MORPHOLOGICAL EVOLUTION OF FLUVIAL AND ESTUARINE SEGMENT FLOWS

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Abstract: Fluvial sedimentological equilibrium is reached when the sediment load discharging into a longitudinal segment equals the solid phase leaving that stretch. In such segments, natural and anthropogenic phenomena may occur as, for example, the formation of sand banks and beaches, erosion, mud slumps, silting, formation of meanders, oxbows and riverbed configurations, with expressive ecosystem interferences. In this paper, the following are shown: (i) qualitative and quantitative descriptions of the hydrodynamic, sedimentological, morphological and phytosociologic processes within fluvial and estuarine systems; (ii) validation and modernization of the methodology for hydrosedimentologic studies developed in Brazil; (iii) the importance of land, bathymetric, remote sensing surveying and (iv) application and validation of this methodology in Brazilian open channels systems. Qualitative and quantitative cases are outlined: (1) Sedimentological and morphological aspects of the *Paraguay* River in the *Pantanal of Mato Grosso* State. (2) *Morro Grande* bathymetry estimate of the *Preto* River Reservoir, in the state of *Rio de Janeiro*, using Remote Sensing analysis. (3) Hydrodynamic, sedimentological and morphological aspects of a *São Francisco* River stretch, and (4) the phytosociologic problems carried out by the diversion of the *Macacu* River into the *Guapimirim* River, which cross one of the few remnant mangrove areas in the *Rio de Janeiro* State. Results showed that the periodic land, bathymetric and Remote Sensing surveys are indispensable tools for the qualitative and quantitative descriptions of the sediment movements in open channel flows methodology.

INTRODUCTION

In open channel flows two phases move: a liquid, governed by the laws of Fluid Mechanics and a solid, composed of sediment particles, which moves in contact with the river bed, or in suspension in the middle of the turbulent flow (Wilson-Jr., 2009). When the mass of sediment that penetrates some stretch is equal to the mass that flows out of it in a period of time, it is said that the sedimentological equilibrium was achieved. The size of the stretch and the period of time that characterize this equilibrium define the scales - spatial and temporal - of the morphological process in the stream. In fluvial flows, the equilibrium time scale is a multiple of a hydrological year. The mean longitudinal profile of a river stretch, for example, remains stable during this period of time. However, in the equilibrium segments, natural morphological phenomena of disequilibrium may occur during a hydrological year, as: meandering, sand banks, erosion, mud slumps, cut-off, silting, and others. Sub-stretches of sedimentological disequilibrium appear and advance along the stretch their analysis depending on the spatial scale of observation.

Anthropogenic interferences in the river's bed and on the watershed add up to these phenomena, and must be detached and controlled, because they are capable of modifying the equilibrium conditions of the stretch, with severe consequences to the environment, engineering projects, and specifically to the phytosociological processes.

OBJECTIVES AND STUDIED CASES

The main objectives of this paper are: (i) To consider the concatenation of hydrodynamic, sedimentologic, morphologic and phytosociological processes within fluvial and estuarine systems; (ii) To present a Brazilian methodology for hydrosedimentologic studies in watersheds, (iii) To emphasize the importance of land, bathymetric and Remote Sensing surveys as special measurements to calibrate these studies, and (iv) To apply this methodology in fluvial systems.

Four Brazilian cases were outlined: (1) Sedimentologic and morphological aspects of the *Paraguay* River in the *Pantanal Matogrossense*, MS; (2) *Morro Grande* Reservoir bathymetric estimate using Remote Sensing, RJ; (3) Morphological aspects of a *São Francisco* River stretch, BA, and (4) Phytosociological problems carried out by the diversion of a river into a remnant mangrove area in the *Rio de Janeiro* State.

METHODOLOGY OF SEDIMENTOLOGICAL AND MORPHOLOGICAL PROCESSES

Sediments are placed in motion or have their movement changed by the natural elements' action, e.g. rain, currents, winds, waves, tides; and by human interventions in the river bed and the watershed basin, that sum out with the natural ones, as: dams, navigation, dredging, mining, waste, deforestation, irrigation, sport, leisure and touristic activities (Figure 1). In other words, the sediments are placed in motion or have their movement changed, every time the river bed and watershed suffer an alteration. Then, two types of solid movement can occur in fluvial streams: (i) Movement of sediments from the river bed that either move in contact with the bed most of the time, or in suspension; (ii) Movement of sediments from the watershed basin, mostly carried out by the rain, generating the wash-load. These sediments are finer than the bed load material and are transported in suspension, by the river, through long distances.

