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STUDY OF THE VARIABILITY IN SUSPENDED SEDIMENT DISCHARGE AT MANACAPURU, AMAZON RIVER, BRAZIL

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Abstract: The Manacapuru hydrometric gauge station has been used for more than 30 years by the Brazilian National hydrometric network to provide data on the Solimões-Amazon River. At this place, the Solimões river average water discharge is about 103,000 $m^3 s^{-1}$, the mean width is 3,000 m and the mean depth is 20 m. The gauge station record represents the whole upstream contribution of the total suspended solids (TSS) from the Solimões basin, whose total area is approximately 2×10^6 km^2, representing a runoff of 0.48 $m^3 s^{-1} km^{-2}$. TSS annual flow is approximately 400×10^6 t. The systematic TSS sampling procedures traditionally used at the Brazilian hydrometric network has limitations, some of them being related to local effects affecting the TSS flow. This article aims to study the local variability of TSS flow at Manacapuru station. The study was conducted in the scope of MESASOL and PIATAM IV projects, whose objectives are precisely to consider alternative methods for TSS flow assessment in the Amazon basin. It was identified that local geologic-geomorphologic features are related with the TSS flux spatial variability at the vicinity of the Manacapuru section. This results induce a new interpretation to the general sediment flux for the Solimões river basin, were local flux can't be see as a total flux from the hole up-stream river basin.

Resumo: A estação hidrométrica de Manacapuru é uma localidade utilizada há mais de 30 anos na rede hidrométrica brasileira. Esta estação, cuja seção transversal sobre o Rio Solimões, tem em média: 3000 metros de largura e 20 metros de profundidade, controla praticamente a totalidade das contribuições das MES (Material Em Suspensão) oriundos da bacia do Rio Solimões, cuja área total é de aproximadamente 2 milhões de km^2, a descarga líquida média é de 103.000 $m^3 s^{-1}$, ou 48 $l\ s^{-1} km^{-2}$. O fluxo médio total anual de MES é de aproximadamente 400×10^6 toneladas. A sistemática tradicional de amostragem de material em suspensão (MES) tem limitações quanto a avaliar efeitos locais nesse fluxo. O presente artigo pretende apresentar alguns fenômenos locais que de algum modo interferem no fluxo local de MES do Rio Solimões em Manacapuru. O estudo foi realizado no escopo do Projeto MESASOL e PIATAM IV, projetos que têm investigado métodos alternativos de avaliação do fluxo de MES na bacia Amazônica na busca de melhorar a precisão e diminuir os custos operacionais na aquisição de dados hidrológicos. Os resultados indicam que as características geológicas e geomorfológicas locais influenciam no fluxo de MES, com grande variabilidade espacial em superfície na vizinhança da seção de Manacapuru. Isso resulta induzir uma nova interpretação para o fluxo de sedimentos na bacia do rio Solimões, onde os fluxos locais não podem ser diretamente interpretados como da bacia de montante.

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Palavras-Chaves: sedimentos em suspensão, Perfilador Acústico de Corrente, Rio Amazonas.

INTRODUCTION

The Amazon River, as it flows from Peru, becomes the Solimões River in Brazil, near Tabatinga. From this point it flows more than 2,500 km downstream until the confluence with the Negro River near Manaus, capital city of the Amazonas state. Immediately upstream of the Negro and Solimões confluence is located Manacapuru gauge station, on the left banks of the Solimões. Downstream that junction the Solimões is named again Amazon River up to the mouth in the Atlantic Ocean. The Solimões River basin represents more than 35% of Amazon basin total area. The mean annual discharge at Manacapuru reaches almost 50% of the Amazon total discharge to the ocean (Molinier *et al.*, 1995), even before forming the famous *"Encontro das Águas"* or "water meeting point" where sediment loaded yellow/white waters encounters the organic matter enriched, black waters of the Negro River. Mean suspended matter (here called TSS) is about 400 x 10^6 t (Filizola, 1999; 2003). The Solimões River load is principally formed by total suspended solid (TSS) and it crosses a wide alluvial plain, where mean precipitation can be higher than 3,000 mm y^{-1}, forming large wetlands called *várzeas*.

