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# Challenges and Solutions for Hydrodynamic and Water Quality in Rivers in the Amazon Basin

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## 1. Introduction

This research is part of a multidisciplinary research initiative in marine microbiology whose goal is to investigate microbial ecology and marine biogeochemistry in the Amazon River plume. Aspects related to Amazon River fluvial sources impacts on the global carbon cycle of the tropical Atlantic Ocean are investigated within the ROCA project (River-Ocean Continuum of the Amazon). This project is intended to provide an updated and integrated overview of the physical, chemical and biological properties of the continuous Amazon River system, starting at *Óbidos*, located 800 km from the mouth of the river, and interacting to the discharge influence region at the Atlantic Ocean (Amazon River plume). This geographic focal region includes the coast of the State of *Amapá* and the north of *Marajó* archipelago in Northeast Brazilian Amazon.

The ROCA project is focused on the connection between the terrestrial Amazon River and the ocean plume. This plume extends for hundreds of kilometres from the river delta towards the open sea. This connection is vital for the understanding of the regional and global impacts of natural and anthropogenic changes, as well as possible responses to climate change (Richey et al. 1986; Richey et al. 1990; Brito, 2010). Different phenomena of interest are typically linked to the quantity and quality of river water (flows of carbon and nutrient dynamics) and the dynamics of sediments. All of them are strongly influenced by substances transport characteristics and water bodies physical properties and physical properties in the water bodies, constrained by spatial distribution of water flow (influenced by bottom topography and coastline of river mouth archipelago) and the unsteady interaction with tides and ocean currents. These very complex phenomena at the Amazon mouth are still not fully understood.

Based on this framework, river and ocean plume hydrodinamics are fundamental components in the complex interactions between physical and biotic aspects of river-ocean interaction. They drive biogeochemical processes (carbon and nutrient flows), variations in water quality (physical-chemical and microbiological). They drive biogeochemical processes (river bottom and suspended sediments) (Richey et al., 1990; Van Maren & Hoekstra, 2004, Shen et al. 2010; Hu & Geng, 2011). The understanding of the Amazon River mouth flows is an important and opened question to be investigated in the context of the river-ocean integrated system.

In Brazil, the National Water Agency (ANA) monitors water flows at numerous locations throughout the Amazon basin (Abdo et al. 1996; Guennec & Strasser, 2009). However, the last monitoring station located on the Amazon River and nearest to the ocean is *Obidos* (1°54'7.36"S, 55°31'10.43"W). There are no systematically recorded data available in downriver locations towards the mouth. The Amapá State coast is, *geographically*, an ideal site for such future systematic experimental flow measurements, since about 80% of the net discharge of the Amazon River flows in the North Channel located in front of the city of Macapá (0° 1'51.41"N, 51° 2'56.88"W) (ANA, 2008). The fact that this flow is not continuous and varies with ocean tides, creating an area of inflow-outflow transition makes this region a challenging subject for water research.

This research focus on two main issues: a) to establish an overview of physical aspects over transect $T_2$ in the North Channel of the Amazon River, where measurements were performed for quantification of liquid discharge and additional sampling procedures for assessing water quality and quantify concentration of $CO_2$ in the air and water; b) to evaluate typical local effects of river flow interacting with the shore and small rivers, based on turbulent fluid flow modeling and simulation.

## 2. Main driving forces of the Amazon river mouth discharge

Tidal propagation in estuaries is mainly affected by friction and freshwater discharge, together with changes in channel depth and morphology, which implies damping, tidal wave asymmetry and variations in mean water level. Tidal asymmetry can be important as a mechanism for sediment accumulation while mean water level changes can greatly affect navigation depths. These tidal distortions are expressed by shallow water harmonics, overtides and compound tides (Gallo, 2004). The Amazon estuary presents semidiurnal overtides, where the most important astronomic components are the M2 (lunar component) and S2 (solar component), consequently, the most common overtide is the M4 (M2 + M2) and the main compound tide is the Msf (relative to fluvial flow). Amplitude characteristics of the mouth of the Amazon River is represented by tidal components M2 and S2, of 1,5m and 0,3m, respectively, corresponding to North Station Bar, Amapá State (Galo, 2004; Rosman, 2007).

Form factor (F) expressing the importance of scale on components of the diurnal and semi-diurnal tides, the Amazon estuary can be classified as a typical semi-diurnal tide ($0 < F < 0.25$). However, this classification does not considers the effects of river discharge. River discharge certainly contribut to friction and to balance the effect of convergence in the lower estuary and also to what happens between the platform edge of the ocean station and the the mouth of the Amazon River.

There is evidence of nonlinearity in tidal propagation, which can be observed by the gradual redistribution of power between M2 and its first harmonic M4. Considering tides as the sum of discrete sinusoids, the asymmetry can be interpreted through the generation of harmonics in the upper estuary (Galo, 2004; Rosman, 2007). In the case of a semi-diurnal tide, with its main components M2 and M4 first harmonic, the phase of high frequency harmonic wave on the original controls the shape of the curve and therefore the asymmetry.

Three major effects characterize the amount and behaviour of flow it the mouth of the Amazon River: (a) relative discharge contributions from sub-basins of the main channel; b) tidal cycles and; (c) regional climate dynamics.

According to Gallo (2004) the Amazon River brings to the Atlantic Ocean the largest flow of freshwater in the world. Based on *Óbidos* records, there is an average flow of approximately $1.7x10^5$ $m^3/s$, with a maximum of approximately $2.7x10^5$ $m^3/s$ and a minimum of $0.6x10^5$ $m^3/s$. According to ANA (2008), the flow reaches a net value of approximately 249,000 $m^3/s$, with a maximum daily difference of 629,880 $m^3/s$ (ebb) and a minimum of -307,693 $m^3/s$ (flood). The most important contributions come from the *Tapajós* River with an average flow of approximately $1.1x10^4$ $m^3/s$, the *Xingu* River with an average of approximately $0.9x10^4$ $m^3/s$ and *Tocantins* River, at the southern end of the platform, with an approximate average flow of $1.1x10^4$ $m^3/s$.

Penetration of a tidal estuary is result of interaction between river flow and oscillating motion generated by the tide at the mouth river, where long tidal waves are damped and progressively distorted by the forces generated by friction on river bed, turbulent flow characteristics of river and channel geometry. Gallo (2004) describes that propagation of the tide in estuaries is affected mainly by friction with river bed and river flow, as well as changes in channel geometry, generating damping asymmetry in the wave and modulation of mean levels. Such distortions can be represented as components of shallow water, over-tides and harmonic components. The Amazon River estuary can be classified as macrotidal, typically semi-diurnal, whose most important astronomical components are $M_2$ (principal lunar semidiurnal) and $S_2$ (Principal solar semidiurnal) and therefore the main harmonics generated are high frequency, $M_4$ (lunar month) and the harmonic compound, Msf (interaction between lunar and solar waves) (Bastos, 2010; Rosman, 2007).

In the Amazon the most important climatic variables are convective activity (formation of clouds) and precipitation. The precipitation regime of the Amazon displays pronounced annual peaks during the austral summer (December, January and February - DJF) and autumn (March, April and May - MAM), with annual minima occurring during the austral winter months (June, July and August - JJA) and spring (September, October and November - SON). The rainy season in Amapá occurs during the periods of DJF and MAM (Souza, 2009; Souza & Cunha, 2010).