Depending on the case, a non-linear relationship between the liquid flow and the bed sediment discharge is possible:

$$q_b = a\, q^{n_s} \tag{1}$$

where q_b = the solid discharge per unit width, in mass, force or volume per time; q = liquid flow, that can be expressed in the same units. a and $n_s > 1$, are positive constants, that depend on the hydrosedimentological characteristics of the river stretch.

However, the wash load movement, which corresponds to the quickest response of the river to the fluvial basin modification, relates directly to the soil loss in the watershed. Thereby, to estimate the solid discharge of river stretches, it is essential to distinguish and to know the sources of sediments that are being transported and spread over the studied reach.

For some decades, Wilson-Jr. (2009) has dedicated himself, through tests in laboratory channels, creeks, brooks, rivers and estuaries, to developing a methodology to characterize sediment motion in open channel flows. This methodology allows the simultaneous application of bathymetric, hydrometric and sedimentometric measurements, the use of tracers (radioactive, chemicals and fluorescent), Remote Sensing and GIS.

According to this methodology, for the sediment motion description in water streams, three steps are necessary (Figure 2) (Wilson-Jr., 1999, 2009): (i) Knowledge of the watershed; (ii) *In-situ* measurements of the solid motion, in a representative reach of the flow, and during these measurements' period; (iii) Determination of the hydrodynamic, sedimentologic and hydrometeorological characteristics of the representative watershed segment.

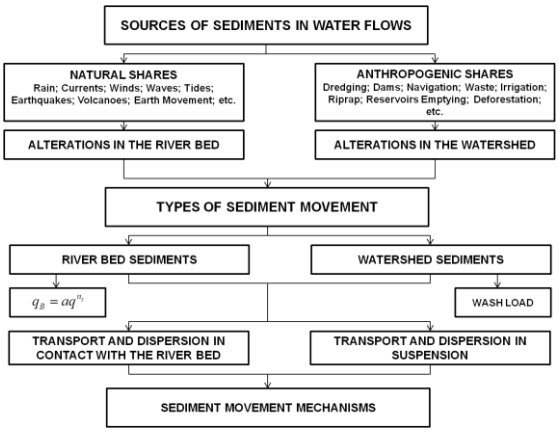

Figure 1. Sources and types of sediment movements (Wilson-Jr., 2009)

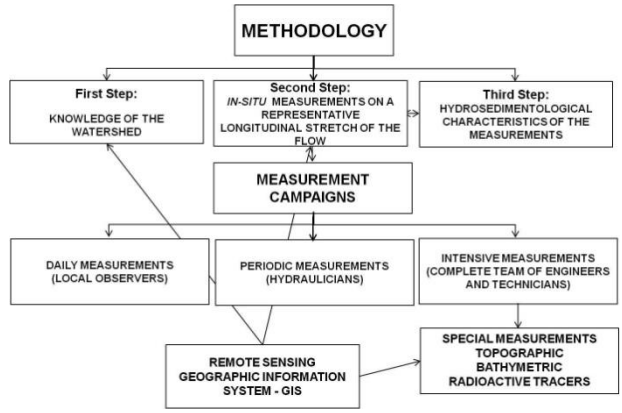

Figure 2. Methodology for sedimentological and morphological studies in open channel flows (Wilson-Jr., 1999, 2009)

First step: Knowledge of the watershed basin

The knowledge of the watershed delimited by the project involves the understanding of their geographic, geologic, hydro-meteorological, sedimentologic, socio-economic and historical characteristics, among others. Knowledge of these characteristics comes from office and field works, and involves the interaction of specialists in these specific fields. In this step, the aerial photography, satellite images and GIS techniques are very useful. They allow identifying fixed (topographic, pedology) and varying (forest cover and soil type) characteristics of the basin, which condition the water and sediment contributions.

Second step: *In-situ* measurements campaigns

It is recommended that the hydrosedimentological measurements in the river be conducted in a stretch of uniform flow and that its hydrodynamic and morphological characteristics be representative of a great extension of the flow. However, in many cases, the studied river stretch is determined by the project: the erosion downstream of a dam, the aggradation of a hydroelectric power plant reservoir and a complex navigational stream due to its sediment banks are some examples. For the quantification of the sediment movement in this representative river stretch, three superposed measurements campaigns are necessary: daily, periodic and intensive.