Manacapuru hydrometric gauge station has been used for years by the Brazilian Water Agency (ANA) jointly with the World Meteorological Organization (WMO) as the practical location of the annual School "Measurement in Great Rivers". This gauge, where the river is in average 3,000 m wide and 20 m depth, controls actually the total amount of TSS carried out the Solimões basin, with a total area of about 2 x 10^6 km^2 for a mean discharge of 103,000 m^3 s^{-1}, i.e. an areal discharge of 0.48 m^3 s^{-1} km^{-2}, rather regularly distributed throughout the year (Molinier *et al.*, 1995). The gauge is operated 4 times per year, following the "Work Plan of the National Hydrometric Network", which is under the responsibility of ANA.

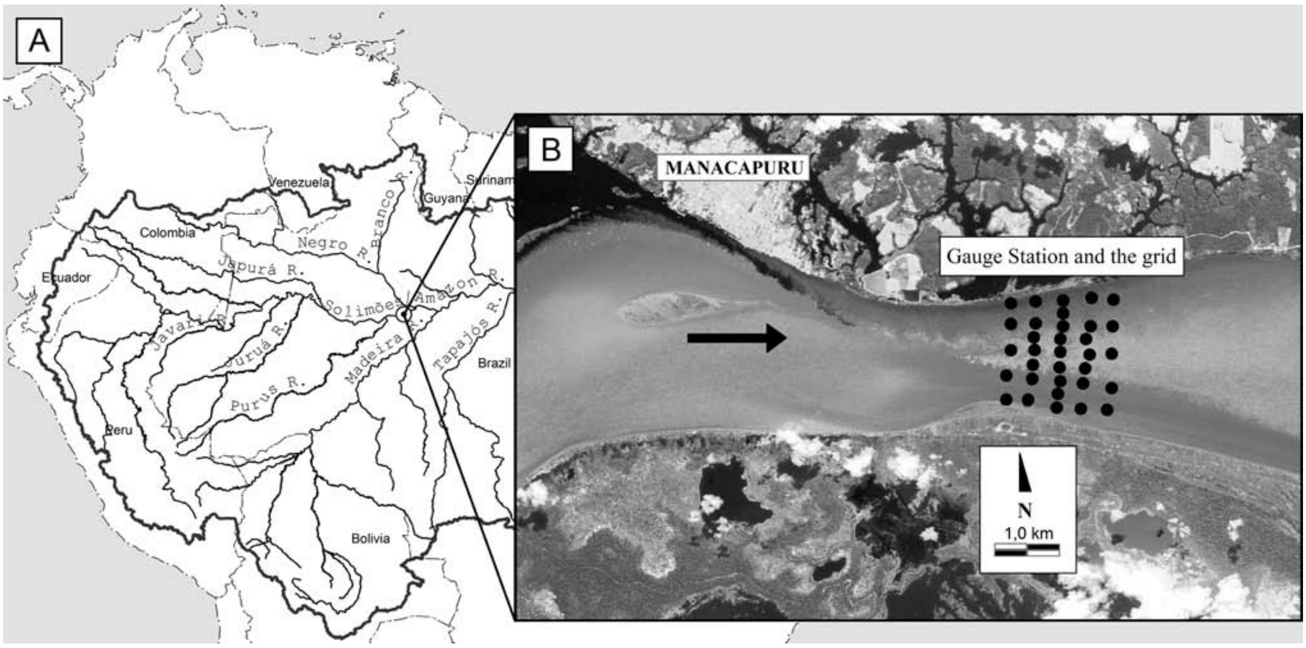

Figure 1. a) Location of the hydrometric gauge at Manacapuru on the Solimões River, study area of the MESASOL project. b) The measurement point grid (33) used to collect superficial water samples at Manacapuru. The central section (with 9 points) is the section used by ANA and WMO to measure discharge during the annual school of discharge measurement for great rivers. On this section, water at 2 m depth was also sampled. Between points 5 and 6, a vertical sampling scheme of one sample every 2 m was performed.