The variability of rainfall during the rainy season is directly dependent on the large-scale climatic mechanisms that take place both in the Pacific and the Atlantic Oceans (Souza, 2009). In the Pacific Ocean, the dominant mechanism is the well-known climatic phenomenon El Niño / Southern Oscillation (ENSO), which has two extreme phases: El Niño and La Niña. The conditions of El Niño (La Niña) are associated with warming (cooling) anomalies in ocean waters of the tropical Pacific, lasting for at least five months between the summer and autumn. In the Atlantic Ocean, the main climatic mechanism is called the Standard Dipole or gradient anomalies of Sea Surface Temperature (SST) in the intertropical Atlantic (Souza & Cunha, 2010).

This climate is characterized by a simultaneous expression of SST anomalies spatially configured with opposite signs on the North and South Basins of the tropical Atlantic. This inverse thermal pattern generates a thermal gradient (inter-hemispheric and meridian) in the tropics, with two opposite phases: the positive and negative dipole. The positive phase of the dipole is characterized by the simultaneous presence of positive / negative SST anomalies, setting the north / south basins of the tropical Atlantic Ocean. The dipole negative phase of the configuration is essentially opposed. Several observational studies showed that the phase of the dipole directly interferes with north-south migration of the Intertropical Convergence Zone (ITCZ). The ITCZ is the main inducer of the rain weather system in the eastern Amazon, especially in the states of Amapá and Pará, at its southernmost position defines climatologically the quality of the rainy season in these states (Souza & Cunha, 2010). The behavior of the climate is important because it significantly influences the hydrological cycle and, therefore, the hydrodynamic and mixing processes in the water.

According to Van Maren & Hoesktra (2004) the mechanisms of intra-tidal mixing depend strongly on seasonally varying discharge (climate) and therefore hydrodynamics. In this case, during the dry season, there is a breakdown of stratification during the tidal flood that occurs in combination with the movements of tides and advective processes. Intra-tidal mixing is probably greater in semi-diurnal than in diurnal tides, because the semi-diurnal flow velocity presents a non-linear relationship with the mixture generated in the river bed and the mean velocity.

A second, Hu & Geng (2011), studying water quality in the Pearl River Delta (PRD) in China, found that coupling models of physical transport and sediments could be used to study the mass balance of water bodies. Thus, most of the flows of water and sediment occur in wet season, with approximately 74% of rainfall, 94% water flow and 87% of suspended sediment flow. Moreover, although water flow and sediment transport are governed primarily by river flow, tidal cycle is also an important factor, especially in the regulation of seasonal structures of deposits in river networks (deposition during the wet season and erosion in the dry season). As well as net discharge there are several types of physical forces involved in these processes, including: monsoon winds, tides, coastal currents and movements associated with gravitational density gradients. Together these forces seem to jointly influence the control of water flow and sediment transport of that estuary.

A third example, according to Guennec & Strasser (2009), hydrodynamic modeling along a stretch of the Manacapuru-Óbidos river in the upper Amazon a stretch of the *Manacapuru-Óbidos* river in the upper Amazon revealed that the ratio of liquid flow that passes through the floodway changes from 100% during the low water period to 76% (on average) during the high water period. Expressed in volume, this means that about 88% of the total volume available during a hydrological cycle moves through the floodway of the river, and only 12% moves through the mid portion. The volume that reaches the fringe of the flood plain is approximately 4% and appears to be temporarily stored.

Based on the climatic characteristics of the State of Amapá, one of the main challenges for both hydrological and hydrodynamic studies is to integrate meteorological information from the Amazon Basin and include these forces when evaluating the responses of aquatic ecosystems in the Lower Amazon River estuary (Brito, 2010; Bastos, 2010; Cunha et al., 2006; Rickey et al., (1986), Rosman (2007), Gallo (2004), ANA (2008) and Nickiema et al., (2007).

## 3. River flow measurements in Amazon North Channel

In the Amazon River (North Channel) two up to date measurements of net discharges were made. The measuring process, consists of: 1) performing a series of flow measures over a minimum period of 12.30 h, using ADCP with an average of 12 experimental measurements;

2) interpolate the temporal evolution of flow and velocity from these measurements; 3) integrate the values with the tidal cycle to obtain the average flow rate (or velocity); 4) analyze the maximum and minimum flow, and the relationship between flow/velocity and level, as described by ANA (2008), Cunha et al. (2006) and Silva & Kosuth (2001).

Fig. 1 shows the location of Transect T2 (blue line) of the North Channel and Matapi River, both studied by Brito (2010) and Cunha (2008) nearly to city of *Macapá*, respectively .The requirement for local knowledge of the river bathymetry is demonstrated by the geometric complexity of the channels and variations in the average depths of the channel. Cunha (2008) observed depths ranging from 3 m (minimum) to approximately 77 m (maximum) in the section indicated.

Brito (2010) has studied the water quality sampled water quality and participated in the quantification of the measurements of liquid discharge in the North Channel. The width of the North Channel is approximately 12.0 kilometres (30/11/2010). The width of the South Channel was approximately 13.0 kilometres (12/02/2010).

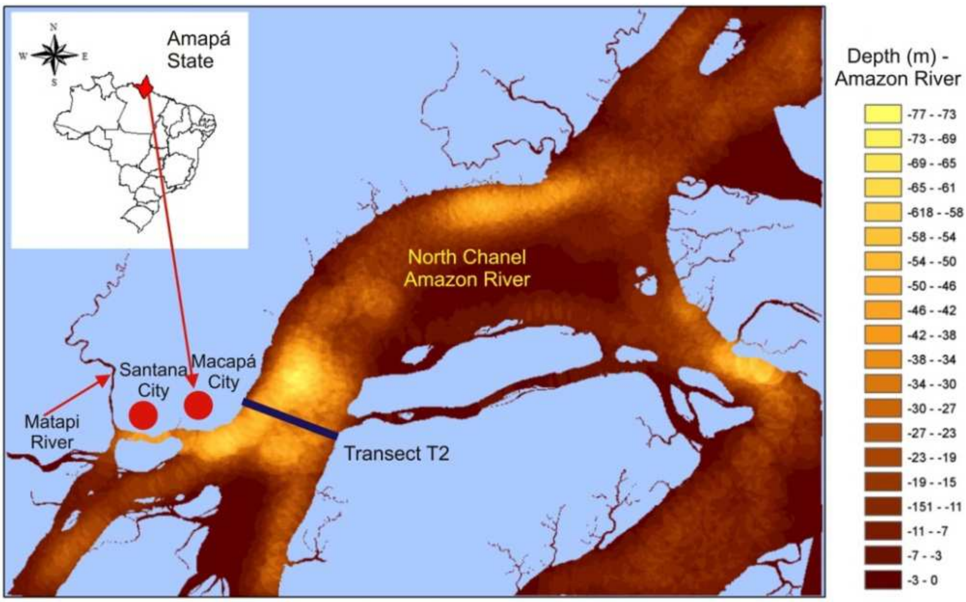


Fig. 1. Features in river sections close to Transect T2 located in the North Channel of the Amazon River – Amapá State (S0 03 32.2 W51 03 47.7)

### 3.1 Methodological approach for discharge measurement in large rivers

Muste & Merwade (2010) describe recent advances in the instrumentation used for investigations of river hydrodynamics and morphology including acoustic methods and remote sensing. These methods are revolutionizing the understanding, description and modelling of flows in natural rivers.