Daily measurements campaign

This consists of the water level record and the water sample collection to determine the concentration and granulometry of the suspended sediment. These daily values, along with the pluviometric and evaporation data, characterize the hydrologic cycle considered.

Periodic measurements campaign

They must be performed as a function of the hydrometeorological conditions, as a complement to the daily observations. They consist of, e.g. velocity measurements and liquid discharge calculations; watershed erosion and aggradation monitoring; detailed sample of the bed sediments; bathymetric survey, including the measurement of the waterline and bed slopes, flood levels, bed forms records, water flow and watershed basin morphological characteristics.

Intensive measurements campaign

Performed in well defined hydrological conditions, generally during the rainy seasons, when there is a larger sediment production, or during the average discharge period, when there is a sediment

motion representative of the bed forming discharges. Intensive measurements are performed at the same time as the ones of the previous campaigns and include: longitudinal bathymetry of the stretch, bed forms records and special measurements of the bed sediment discharges.

Third step: Hydrometeorologic characteristics during the *in-situ* measurements

The information obtained during the measurements campaign, especially those obtained during the Intensive Measurements Campaign, are limited in time and to defined hydrometeorological conditions, which need to be well known, so the data can be extrapolated.

Special measurements of the sediment movement

The periodic observations campaign results enable the definition of analytical relations between hydrodynamic and sedimentological quantities for the representative river stretch. The daily campaign allows those relations to be extended to hydrological cycle(s). However, the special measurements results are the ones that enable the **calibration** and **validation** of the analytical expression and models obtained. This methodology was developed in Brazil with the use of radioactive tracers and bathymetric surveys as special measurements. It was successfully applied in the *Ivai* River's watershed, in *Paraná* State (Wilson-Jr. *et al.*, 1980). The radioisotopes technique has been very efficient as a selective criterion of bed load formulas. In the *Ivai* River, the methodology enabled the selection of classic sediment motion formulas and their validation through comparison with data obtained by labeled sediments with radioisotopes. The use of tracer techniques enables the determination of kinematic and dynamic characteristics of the flow and sediment. They provide accurate data of the amount transported; sediment trajectories and velocities; residence time in the water flow; liquids and solid circulation; dispersion of liquid pollutants and of those fixed on sediments.

However, as the usage of radioisotopes in open channel flow is restricted to the Nuclear Energy Institutes, other methods are being considered for the direct measurement of sediment motion. In this paper, the usage of Remote Sensing technique and GIS as special measurements is considered, along with bathymetric surveys, for models calibration and validation. This technique is also being used for the knowledge of the watershed basin, as schematized in Figure 2. Following, four Brazilian cases were selected to illustrate the use of special measurements to calibrate and validate the descriptive models of sediment in open channel flows. The regions were the studies took place were outlined in the Figure 3.

Figure 3. Regions where studies were realized

SEDIMENTOLOGICAL BALANCE OF THE FERRADURA ISLAND STRETCH OF THE *PARAGUAY* RIVER (CASE I)

The morphological evolution with time, of a bed stretch of the *Paraguay* River was performed through comparisons between the topobathymetric measures taken in different occasions by the Brazilian Navy and published in 1:10,000 scales. The considered stretch, in which it was possible

to count on two measurements, was that of *Ferradura* Island, in Km 1255 of the *Pantanal* International Waterway. The bathymetries of the Figures 4 and 5 were made in 1974 and 1994, respectively, allowing for the stretch's morphological comparison in this 20-years period. Erosion and sedimentation rates were determined through the calculation of liquid and solid volume variations between the limits established for the stretch. Three methods were used: Contour Lines, Cross Sections Methods and Software Surfer® 7.0's use (Wilson-Jr. and Andrade, 2000).

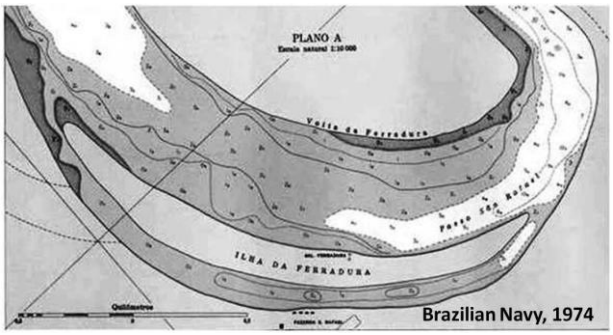

Figure 4. Topobathymetric measures on the *Ferradura* Island Region of the *Paraguay* River at 1974