Mean data	Q [m^3 s^{-1}]	A [m^2]	W [m]	P [m]	V [m s^{-1}]	DF [°]
Nov/2005	59,901	56,175	3,032	18.26	1.08	99 to 101
SD	5.67	5.10	17	0.18	0.02	
SD/M	0.01	0.01	0.01	0.01	0.02	
Jun/2006	122,001	93,075	3,266	27.44	1.36	105 to 107
SD	2,023	1,465	38	0.45	0.006	
SD/M	0.02	0.02	0.01	0.02	0.005	

Table 1. Discharge measurements obtained with an ADCP of 600 kHz, in the ANA cross-section at Manacapuru. Each value is the average value of, at least, 4 measurements performed in the central section as shown in figure 1. (Q: Discharge, A: Section wet area, W: Width, P: Mean depth, V: Mean velocity, DF: Flux direction, SD: Standard Deviation, M: Mean).

At the Manacapuru gauge station, a sampling and measurement protocol is used by the companies contracted by ANA. This protocol is based on improved methods that had been used for 30 years, as derivations from the United State Geological Survey (USGS) (Guy and Norman, 1976), and WMO (WMO, 1994 Hydrological Operational Guide) sampling procedures. For TSS, the gauge is also operated by the Observatory for Research in Environment (ORE) HYBAM with a regular high frequency schedule of superficial water sampling (500 ml sampled every 10 days).

Measurement protocols used at Manacapuru have been designed to study the temporal variability of TSS (Total Suspended Solids) exiting in the basin at regional scale. However the spatial local distribution of the TSS within the cross section had been not analyzed. The present study aims to analyse with more accuracy the spatial variability of TSS at Manacapuru gauge station (Fig. 1).

METHODOLOGY

The MESASOL project established a sampling grid for sampling superficial water of the Solimões River on the Manacapuru section (Fig. 1). Two transversal sections upstream and two downstream of the Manacapuru section were incorporated to the sampling scheme. The grid is basically 600 m spaced. At the central part, four more samples were taken in order to increase the density of the grid to 300 meters. This scheme generated 33 sampling points, where superficial water TSS was analysed (Fig. 1). The collected samples were filtered using gravity filtration inox-steel units, organized in horizontal ramps and assisted by low pressure vacuum pump. The afore-weighted filters were acetate of cellulose, 4.6 cm in diameter with a 0.45 μm mesh. The filters were dried after filtration, following the GEMS/Water program protocol, as defined by Filizola and Guyot (2004). Weights were normalized in mg l^{-1} and registered. In addition, the concentrations of the superficial water grid points were represented in a geographical information system (GIS). Sampling and data processing were performed at specific time during the hydrological cycle (Table 1). An extensive current velocity and bathymetry survey was performed with an Acoustic Doppler Current Profiler (RDInstruments ADCP at 600 kHz frequency), in order to help in the validation of the TSS superficial sampling grid net. The measurements were designed to study the local effects of fluvial morphology on TSS superficial concentration. Various ADCP transects were performed from upstream to downstream of the Manacapuru section. The ADCP data were processed using the software Multi-Dimensional Surface Water Modelling System (MD-SWMS) from USGS. USGS model allows simulating 3D liquid and solid fluxes from ADCP data. We used it only to generate 3D figures in order to analyse the geometry of the section. In addition, SPOT images obtained on June 13th, 2006, from IRD Caiena (French Guyana) antenna, were used to visually interpret the superficial figures of TSS concentrations.