Stone & Hotchkiss (2007) report that accurate field measurements of shallow river flows are needed for many applications including biological research and the development of numerical models. Unfortunately, data quantifying the velocity of river current are difficult to obtain due to the limitations of traditional measurement techniques. These authors comment that the mixing processes and transport of sediment are among the most important impacts on aquatic habitat. The velocity of large rivers is typically measured in either stationary or moving boats with reels or ADCP (Acoustic Doppler Current Profiler).

ADCPs are designed to measure the velocity of the current in a section of a watercourse, producing a velocity profile of the section based on the principle of sound waves from the Doppler effect. This effect is a result of the change in the frequency of the echo (wave) which varies with the motion of the emitting source or reflector. Using this technique, it is possible to measure more accurately net discharge i) in sites and ii) on occasions where the task of measuring flow is more difficult with traditional techniques. At the same time results from ADCP are comparable with results from techniques using traditional methods and can be used to evaluate the qualitative discharge of suspended sediments. In both cases, the technique can be applied in specific monitoring programs (Abdo et al., 1996).

The ADCP has some technical advantages over more traditional techniques (e.g. quantitative net discharge) in places where there are difficulties in applying traditional methods, such as large rivers, during the wet season, discontinuous river sections, and some authors recommend that its use should become more common in estuaries (Guennec & Strasser, 2009). The main advantages of using ADCP are: a greater quantity and quality of data, improved accuracy (5%); measurements are obtained in real time, with a high rate of reproductibility. The technique for measuring liquid discharge using ADCP technique is also faster is also faster than conventional methods and can be used in large and small water bodies. Furthermore, it requires less effort, does not need alignment, allows for the correction of detours in discrete river sections, and estimating the motion of sediment on the river bed. It also demonstrates a good correlation with the more conventional methods, permitting to obtain of section profiles, river width, flow velocity, the qualitative distribution of suspended sediments, measurement time, boat speed, water temperature and salinity (Guennec & Strasser, 2009).

According to Muste & Merwade (2010) recent advances in instrumentation for the analysis of river flows include the combination of acoustic methods with remote sensing to quantify variables and hydrodynamic and morphological parameters in natural bodies of water, and notably the degree of importance of these new technologies is more evident when applied to large rivers under tidal influence (Abdo et al. 1996; Martoni & Lessa, 1999).

These instruments can be quick and efficient in providing detailed multidimensional measures that contribute to the investigation of complex processes in rivers, especially hydrodynamics, sediment transport, availability of habitats and ecology of aquatic ecosystems.

Muste & Merwade (2010) describe how to quantify the hydrodynamic characteristics and morphology of complex channels. In addition to the ability to extract information that is available through conventional methods in the laboratory, the ADCP and MBES (Multibeam Echosounder) can provide additional information that is critical to the understanding and development of modelling processes in rivers, for example providing a 3D view of river hydrodynamics that was previously unavailable to hydrological studies of large rivers.

A major challenge for studies involving large rivers in the Amazon is the operation of flow meters. For example, the United States Geological Survey (USGS) operates more than 7,000 net discharge monitoring stations in the U.S. These stations provide a near real-time data flow from all stations on the Internet, generating data of water column depth, or the flow stage discharge-curves at each location.

However, a significant challenge for large rivers is the fact that the channel bed, sediment and/or sand banks move location over time. Thus, the discharge-curves need to be updated through regular measurements of the depth, breadth and speed of the river at the monitoring stations. Such difficulties have led to the replacement of conventional techniques with measurements of velocity and net discharge. But at the same time, a vast storage capacity for the data obtained is required, especially when the ADCP data are combined with topography. For example, the data storage requirements have increased from the order of hundreds of thousands to the order of millions of bathymetric and hydrodynamic information points (Muste & Merwade, 2010).

This obstacle requires massive investments in instruments with extraordinary data processing abilities in order to store, group, process and quickly distribute data in a myriad of different formats to fulfil information needs of users. On the other hand, the numerical models developed to accommodate the 3D information of hydrodynamics and bathymetry is only available with the use of intensive techniques like ADCP or MBEs.

Dinerhart & Burau (2005) used the ADCP in the Sacramento River (CA/USA) in diurnal tidal rivers for mapping velocity vectors and indicators of suspended sediment. They observed that in surface waters, the ADCP is particularly useful for quickly measuring the current discharge of large rivers with non-permanent flows, presenting several advantages such as visualisations of time based flows and sediment dynamics in tidal rivers.

Another important parameter in the biogeochemical cycle of aquatic ecosystem is the longitudinal dispersion. The longitudinal dispersion coefficient (D) is an important parameter needed to describe solute transport along river currents (Shen et al., 2010). This parameter is usually estimated with tracers. For economic and logistical reasons, the use of the latter is prohibitive in large rivers.

The same authors argue that these shortcomings can be overcome with the use of ADCP simultaneously with tracers in the stretch of river, by examining the conditions under which both methods produce similar results. Thus, ADCP appears to be an excellent alternative / addition to the traditional tracer based method, provided that care is taken to avoid spurious data in the computation of weighted average distances used in the representation of the average conditions of the river stretch in question.

Stevaux et al. (2009) studied the structure and dynamic of the flow in two large Brazilian rivers (the Ivaí and the Paraná) using eco-bathymetry and ADCP together with samples of suspended sediments. This occurred in two phases of the hydrological cycle (winter and summer). The methodology proved to be valid and easily transferable to other river systems of similar dimensions. For example, at the confluences of river estuaries with complex hydraulic interactions resulting from the integration of two or more different flows, constituting a “competition and interaction" environment. This is because continuous changes occur in flow velocity, discharge and structure, in addition to the changes in the physical and chemical properties of water quality and channel morphology. These dynamic systems are very important in river ecology, reflecting many features and limiting conditions of the environment.

According to Stevaux et al. (2009), from a hydrological perspective, the confluences can be considered as likely sites of turbulence and convergent or divergent movements, forming upward, downward or lateral vortices. These effects generate chaotic motion, generating secondary currents of differing velocities and directions, including some that feedback to the flow main current.

For these authors these dynamics induce the main movement of the sediment formed in the river bed and consequently the main source of variation and alteration in the shape of the channel bed. In this case, highlights the main factors controlling mixing in channel confluences: morphological, such as the confluence angle and asymmetry of the channel bed; and hydraulics, such as momentum and contrast in the flow density. These results also confirmed that the identification and understanding of flow mixing at river confluences is very important in studies of pollution, nutrients, dispersal of dissolved oxygen, and other ecological variables (Rosman, 2007; Bastos, 2010; Cunha, 2008; Pinheiro, 2008). The rate of movement of the flow can be used to determine flow predominance in the confluence.

### 3.2 ADCP Measurements in North Channel

According to ANA (2008) measurements occurred in the section of the channel, located between *Amapá* Coast and island of *Marajó*, North Channel of the Amazon River, with the total time to perform the measurement of the 12 hours and 40 minutes.

Due to the effect of tidal flow and the flow directions of the channel of the Amazon River at its mouth, to determine the actual flow of the river the flow is continuously measurement during a tidal cycle. Or more precisely, it is necessary to perform measurement during a wave variation of flow generated due to influence of the tide.