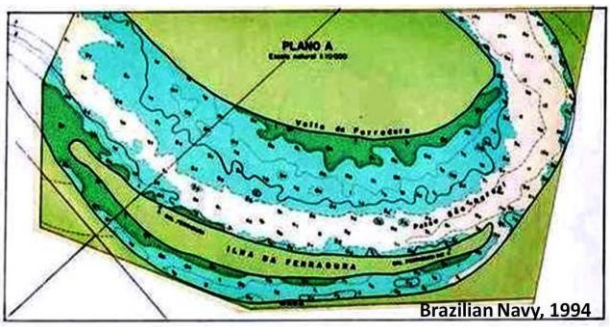

Figure 5. Topobathymetric measures on the *Ferradura* Island Region of the *Paraguay* River at 1994

The **Contour Lines Method** is based on the determination of the areas corresponding to each water level. For a better visualization of the area to be determined, a plane cutting the river segment in the desirable level is considered. The superior flooded areas also contain the interior levels' areas. Thus, obtaining the values of the areas corresponding to each level, a graph of flooded areas as a function of the water level can be constructed, and through the resulting curve, the final reach volume calculated. The increase in flooded areas can be seen for all levels in Figure 6. The volumes were: $V_{1974} = 4.04 \times 10^{-3}$ km^3 and $V_{1994} = 4.61 \times 10^{-3}$ km^3, with a volumetric increase of 0.57×10^{-3} km^3, i.e. an erosion rate 28,500 m^3/year.

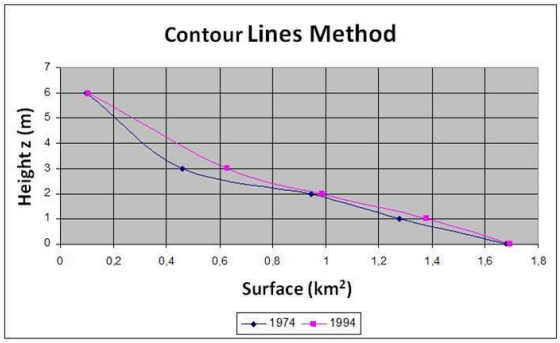

Figure 6. Flooded areas as function of water level

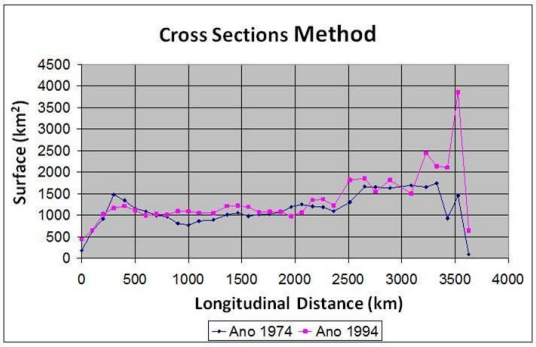

Figure 7. Longitudinal profile in the *Ferradura* Island reach

The **Cross Sections Method** consists in dividing the river stretch in sections whose areas can be determined. Afterward, the studied stretch's volume is calculated. Since it is a curved stretch, it was decided to consider four rectilinear sections of the longitudinal axis, from which were traced perpendicular lines spaced 100.0 m of terrain, considered such as not to intercept within the river channel. Results of this application are presented in Figure 7, where the segments of erosion and sediment deposition can be distinguished along the twenty years. The water volumes were: $V_{1974} = 4.15 \times 10^{-3}$ km^3 and $V_{1994} = 4.99 \times 10^{-3}$ km^3, presenting a volumetric increase of 0.84×10^{-3} km^3, that is, an erosion rate 42,000 m^3/year.

The **Surfer Software** makes the volume determination very fast, besides generating several graphical outputs, among which 3D drawings, as shown in Figures 8 and 9. Results obtained with Surfer® were: $V_{1974} = 4.38 \times 10^{-3}$ km^3 and $V_{1994} = 4.96 \times 10^{-3}$ km^3, presenting a volumetric increase of 0.58×10^{-3} km^3, that is, an erosion rate 29,000 m^3/year.