RESULTS AND DISCUSSION

We present here the results obtained from the sampling performed during two extreme hydrological events: a) the drought of November 2005 and b) the

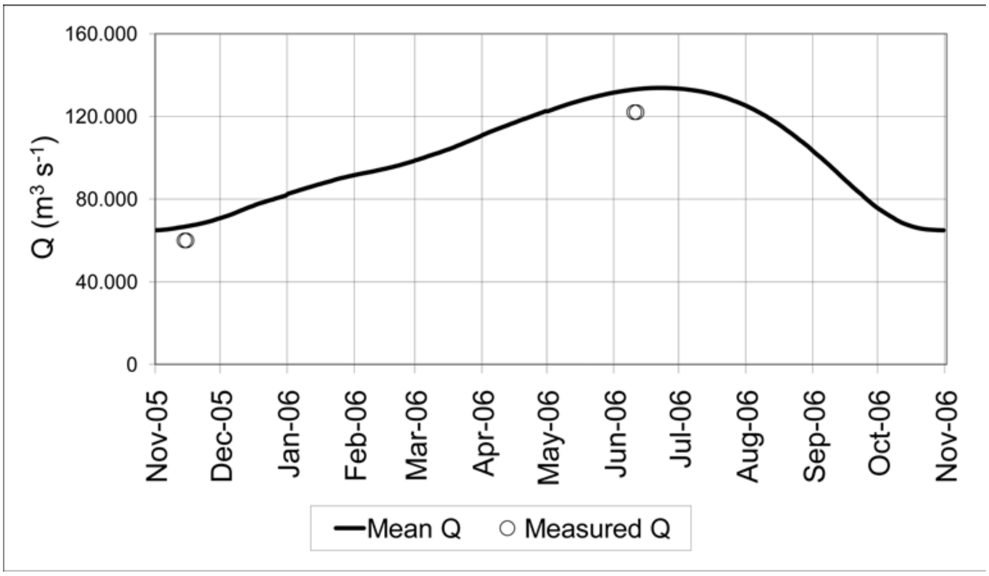

Figure 2. Mean hydrograph at Manacapuru. Squared points indicate the discharge measurements obtained by the MESASOL project. Only the circled measurement points are analysed in this work and they belong to the extreme events that spread from November 2005 to l June 2006.

flood of June 2006.

The water discharge between both extreme events differs by 100% (Table 1). The river width changed a little more than 7%, from November 2005 to June 2006. The mean velocity was slightly more than 25% higher in June 2006 than in November 2005. The low width variability and the significant increase in velocity in relation to higher discharges are in good agreement with the empirical hydraulic geometry equations obtained at Manacapuru by Latrubesse and Franzinelli (2002). The mean current direction between both surveys also differs about 6%. The variations observed for the main parameters of the wet section are consistent with the hydrological cycle variability, between low and high stage (Fig. 2).

TSS results are presented in Table 2. The mean TSS concentration for the dry season, when water discharge was 59,901 m^3 s^{-1}, was 139 mg l^{-1}, i.e. a superficial flux of 719,387 t d^{-1}. For the 2006 flood, TSS mean concentration was 32.2 mg l^{-1} and the water discharge was 122,001 m^3 s^{-1}, i.e. a superficial suspended sediment flux of 339,522 t d^{-1}. The spatial superficial distribution of TSS was heterogeneous, especially during the dry season when the concentrations were higher in the middle of the channel, forming a triangular figure that opened from upstream to downstream. At high stage, a slight increase in concentration was observed also in the central part of the channel. In both cases, the highest concentrations were observed at the location of the ANA sampling section. The difference between the mean values for both dates was 76% that of the November value. The minimum recorded value for TSS concentration in November was more than two times higher than the mean value obtained in June.

The highest concentrations were observed at the right bank of the stream in both periods (Fig. 3a, b). The highest values were in both, low and high stage, coincidently aligned with the transversal section sampled by ANA.

In order to interpret these different patterns, satellite image and bathymetry obtained by ADCP (Fig. 4) were used. A triangular plume of suspended matter can be observed on SPOT images. For a better interpretation, the grid obtained for the November

N = 33	TSS (11/2005) [mg l^{-1}]	TSS (06/2006) [mg l^{-1}]
MEAN	139	32.2
MAX	230	81.5
MIN	63	1.0
SD	44	16.3
A	167	80.5

Table 2. Results from processed data of TSS samples at the 33 sampling points. (MAX: maximum, MIN: minimum, SD: Standard Deviation, A: amplitude).