Considering the peculiarities of the flow measurement under the influence of the tide and large transect of the North Channel of the Amazon River at its mouth (about 11.9 km), the traditional methods of measuring flow in large rivers do not apply to flow measurement in this situation.

The measurements of flow at the mouth or the Amazon were only possible through the development of equipment for flow measurement by Doppler effect (ADCP) due to the drastic reduction of time required for measurement and reduction of risk associated. Calculation of the total duration of measurement: the total length is determinate by measurement the time difference between initial and final wave flow due to the tidal cycle, expressed in seconds.

Since the wave due to the tidal cycle can be represented by a periodic wave, the start and end times are obtained by the abscissas corresponding to the intersection points of the flow versus time curve with a straight parallel to the axis "x" vs Q (discharge), whose first derivative has the same sign, i.e. at points where the curve is increasing (positive derivative) or descending (negative derivative). The calculation of the actual flow in the section is done by determining the area under curve Q x t, which corresponds to the total volume of water that passed through the measurement section during the period of the wave flow, divided by the total time duration. Determination of the flow of the North Channel were performed on different days, the first is the simple sum of three part of effective flow rates measured. The second involves the propagation of waves flow measurements performed by the same reference time, the sum of curves "overlapping" and integrating.

The expected outcome of this type of information is the realisation of regular "in situ" hydrodynamic measurements, to understand the relationship between river hydrodynamics and biogeochemical factors along this key stretch of the Amazon River (Transect T2) near Macapá-AP. The idea is to integrate them to control upstream hydrodynamics and biogeochemistry, as well as to understand how the ecosystem may responds to anthropogenic climate change (Fig. 2).

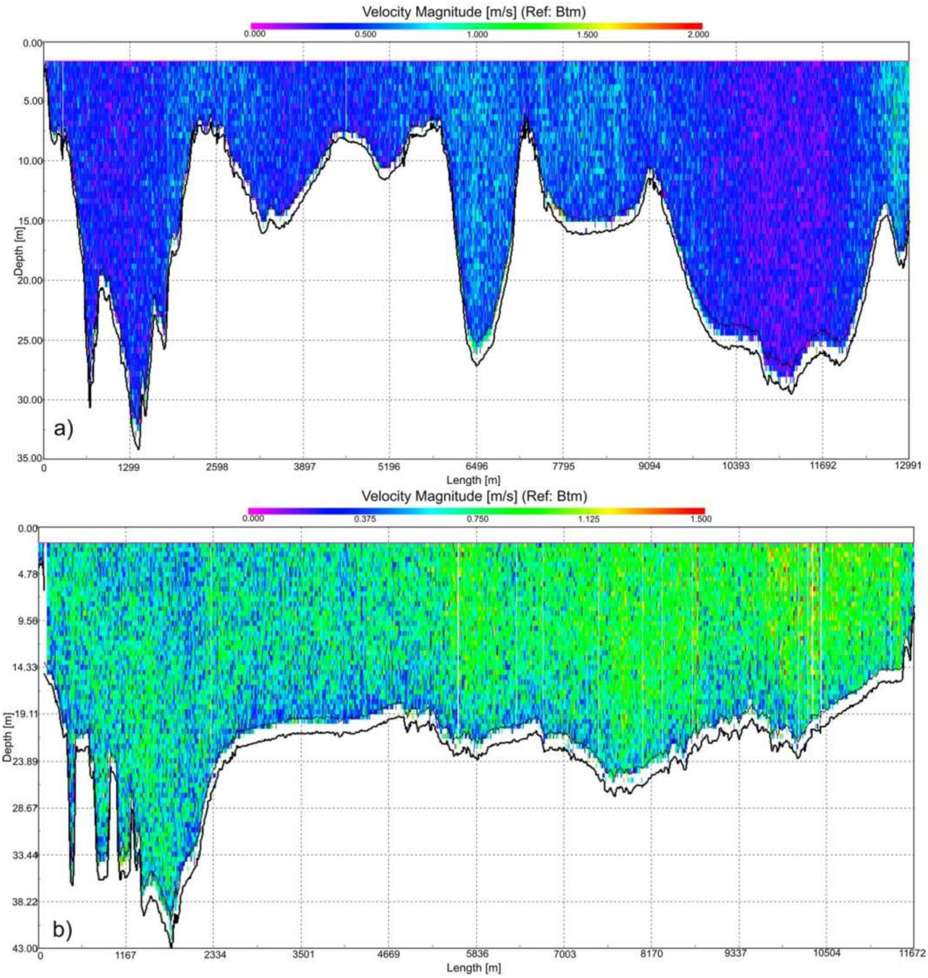


Fig. 2. Net discharge measured with ADCP (600Hz). a) North Channel profile, with $Q = 1.3x10^5$ $m^3/s$ (12/05/2010), b) South Channel, with $Q = 1.2x10^5$ $m^3/s$ (12/07/2010).

## 4. Carbon and nutrient biogeochemistry at the Mouth of the Amazon River

Brito (2010) prepared a review based on some of the main studies from the ROCA project that indicated that the tropical North Atlantic Ocean can be considered a source of approximately 30 Tg C yr-1 into the atmosphere.

But Subramaniam et al (2008) found a carbon sink of similar magnitude with biologically measures of approximately 28 Tg C yr-1 from the atmosphere to the ocean, resulting from nitrogen and phosphorus in the river, in addition to the fixation of $N_2$ in the plume of the Amazon River. Thus, the Amazon plume reverses the normal oceanic conditions, causing carbon capture and sequestration of $CO_2$, defined as the net remover of carbon from the atmosphere to the ocean (Dilling, 2003; Battin et al, 2008; Ducklow et al., 2008; Legendre and Le Freve, 1995).

Subramaniam et al (2008) revealed the importance of symbiotic associations of diazotrophic diatoms (DDAs) in nitrogen fixation in the Amazon plume and showed that the chemical outputs associated with these organisms represent a regionally significant carbon sink. DDAs or other agents of $N_2$ fixation have also been found in other tropical river systems, such as the Nile (Kemp et al., 1999), Congo (AN, 1971), the South of China Sea (Voss et al., 2006) and the Bay of Bengal (Unger et al., 2005), and it is speculated that these have global significance, as a previously neglected biological carbon pump.

These results suggest that techniques used to study inland waterways of the Amazon may be applied to other systems e.g. the Amazon plume. However, knowledge about the magnitude, spatial extent and final destination of this plume is limited. The importance of connections with the processes that occur upstream are also very poorly known. Independent measurements of net community production, diazotrophic production and flow of particles near the surface of the plume agree with the export of carbon (Subramaniam et al., 2008), but the ultimate fate of carbon and nitrogen and the sensibility of the plume front to global climate change are currently unknown.

The microbial community is a driving force behind the processing of material along the Amazon continuum, from land to sea. Cole (2007) suggested that the biosphere should be considered as a metabolically active network of sites that are interconnected by a fluvial network.

Despite indications that the organic carbon derived from soil is resistant to degradation on land, remaining stored for decades or centuries (Battin et al., 2008), once released into aquatic ecosystems, there is evidence that this carbon is dissolved rapidly in the rivers in a matter of days or weeks (Cole & Caraco, 2001).