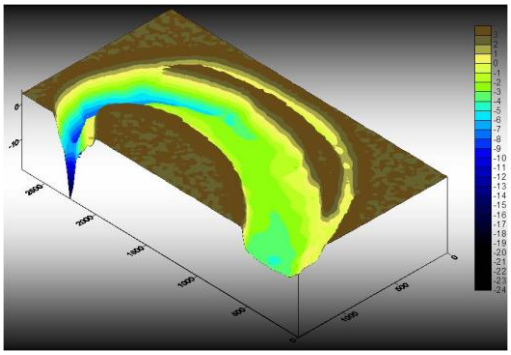

Figure 8. 3D representation of the *Ferradura* Island stretch of the *Paraguay* River in 1974

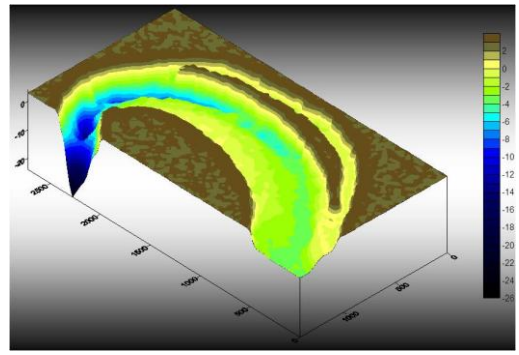

Figure 9. 3D representation of the *Ferradura* Island stretch of the *Paraguay* River in 1994

For the final erosion rates determination, the mean of the values obtained by the Contour Lines Method and the Surfer® application was calculated, obtaining an erosion rate 28,750 m^3/year. Results obtained with the Cross Sections Method presented an erosion rate larger than those obtained by the other ones. This may be due to the distance between cross sections. The larger is the distance between sections, the larger is the interpolation error between the sections' areas. This method is not recommended for very sinuous and irregular reaches.

From the analysis of the Figures 4 to 9, it is observed that along with the deepening of the riverbed that occurs, mainly in the downstream stretch, there is a sandbanks' increase at the upstream entrance of the river's right arm that goes around the *Ferradura* Island. This makes navigation harder through this arm, and also, in the convex part of the left margin, in the center of the segment. The sandbanks' volumes calculated in the years 1974 and 1994, are the following: $V_{Sb1974} = 1.06 \times 10^5$ m^3 and $V_{Sb1994} = 2.52 \times 10^5$ m^3, with a volumetric sandbanks' increase of 1.46×10^5 m^3, i.e., an aggradation rate equal 7.300 m^3/year during these 20 years.

Comparing all these values, it can be concluded that in the study period, the segment presented a sedimentological disequilibrium with predominantly erosive process. However, it has to be mentioned that the aggradation consequences at the entrance of the right arm of the *Ferradura* Island were serious, making navigation and access to the farms located in these margins difficult.

MORRO GRANDE RESERVOIR BATHYMETRIC ESTIMATE USING REMOTE SENSING ANALYSIS (CASE II)

Borges (2004) and Borges *et al*. (2007) used Remote Sensing to study the aggradation in the *Morro Grande*'s reservoir, *Rio de Janeiro* State, Brazil, using a high IKONOS resolution image and some bathymetric survey data, related by Bayesian Kriging method. They investigated the spatial variability in the ground-truth bathymetric dataset and the spatial variability in the image.

The geostatistical analysis showed that a similar behavior and correlation structure is present in both data sets (ground-truth and image) as well as a relationship does exist between the ground and the image. Indeed, the results showed a good correlation between the IKONOS image and the bathymetric measurements, where the Kriging method improved the estimates obtained by the common methods of statistical regression.

The data analysis was recommend for : (i) the estimation and monitoring of reservoirs and rivers aggradation, and (ii) for dredging management and maintenance of navigation channels, once the best correlation between imagery and bathymetric data are obtained for stretches with low depth, i.e., the most aggradated or shallow stretches.

Figure 10 (Borges *et al.*, 2007) shows the IKONOS image and, superposed, the estimated bathymetric through the image, which was adjusted with field data. Continuing this work, Wilson-Jr. (2009) proposed the study of the temporal evolution of sediment banks and river reaches morphology, assisted by Remote Sensing and GIS, for the calibration and validation of sediment transport models.

