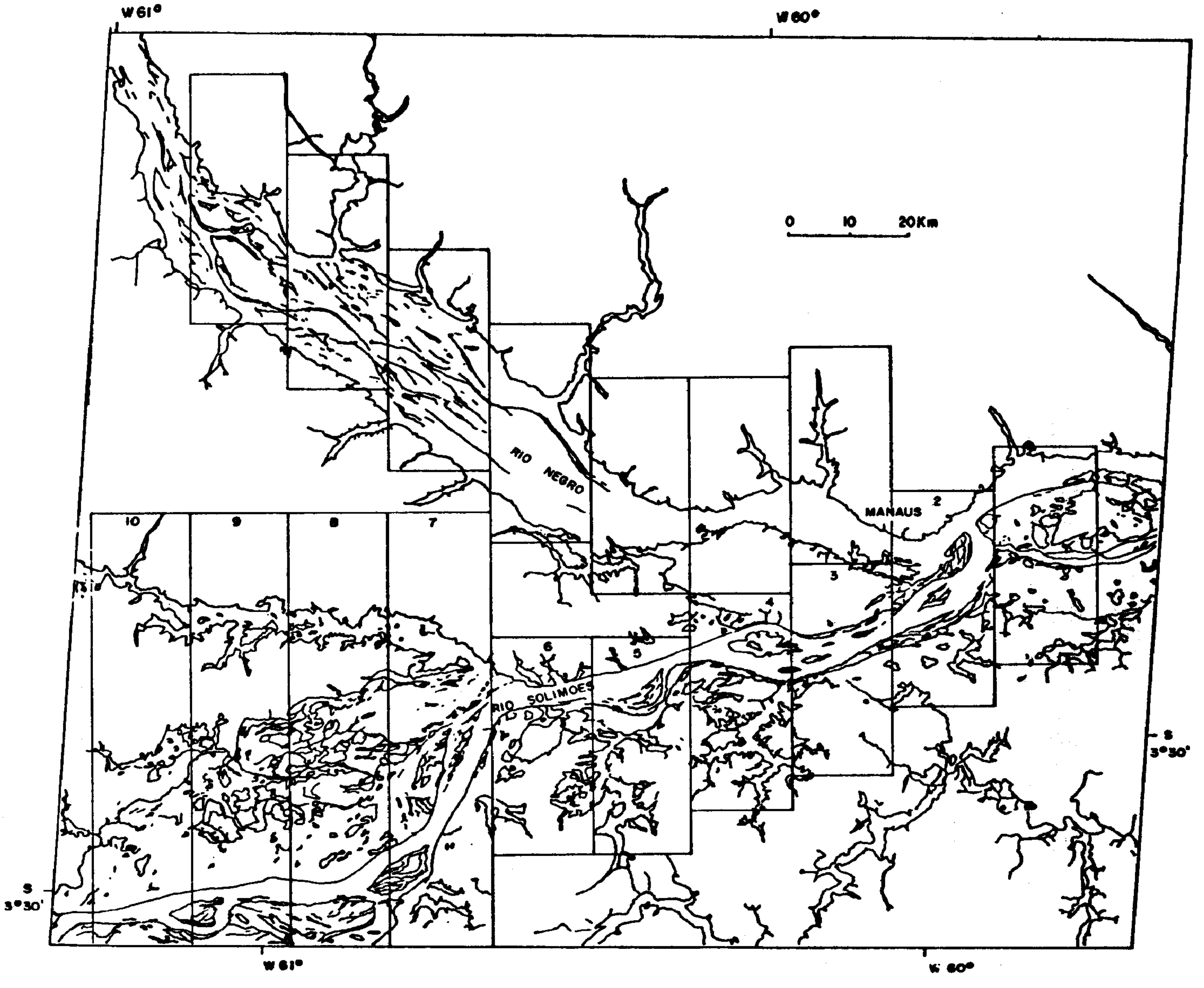

Fig. 1 - Map of study area drawn from high water image with numbered quadrats. (Quadrats not numbered on Rio Negro used in this analysis).

TABLE 1

AREAS OF AQUATIC BIOTEPES AT HIGH AND LOW WATER
(values are in units direct proportional to actual areas)

		QUATRAT NUMBER: PROCEEDING UPSTREAM FROM R. SOLIMÕES-NEGRO CONFLUENCE ⟶									
		1	2	3	4	5	6	7	8	9	10
High Water Image (27.85 m)	"White" water	7.7	15.2	9.7	9.3	8.7	8.5	13.4	8.9	6.5	6.2
	Cleared/mixed water	3.5	5.8	3.3	4.4	4.0	2.4	6.3	4.8	4.9	4.0
	"Black" water	12.8	10.2	0.9	13.7	6.4	10.7	27.5	24.4	14.7	4.9
	Aquatic macrophytes	5.4	8.0	5.3	5.0	4.7	4.1	9.5	11.4	13.4	7.4
	Total flooded area (less forest)	29.4	39.2	19.2	32.3	23.7	25.6	56.6	49.4	39.5	22.5
Low Water Image (19.23 m)	"White" water	9.1	11.7	6.9	8.9	9.0	9.7	11.8	6.6	5.3	5.3
	"Clear" + "cleared/mixed" water	8.1	3.8	2.8	7.8	6.4	4.7	17.8	11.3	3.7	4.7
	"Black" water	0.02	7.4	0.2	1.1	0.0	0.1	6.0	2.3	6.5	3.0
	Total flooded area	17.3	22.9	9.9	17.8	15.4	14.5	35.7	20.2	15.6	13.0
Length of Solimões-Amazonas channel (km) per quadrat		18.5	30	18	17	18	18.5	31.5	19	17	17.5

TABLE 2

SOME CORRELATIONS BETWEEN AREAS OF AQUATIC BIOTEPES PER KILOMETER OF THE R. SOLIMÕES-AMAZONAS (LOG/LOG RELATIONSHIPS FROM 10 QUADRATS)*

VARIABLES	Correlation Coeff. (d.f. = 8)
Total water area (inc. aquatic macrophytes) less "black" water versus aquatic macrophyte area	.915
Total water area (inc. aquatic macrophytes) versus aquatic macrophyte area	.697
Total area of "clarified/mixed water" at high water versus aquatic macrophyte area	.746
Total water area (excluding "black water and aquatic macrophytes) versus aquatic macrophyte area	.098
Increase in total area flooded (inc. aquatic macrophytes) from low to high water versus aquatic macrophyte area	.819
Total water area at high water (inc. aquatic macrophytes) versus area at low water	.807

* all "total areas" exclude flooded forest.