High levels of $CO_2$ and low $O_2$ concentrations are often found in muddy rivers (Brito, 2010) which suggests that organic carbon derived from the soil represents a substantial carbon source for the heterotrophic network of the river ecosystem (Richey, 1990).

Current knowledge about the diversity and dynamics of bacterioplankton comes almost exclusively from studies of lakes (Crump et al., 1999). Various small rivers have also been sampled (Cottell et al., 2005; Crump & Hobbie, 2005), but from 25 of the world's major rivers, only four had their genetic sequences recorded in the bacterioplankton "Genbank" (National Center for Biotechnology and Information, U.S. National Library of Medicine): the Columbia River, USA (Crump et al., 1999), the Changjiang River, China (Sekigushi et al, 2002), the Mackenzie River, Canada (Galand et al., 2008) and the Paraná river, Brazil (Lemke, 2009).

The lack of information regarding bacterioplankton in large rivers limits understanding of global biogeochemical cycles and the ability to detect community responses to biotic and anthropogenic climate impacts in these critical ecosystems (Crump et al., 1999).

In less turbid areas of the continuum, the process of photosynthesis can reduce or even reverse the $CO_2$ emission rate (Dilling, 2003). Likewise, when the river meets the sea, the loss of suspended sediment increases the penetration of light sufficiently to stimulate marine primary production (Smith & Demaster, 1995). Once light has been removed as a limiting factor nutrients released by river “metabolism” allow phytoplankton blooms, whose community structure is probably dependent on concentrations and ratios of (limiting) nutrients such as nitrogen, phosphorus and iron (Dilling, 2003; Subramaniam et al., 2008).

One of the main unifying conceptual frameworks in biological oceanography is the idea that the structure of the phytoplankton community profoundly affects the export and sequestration of organic material. That is, the biological carbon pump and chemical nutrient cycles (Michaels & Silver, 1988; Wassman, 1988; Peinert et al., 1989; Legendre & Le Fevre, 1995, Ducklow et al., 2001).

Cyanobacteria are recognised as a particularly important group of organisms in the carbon cycle, occurring in a wide variety of ecosystems, especially in aquatic environments. Cyanobacteria can survive in extreme conditions and are found in habitats with wide ranges of temperature, salinity and nitrogen availability (Falconer, 2005). The abundance of cyanobacteria varies seasonally, as a consequence of changes in water temperature and solar radiation as well as weather conditions and nutrient supply (Falconer, 2005). It is known that their distribution it is not homogeneous on the surface or in water column. The distribution of cyanobacteria assemblages may vary depending on gradients such as depth, salinity, temperature, space and seasonality. However, as well as a lack of studies in this area, it is difficult to analyze the dynamics and diversity of planktonic groups such as cyanobacteria, especially when the analytic scale is at the species level, where diversity is high and the river area to be sampled is enormous.

### 4.1 Methods and preliminary biogeochemistry results of transect T2

In the North and the South Channel in Amapá, sampling of water quality was conducted with i) quarterly and ii) in the Channel North monthly frequency (Brito, 2010). Quarterly collections are used to obtain vertically and horizontally integrated samples for the calculation of dissolved and particulate loads in the water column with the use of 15 to 20 metre boats. The monthly samples are used for seasonal interpolation and are obtained from the surface and 60% of water depth. The measures routine collected are used to derive parameters relating to the ion and nutrient system, carbonates, organic material, water discharge and suspended sediment.

The depth and surface samples are obtained by immersion pumps, where water is then pumped into a graduated cylinder of 2 litters, which is flooded for at least three times prior to sampling and the overflow is maintained during the procedures sampling.

Transect T2 (Table 1) defines the main flow of the river to the north of the island of Marajo. As sea water never passes the dividing line at the mouth of the river in front of the city of Macapá (Nikieme et al., 2007), this is considered a final a purely fluvial compounent of the river.

| Point | Local | Coordinates | |
|---|---|---|---|
| Left Bank - North Channel | Amazon | S0 03 32.2 | W51 03 47.7 |
| Middle River - North Channel | Amazon | S0 04 35.9 | W51 01 46.7 |
| Right Bank - North Channel | Amazon | S0 05 01.9 | W51 00 21.9 |
| Left Bank - South Channel | Amazon | S0 09 51.8 | W50 37 48.9 |
| Middle River - South Channel | Amazon | S0 10 43.0 | W50 36 59.4 |
| Right Bank - South Channel | Amazon | S0 11 59.8 | W50 35 59.7 |

Table 1. Geographical coordinates of sampling sites

The graduated cylinder 2 liters are removed aliquots with syringes of 60 mL for routine analysis of chemical parameters $Na^+$, $K^+$, $Ca^{2+}$, $Mg^{2+}$, Al, Si, $Cl^-$, $SO_4^{2-}$, $NO_2^-$, $NO_3^-$, $NH_4^+$, $PO_4^{3-}$, total nitrogen and dissolved organic carbon (DOC). Chemical parameters for the samples are filtered using cellulose acetate filters with pore size 0.45 micrometres in bottles of high density polyethylene capacity of 60 mL containing 6 mg of thymol as a preservative. For DOC, samples are filtered in triplicate using glass fiber filters preheated (500 °C for 5 hours) GFF type with pore size 0.7 mm, in glass vials of 25 mL, also preheated. Samples are preserved with 25 mL of HCl 50%.

In situ measurements (meter used) are: electrical conductivity (Amber Science 2052); pH and temperature (Orion 290A plus), and dissolved oxygen (DO) with the YSI 55 meter.

To fill the collection tube, using the same technique of overflow, ten bottles of glass BOD (Biochemical Oxygen Demand) of 60 mL for measurements of respiration rates are used. Of these, five bottles are preserved with 0.5 mL of manganous sulfate and 0.5 mL of sodium azide and five bottles are incubated in coolers containing water from the river, staying in the dark for 24 hours.

To measure the concentration of suspended sediment in the water, are filled with twenty gallons of polyethylene-liter and transported to the laboratory for further processing to separate the coarse particles (up to 63 µm) of fine particles (between 0 and 63 µm, 45 µm) samples.

The sampling parameters of fecal coliform and Escherichia coli, coliform, sterile bags are made directly from the collector tube connected to the pump.

During the sampling process, a phytoplankton net (63µm mesh) is submerged in the side of the boat to collect coarse sediments. At the end of sampling, the content network is rinsed polycarbonate flask of 250 ml wide mouth and preserved with 250 mL of HCl 50%. To measure the isotopic composition of carbon and nitrogen.

To measure the concentration of dissolved $CO_2$, water is pumped through a closed plexiglass tube in which a small part is filled with air, this air is pumped out of the pipe to a device called a $CO_2$ analyzer IRGA (InfraRed Gas Analyzer ) Licor LI820 model, after passing through the analyzer back to the air pipe to reach the equilibrium (Cole et al, 1994. With modifications). Expected to balance the flow of air, so it made measurements of $CO_2$ dissolved in water for 5 minutes.

The flux measurements of $CO_2$ in surface water are made by the same method, but instead of the plexiglass tube to balance the flow of $CO_2$ it uses a static camera that is floating on the surface of the river connected to tubes to circulate air to the IRGA for 5 minutes.

In addition, samples are collected to characterization of phytoplankton for identification and determination of density.