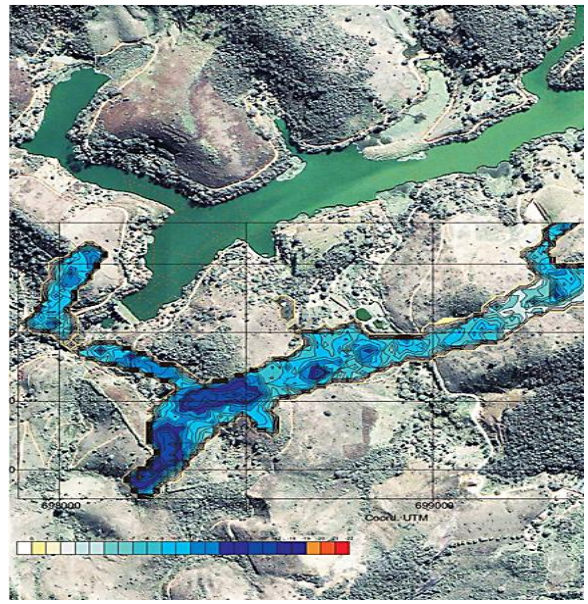

Figure 10. IKONOS image and estimated bathymetry of the Morro Grande Reservoir (Borges et al., 2007)

MORPHOLOGICAL CHARACTERIZATION OF A STRETCH OF THE *SÃO FRANCISCO* RIVER (CASE III)

São Francisco headwater is located in *Minas Gerais* State – Brazil, in *Serra da Canastra*. Until its mouth, in the Atlantic Ocean, on the border of *Sergipe* and *Alagoas* States, it travels 2,830 km, draining areas of seven states. Approximately 2,000 km are (or were!) navigable, so this river is also responsible for the flux of Brazil's Southeast, Midwest and Northeast regions' productions.

***Iuiú* Irrigation Project**

The *Iuiú* Basic Irrigation Project was elaborated in the year 2000 and intended for the agricultural development of an area of 500 km^2, located Southwest of *Bahia* State (Figures 11 and 12), on the border of *Minas Gerais* State, near the *Verde Grande* River mouth. The expected liquid flow for the *Iuiú* Project was 29.7 m^3/s of water captured from the *São Francisco* River. The river stretch of the project is located between two hydrosedimentological stations: *Manga* 30.0 km upstream, in *Minas Gerais* State, and *Carinhanha* 20.0 km downstream, in *Bahia* State.

Figure 12 highlights the river stretch that is being studied for the *Iuiú* Irrigation Project, the location of the hydrosedimentological stations, the alternatives for water intake and the sediment banks that were analyzed during the period of 1985 to 2011. In the drought period, when the hydrosedimentological survey was made by Wilson-Jr. (2000), the measured liquid flow was 1,045 m^3/s. It corresponds to 3.0 % of the minimum flow rate of the *São Francisco* River.

Hydrosedimentological and morphological aspects of the *Iuiú* Irrigation Project stretch

The Water Intake Project in the *São Francisco* River represents an anthropogenic interference in a river stretch whose sediment dynamics have special qualitative and quantitative characteristics. As this stretch is 10.0 km long, the sedimentological and morphological processes assume local importance, and must be addressed on a medium (≤ 30.0 m) and high resolution scale (≤ 2.0 m).

For the water intake alternative selection and for future hydrosedimentological studies, Wilson-Jr. (2000) proposed the methodology presented on Figure 2, in which parts of the first and second steps were completed. Concerning the first step, called Watershed Basin Knowledge, beyond the studies of reports, a field visit was made to the *São Francisco* River Watershed, on the segment between *Manga* (MG) and *Carinhanha* (BA), on the downstream stretches of the *Verde Grande* and *Carinhanha* Rivers and on the port regions of *Malhada*, *Carinhanha* and *Manga*. As the representative stretch of the *São Francisco* River was imposed by the project and it is delimited by *Manga*'s and *Carinhanha*'s stations, a special measurement campaign involving hydro-sedimentological, morphological and bathymetric surveys was conducted on the alternative stretch and was described in Wilson-Jr. (2000).

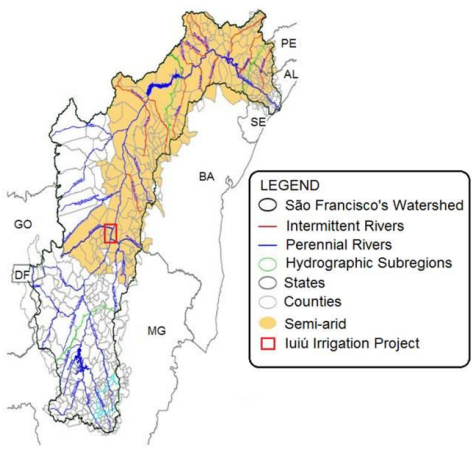

Figure 11. Semi-arid region of the *São Francisco* River watershed (Souza e Silva, 2013)