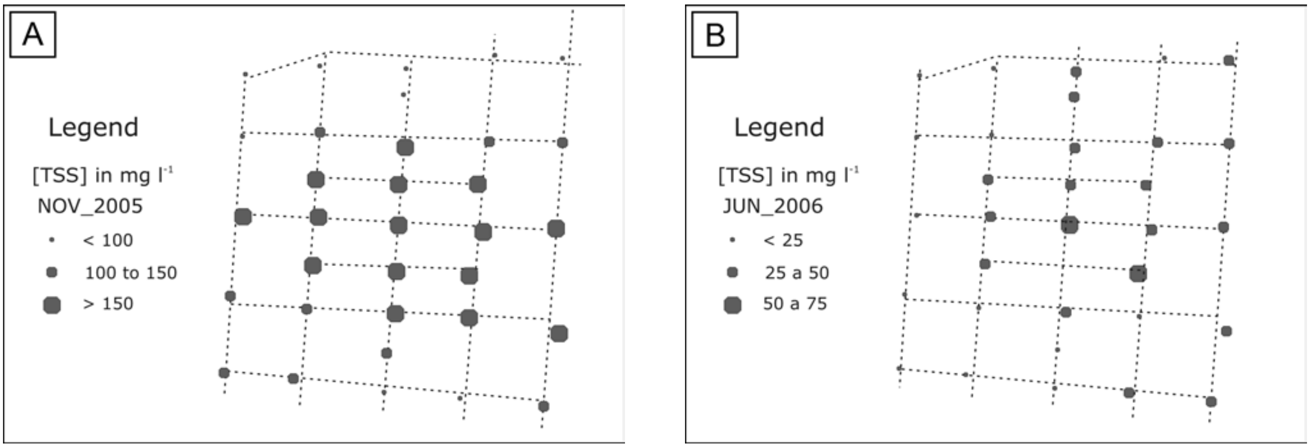

Figure 3. Results of the TSS concentrations at the 33 grid points for the two different period of time analysed at Manacapuru section. a) High TSS concentrations during low stage (November). b) Dilution encountered at high stage (June).