Table 2 shows the preliminary results of some parameters obtained in the first gathering held in the channel north, following Brito (2010):

With preliminary data observed, we cannot make qualitative and quantitative analysis representative. But we can highlight some features of the river, such as the harmony of the data of surface and depth, the good condition of dissolved oxygen in water, acid pH which is a characteristic of the Amazonian rivers, the presence of considerable amounts of iron in water, low water hardness, the presence of nutrients in the water and the high level of carbon dioxide dissolved in water (mass transfer through air-water interface).

| Station | Depth (m) | Time | Conductivity (µS/cm) | $O_2$ CENA (mg/L) | $O_2$% CENA | $O_2$ UNIFAP (mg/L) | $O_2$% UNIFAP | Temperature (ºC) | pH | $CO_2$ Air (ppm) | $CO_2$ water (ppm) | DIC (mg/L) | Alkalinity (mg/L) | Respiration (µM/hour) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Left Bank Surface | 0.50 | 18:55 | 45.70 | 5.80 | 76.90 | 6.05 | 80.20 | | 6.62 | 477.91 | 2059.30 | 9.02 | 8.98 | 1.223 |
| Left Bank Depth | 15.00 | 18:20 | 46.50 | 5.87 | 77.60 | 6.08 | 78.10 | 30.00 | 6.78 | - | - | 9.06 | 9.17 | |
| Half Surface | 0.50 | 16:10 | 46.60 | 7.13 | 94.30 | 6.09 | 81.40 | 30.80 | 6.95 | - | - | 9.13 | 9.38 | 1.882 |
| Half Depth | 20.00 | 16:30 | 52.10 | 5.06 | 92.10 | | | 31.30 | 6.79 | - | - | 9.25 | 9.35 | |
| Right Bank Surface | 0.50 | 12:00 | 46.70 | 6.10 | 81.40 | 6.00 | 79.70 | 30.50 | 6.91 | 415.88 | 1628.31 | 9.29 | 9.21 | 0.430 |
| Right Margin Depth | 18.00 | 11:40 | 46.70 | 5.87 | 78.20 | 5.75 | 76.30 | 30.30 | 6.84 | - | - | 9.26 | 9.50 | 0.192 |

| Station | Al (mg/L) | Fe (mg/L) | Ca (mg/L) | K (mg/L) | Mg (mg/L) | Na (mg/L) | $Cl^-$ (mg/L) | $SO_4^{2-}$ (mg/L) | Si (mg/L) | $PO_4^{3-}$ (mg/L) | $NH_4^+$ (mg/L) | $NO_3^-$ (mg/L) | $NO_2^-$ (mg/L) | TN (mg/L) | DOC (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Left Bank Surface | 0.00 | 0.22 | 3.40 | 0.59 | 0.57 | 0.91 | 3.71 | 3.24 | 3.29 | 0.02 | 0.00 | 0.61 | 0.04 | 0.27 | 4.11 |
| Left Bank Depth | 0.00 | 0.21 | 3.69 | 0.61 | 0.60 | 0.95 | 2.65 | 3.51 | 3.31 | 0.05 | 0.00 | 0.45 | 0.04 | 0.28 | 4.42 |
| Half Surface | 0.00 | 0.22 | 3.66 | 0.64 | 0.59 | 0.90 | 2.11 | 3.73 | 3.31 | 0.04 | 0.02 | 0.61 | 0.03 | 0.26 | 3.69 |
| Half Depth | 0.00 | 0.20 | 3.73 | 0.62 | 0.60 | 0.91 | 2.23 | 4.05 | 3.32 | 0.03 | 0.02 | 0.61 | 0.03 | 0.25 | 4.42 |
| Right Bank Surface | 0.00 | 0.25 | 3.74 | 0.62 | 0.60 | 0.90 | 2.27 | 3.88 | 3.36 | 0.03 | 0.00 | 0.39 | 0.04 | 0.26 | 3.69 |
| Right Margin Depth | 0.00 | 0.11 | 3.73 | 0.62 | 0.60 | 0.91 | 2.34 | 4.08 | 3.27 | 0.03 | 0.00 | 0.65 | 0.04 | 0.25 | 3.95 |

Table 2. Preliminary results and physical-chemical in Transect T2, in the North Channel (two water sampling).

## 5. Numerical modeling

The propagation of the tidal flow in estuaries is a complex free surface problem. It is unsteady oscillatory and therefore may have reversal flow that is not uniform. The equations governing the flow (conservation of mass and movement) are not linear due to friction, the spatial variations velocity and changes in the dimension of the estuary (Gallo, 2004, Cunha, 2008). Thus, to resolve the hydrodynamic in general and the propagation of the tidal estuary, taking into account this complexity, it is necessary to use numerical models to represents the average flow.

According to Versteeg & Malalasekera (1995) a turbulence model can be considered a computational procedure applied to close the system of equations used to represent the average flow, and calculations applicable to a variety of generic problems regarding flow dynamics. The authors state that one of the models most useful in solving the set of equations to be solved for the transport of Reynolds stresses is the $k$-$\varepsilon$ model. The standard $k$-$\varepsilon$ model presents two equations, one for $k$ and one for $\varepsilon$ based on our understanding of the processes that cause relevant changes in these variables. The turbulent kinetic energy $k$ is defined as the variance of velocity fluctuations and $\varepsilon$ is the dissipation of turbulent kinetic energy (the rate at which turbulent kinetic energy is dissipated in the flow). $k$-$\varepsilon$ turbulence model and the SST (Shear Stress Tensor - a more complex variant of the $k$-$\varepsilon$ model) were used respectively for closing the Reynolds equations (Cunha, 2008; Pinheiro & Cunha, 2008).

Cunha (2008) and Pinheiro & Cunha (2008) conducted two case studies with numerical models using the software CFX/ANSYS 1) coastal area on the coast of the city of Macapá, and 2) the Matapi River, near the Industrial District of the city of Santana (0° 0'32.53"S, 51°12'7.43"W) (Fig. 3a and 3b). In both cases, the objective was to study the dispersion behaviour of pollutant plumes into surface waters in the estuary of the Lower Amazon and their behaviour during a semi-diurnal tidal cycle.

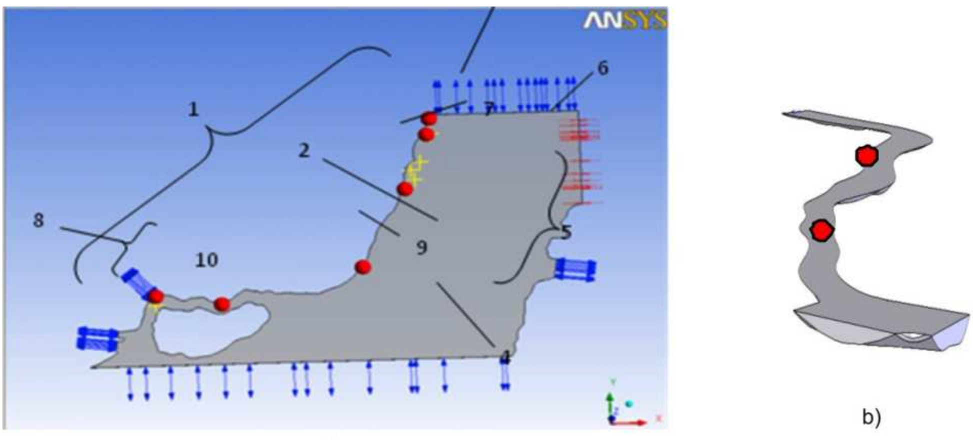


Fig. 3. Pre-processing within a CFX (Computational Fluid Dynamics) study of the dispersion of pollutants in the estuarine zone next to Macapá: a) Macapá and Santana Coast; b) Matapi River (point 8 in Fig. 3a), near the Island and Industrial District of Santana-AP.