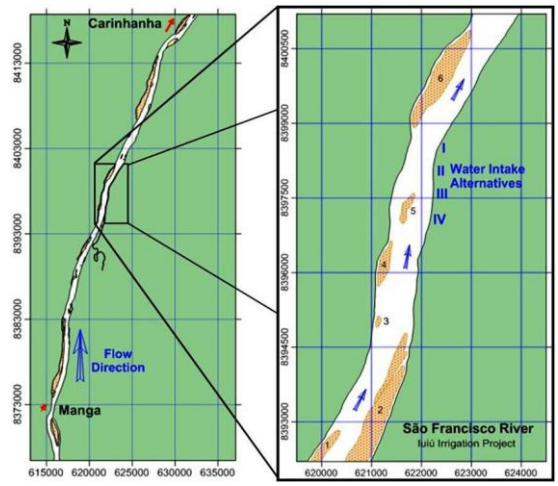

Figure 12. *Iuiú*'s irrigation project stretch water intakes alternatives and sediment banks localization

Movable sediment banks

The *São Francisco* River stretch on the site of the water intakes alternatives is not rectilinear (Figure 12). Its cross sections are asymmetric and because of the liquid flow variations during the hydrological cycle ($Q_{min} \cong 1{,}000$; $Q_{max} \cong 12{,}000\ m^3/s$), varied bed forms, islands and sediment deposits can be observed *in-situ* and on the satellite images. During the drought periods, the sediment deposits emerge, enabling the development of subsistence farming by the riverside population. With the arrival of the rainy season, the water level of the river rises, floods and washes most of the plantations, modifies the banks and islands, removes and deposits sediments, fertilizes the soil, sculpts the margins, the river bed, the movable banks, alters old bed forms and create new ones. During the field visit of July 2000, three sediment banks were observed: Banks 2, 4 and 6 (Figure 12). In this paper, assisted by Remote Sensing techniques during the period of 1985 to 2011, three other sediment banks were noted: Banks 1, 3 and 5. The temporal evolution analysis of these six banks is one of the main objectives of this work.

Remote Sensing Techniques Usage

The morphological evolution study of the *São Francisco* River stretch started with the use of LANDSAT-5 TM satellite images that were immediately provided by INPE (National Institute of Spatial Research) at no cost and extended for a period of 27 years. The first objective of this step was to verify that the LANDSAT-5 image has sufficient resolution to reproduce the borders of the river and sediment banks in the *São Francisco* River stretch, on the *Iuiú* Project area.

This step was called LANDSAT-5 TM Image Validation, and it is shown in Figure 13. Three softwares were used to manipulate the satellite images: ENVI®, Surfer® and AutoCAD®. The first one to manipulate the images and digitize the river stretch and sediment banks' borders; Surfer® to draw the maps, calculate the geometries and evaluate the morphological characteristics of the stretch, and AutoCAD® to adjust the map dimensions obtained in the field and satellite images. The forms and borders of the margins and banks determined by the LANDSAT-5 images and the field topographic and bathymetric survey were compared, as shown in the Figure 13. The image used was from 07/11/2000, because it was the closest to the period when the field survey was made: 07/06 to 07/09/2000 (Wilson-Jr., 2000). The field's survey calibration was made through the determination, with a GPS (Global Positioning System), of known polygons areas on the ground.