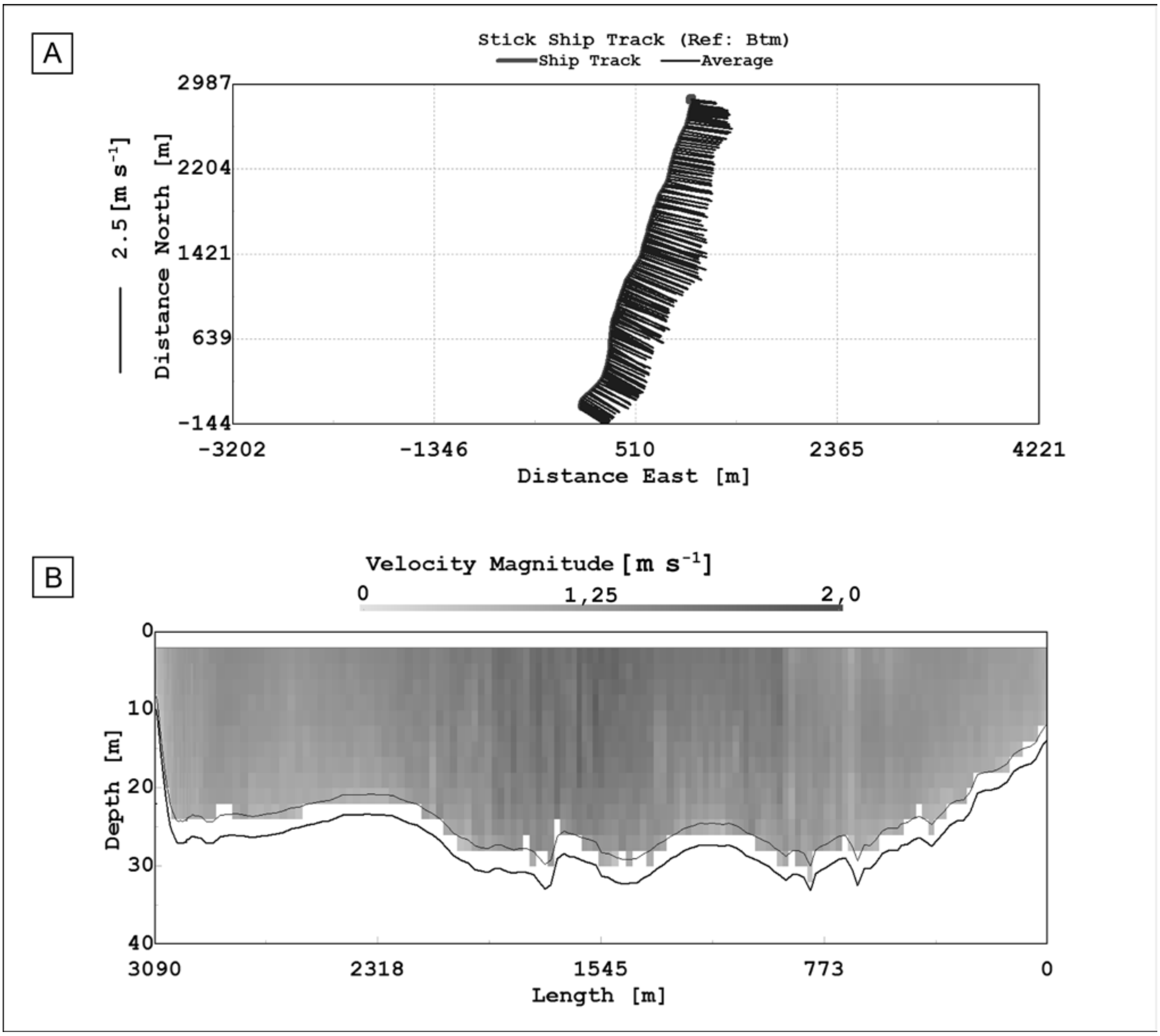

Figure 4. a) Interpretation of the MESASOL field surveys that were linked with the PIATAM IV project measurements, in the Manacapuru area, Amazonas state. b) The ADCP processed data shows a velocity vertical profile with highest values at the centre of the section, a typical behaviour over a good section for discharge measurement.