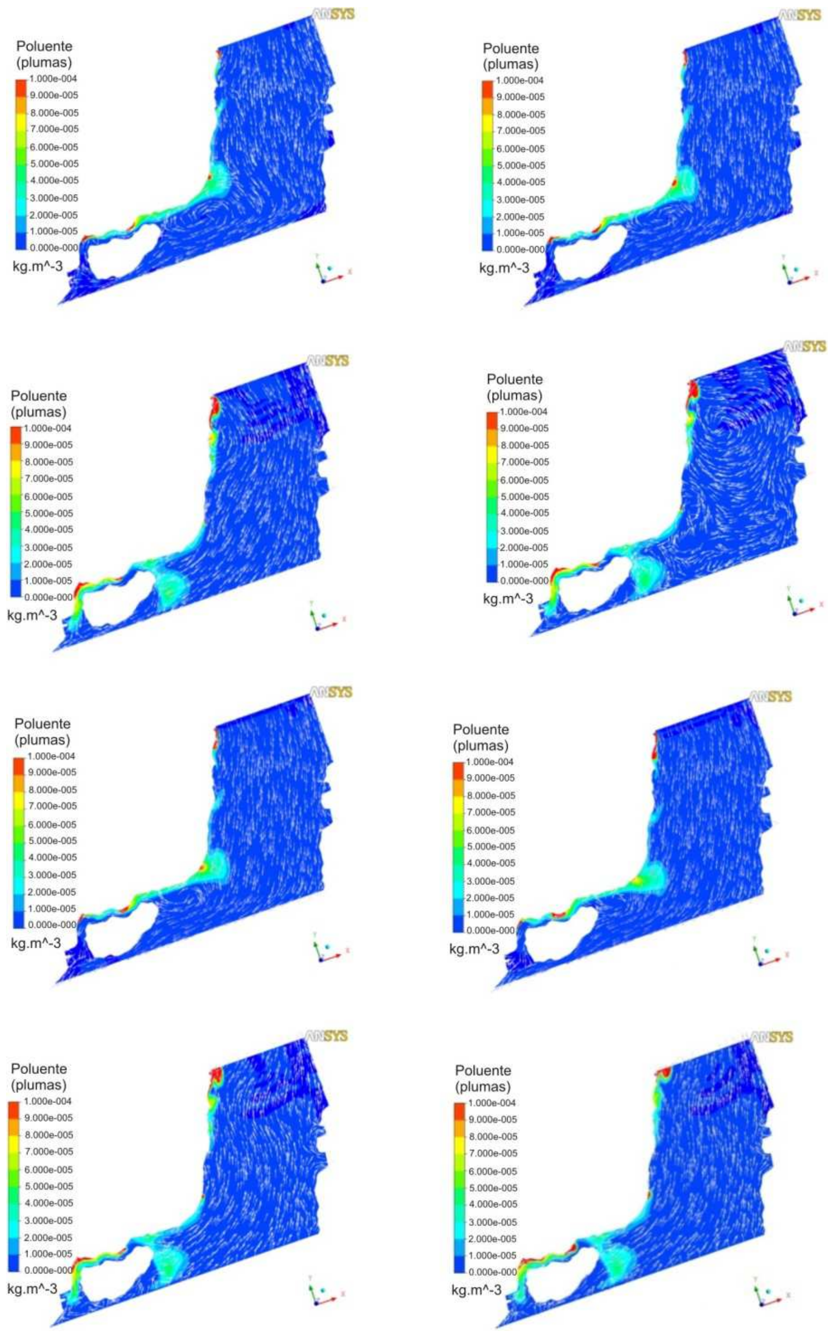


Fig. 4. Velocity and dispersion of pollutants in natural runoff - in the coast of the cities of Macapá and Santana. Representation of a semi-diurnal tidal cycle.

Fig. 3a illustrates the pre-processing step for simulation of pollutant dispersion and demonstrates the complex geometrical configuration required to represent the turbulent flow. There are six continuous pollution sources in the cities of Macapá and Santana, from the mouth of the Matapi River (southern area) to the north of the city, the upper area of the figure. The natural flux of flows passes from the bottom (left) to top (far right, in the north and northeast). The continuous point sources of pollutants are represented by red circles along the coast, which represent the main release points of untreated pollutants into the waters in Macapá and Santana cities (Pinheiro & Cunha, 2008). The same representation occur in Rio Matapi indicated by Fig 3b (Cunha, 2008).

Fig. 4 shows the results of the simulations of pollutant dispersal plumes (light blue and reddish margins) during a tidal cycle. These maps show that the plumes tend to stay close to the shore. From left to right (top row) is the initial phase of a simulated low tide (approximately 7 hours). Again, from left to right (bottom row) begins the high tide phase (approximately 5.5 hours). During the tidal cycle it was possible to simulate the complex interactions between hydrodynamics and a coupled scalar (hypothetical pollutant), with an emphasis on the dynamic plumes between mainland Santana and the island of Santana.

Case study 2 (Fig. 5), shows the phases of the dispersion of pollutant plumes (hypothetical tracer) in the Matapi River during a tidal cycle. The flow pattern (streamlines) changes significantly over a period of the semi-diurnal tide. Simulating the dispersal of pollutants indicates a remarkable complexity in the flow, depending on the geometry of the river channel and the timing of the reversal of the tidal cycle.

In Fig. 5, from left to right depicts changes in pollutant plumes during low tide (approximately 7 hours), during a complete semi-diurnal tidal cycle, where the natural flux of the tide flows from top to bottom. The reverse shows the rising tide.

In Fig. 6, from left to right, there are three different flow fields indicated: a) velocity vectors, b) streamlines (paths of constant speeds), c) dispersion pattern of the scalar from two (hypothetical) continuous point sources of pollutants.

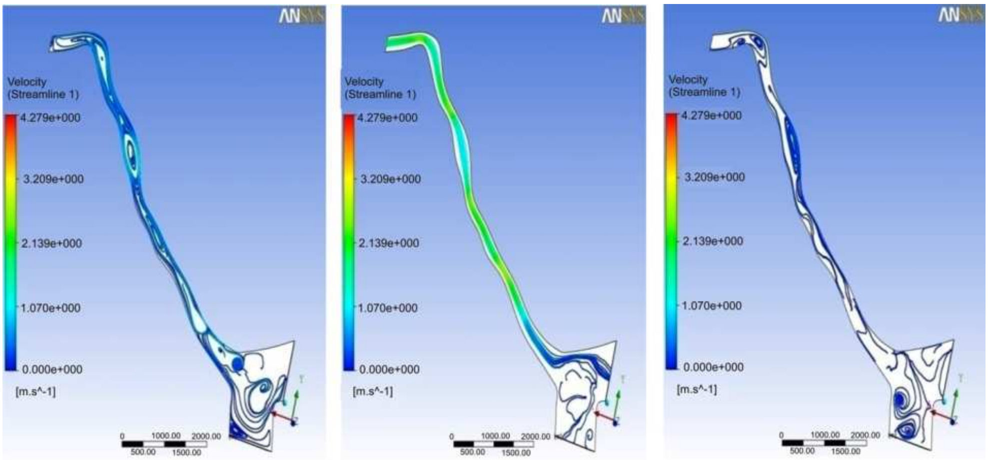


Fig. 5. Lines of transient currents in the Rio Matapi: a) low tide at t = 1h, b) end of the ebb at t = 5.5 h, c) reversal of the tide at t = 6h.

In both case studies, despite the sophistication of the numerical analysis, technical advances such as calibration and validation of models are still necessary. The complexity of the process involving modelling steps, proceedings to investigate the aquatic biogeochemistry and hydrometry of large rivers have yet to beovercome in the estuarine region of Amapá.

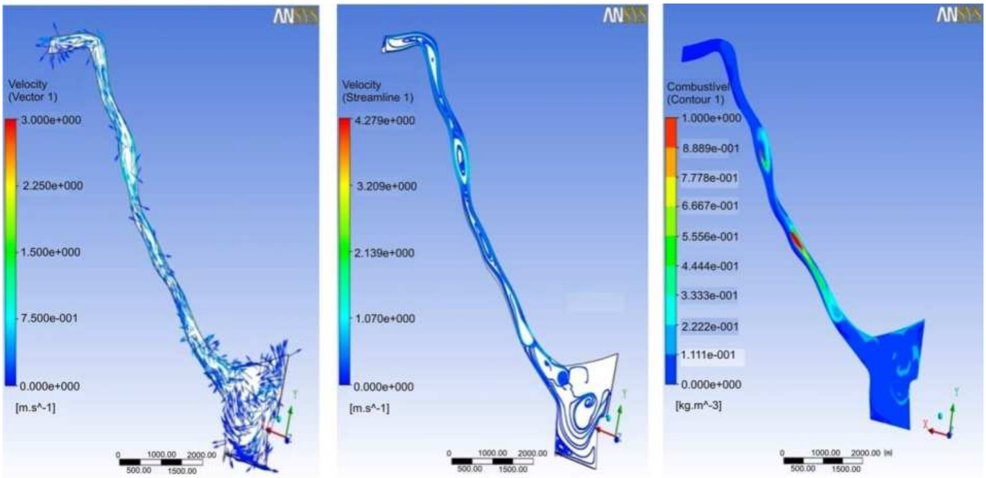


Fig. 6. Low and rising tides. t = 360 min (6.0 h). a) Velocity; b) Stream line; b) Plume Concentration.

## 6. Conclusions

The main conclusions of this research are:

In the estuarine region of the Lower Amazon River, in the state of Amapá, the measurement of net discharges of large tidal rivers is only feasible with the use of devices such as ADCP to integrate hydrodynamic processes and water quality variables (biogeochemical cycle and interaction between the plume of the Amazon River and Atlantic Ocean).

Relevant hydrodynamic parameters such as velocity profiles, stress and identification of background turbulent flow velocity components need to be determined with the aid of modern equipment whose operation must be efficient and economic for hydrometric quantification in complex estuarine environments.

Bathymetric analyses, at the scales of interest, have been a difficult hurdle to overcome because of the intricate system of channels in the Amazon River.

The logistics required for experimental studies in large rivers is a major obstacle that has inhibited research interest in this poorly studied area.

A major challenge to be overcome in systematic studies of water quality parameters is the generation of local physical parameters, such as rating curves, rates of sedimentation and resuspension of sediments, etc, which are a fundamental input for complex numerical models of water quality.

The modelling of water quality in the Amazon estuary is complex due to the absence and / or inadequacy of data describing different physical characteristics. The drainage system imposes enormous difficulties in this area. An example is the absence of long-term time series to obtain necessary parameters and coefficients to build numerical models.
Hydrodynamic simulations of flow and dispersion of pollutant plumes released into the environment are difficult to implement, and require calibration and verification with local data that are not always available.
Existing techniques in numerical modelling can become strong allies in informing public policy and the management of regional water resources.
Among the parameters of interest from numerical models, the generation of 3D computational meshes is potentially the most important source of novel information.
The development of local expertise constitutes one of the biggest challenges in the area, since the best and most efficient option for development of experimental studies in hydrodynamics and computer simulation, is the formation of local human resources. The main advantages are lower operating costs for complex experimental campaigns.
The implementation of a database accessible to the interested user would also be an important technological challenge for the systematic studies of the hydrodynamics and water quality at this region. Thus, would be possible to improve our understanding about the ecosystem functioning and to evaluate the complexity of the Amazon estuary and the role of carbon cycle in these environments.

## 7. Acknowledgements

This research is part of the ROCA project (River-Ocean Continuum of the Amazon), funded by the Gordon and Betty Moore Foundation. The main collaborating institutions are the Center for Nuclear Energy in Agriculture - CENA / USP, the National Institute of Amazonian Research - INPA, the Museu Paraense Emilío Goeldi - MPEG, Federal University of Pará - UFPA and the Federal University of Amapá - UNIFAP (Postgraduate Program in Tropical Biodiversity / PPGBIO and the Laboratories of Simulation and Modeling, Chemistry and Environmental Sanitation / Undergraduate Program in Environmental Sciences). This study was supported by the National Research Council (CNPq/MCT – Productivity Fellowship (Process N. 305657/2009-7), and by the Institute of Scientific and Technologic Research of the Amapá State (NHMET & CPAC/IEPA) and by the Tropical Biodiversity Postgraduate Program (PPGBio) of the Federal University of Amapá (UNIFAP), Brazil; SUDAM Project - "Integrated Network Management for Monitoring and Environmental Dynamics Hydroclimatic State of Amapá"; REMAM II Project/FINEP/CNPq – Extremes Hydrometeorology and Climate Phenomena; and Project CENBAM-FINEP/CNPq/FAPEAM/UNIFAP - INCT "Center for Integrated Studies of Amazonian Biodiversity".

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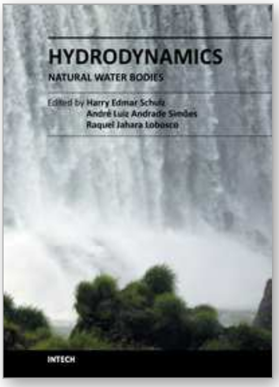


**Hydrodynamics - Natural Water Bodies**
Edited by Prof. Harry Schulz

ISBN 978-953-307-893-9
Hard cover, 286 pages
**Publisher** InTech
**Published online** 05, January, 2012
**Published in print edition** January, 2012

The knowledge of the characteristics of the fluids and their ability to transport substances and physical properties is relevant for us. However, the quantification of the movements of fluids is a complex task, and when considering natural flows, occurring in large scales (rivers, lakes, oceans), this complexity is evidenced. This book presents conclusions about different aspects of flows in natural water bodies, such as the evolution of plumes, the transport of sediments, air-water mixtures, among others. It contains thirteen chapters, organized in four sections: Tidal and Wave Dynamics: Rivers, Lakes and Reservoirs, Tidal and Wave Dynamics: Seas and Oceans, Tidal and Wave Dynamics: Estuaries and Bays, and Multiphase Phenomena: Air-Water Flows and Sediments. The chapters present conceptual arguments, experimental and numerical results, showing practical applications of the methods and tools of Hydrodynamics.