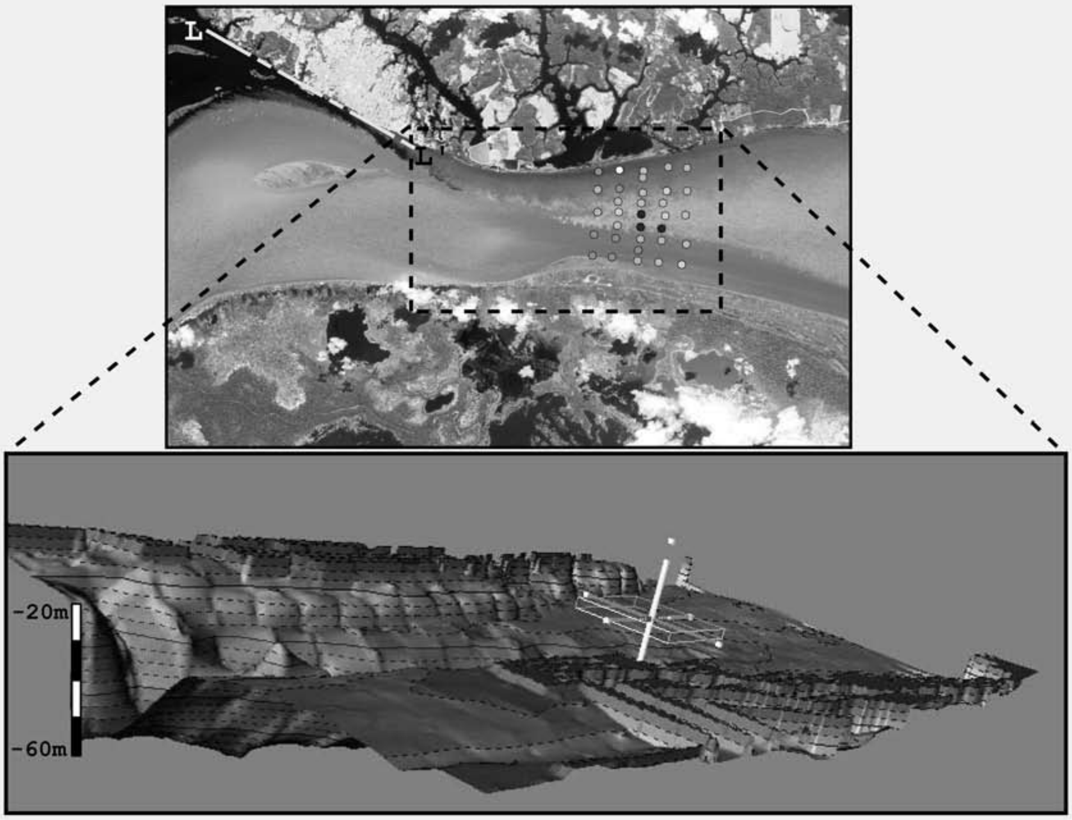

Figure 5. The MESASOL sample grid results for June 2006, superimposed on the SPOT image, indicate the highest concentrations with dark dots. The doted green line is following the tectonic lineament (L – L') in front of Manacapuru. It corresponds to the step presented on the 3D diagram, spreading from more than 60 m depth to less than 20 m depth. The north at the image is inverted if related to the figure 1 just to adjust with river flow direction.

field survey was superimposed on the June SPOT geo-referenced image. The triangular figure is more visible for the low stage due to highest concentrations (low dilution) obtained at this time. However, the location seems identical to that observed on SPOT image during high stage.

The formation of the plume can be related to two morpho-structural local features: 1) the presence of a tectonic lineament (L - L') varying in depth from 60 to 20 m, described by Latrubesse and Franzinelli (2002). This feature was identified in the 3D diagram presented in figure 5, and built by the ADCP data processed with MD-SWMS software; 2) as a result of the end exposure of the lineament near ANA section where the bed bottom climbs up and forms a stair step. The water flux at the contact with the bottom of the river, climbing such an ascending step, reworks the bottom material forming a plume of re-suspended matter. This plume is dispersed vertically and laterally, arriving at the surface and being identified from both image and superficial samples. Another factor that could explain this phenomenon is the entering of the less (under) loaded water from the Manacapuru Ria-Lake, through the lineament (Figure 5). This lake is contributing to the dilution process occurring on the left bank.

CONCLUSION

Based on preliminary study of the data obtained from the MESASOL project in conjunction with PIATAM IV project, it was possible to identify that local geologic-geomorphologic features are related with the TSS flux spatial variability at the vicinity of Manacapuru section. We can conclude that:

- The superficial samples collected following a gridded scheme allowed the identification of local morpho-dynamic features affecting the TSS;
- The superficial flux spatial variability is affected by local fluvial morphology in two ways:
    1. a structural lineament, probably a tectonic

fault, generates local sediment load variability that can be identify and analyzed by both TSS sampling and satellite image processing;

2. the Ria-Lake of Manacapuru could proportionate a dilution effect on the left bank of the Solimões River favouring highest concentrations at the right bank.

Further analysis of the samples collected during additional field surveys will help to identify in more detail these local phenomena affecting the sediment load of the Solimões River. Additionally, our results demonstrate that particular care has to be taken when analysing TSS at a particular gauge station. Other way, significant errors in the total amount of sediment transport in the basin can be assumed. We finally suggest that to increase the level or certainty in terms of TSS at the basin scale, a detailed control like this in other gauge stations of the Amazon basin should be performed.

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