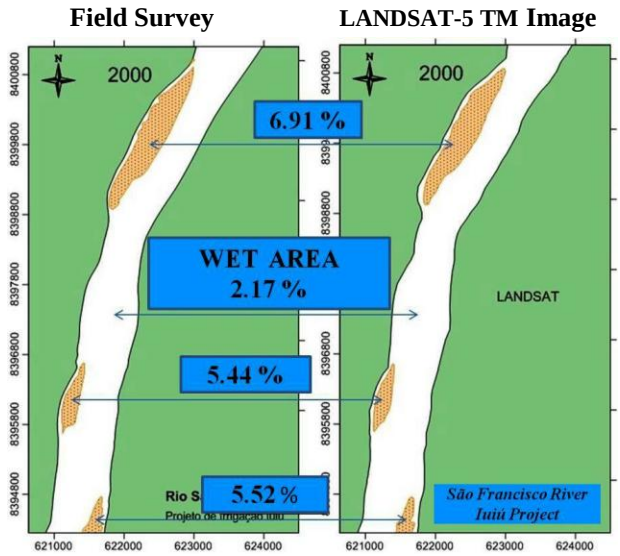

Figure 13. LANDSAT-5 TM image validation

The points' coordinates precision obtained in the field varied from 1.0 to a maximum of 3.0 m, which is inferior to the LANDSAT-5 image resolution. The Image Validation was made by comparing the dry and wet areas seen by satellite on the *São Francisco* River stretch, to the field data, as shown in Figure 13. The maximum discrepancy between the field survey areas and the ones determined with the satellite image was approximately 7.0 %. This value was considered acceptable, and it was concluded that the LANDSAT-5 TM images can be used for the temporal evolution study of the morphological variations of the *São Francisco* River stretch.

Morphological evolution of sediment banks

To evaluate the morphological evolution of the *Iuiú* Project region, 26 satellite images that represented the dry season ($Q \cong 1{,}000\ m^3/s$) and the years of 1985 to 2011, were used. Only the year 2002 was not considered, because an adequate LANDSAT-5 image was not available for the dry season. Afterward the initial images treatments phases, i.e. the georeferencing, resizing and borders' digitations, the banks and islands forms were analyzed, covering these 27 years.

The sum of the emerged areas of the six sediment banks on each image, named Dry Area; and the complement of this sum in relation to the delimited domain of the *São Francisco* River stretch, named Wet Area, were used to estimate the sedimentological behavior of the stretch. The results are shown in Figure 14, hereafter. One realizes that there was an increase of the Dry Area, and consequently, a decrease of the Wet Area, throughout the first 17 years (1985-2001). This finding indicates that the *Iuiú*'s Irrigation Project stretch was not in sedimentological equilibrium and showed a tendency to aggradation. The estimated aggradation value was around 7.70 % in relation to the recorded area values of 1985. Nevertheless, from 2003 to 2011, the dry and wet areas oscillate around constant values, indicating that the *São Francisco* River stretch reached a sedimentological equilibrium during this more recent period.

The aggradation of the *São Francisco* River stretch becomes even more evident when the temporal variations of the dry area of each sediment bank are analyzed. Figure 15 shows the annual variations of dry area of the six banks. The presentation of the banks was made in

ascending order of dry area values in relation to the total area of the studied stretch, so the highest values would stay on the back of the figure and would not hide the value of the smaller banks.

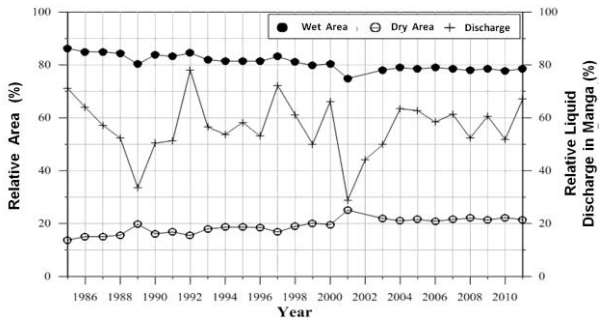

Figure 14. Annual evolutions of the relative dry and wet areas of the *Iuiú* Project in the *São Francisco* River

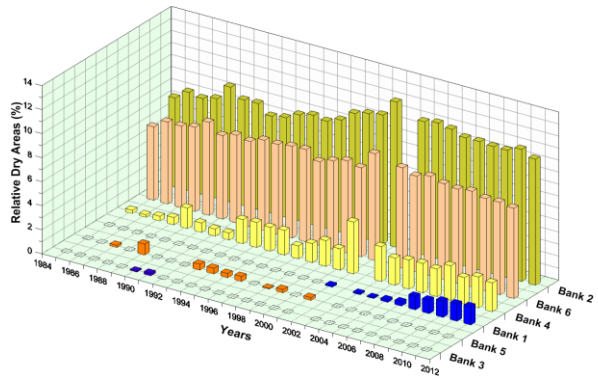

Figure 15. Morphological evolution of the *São Francisco's* sediment banks, from 1985 to 2011

The analysis of the annual images showed that some of the sediment banks are intermittent, while others are permanent. It also showed that some banks migrate downstream, while others remained stationary but had annual morphological modifications. Banks 2, 4 and 6 of Figures 12 and 15 are permanent and present in all of the 26 analyzed images. Bank 1 can also be considered permanent, although it has only reached the *Iuiú*' area in 2001. Before then, the bank fell outside the map's limits, but as Bank 2 it later extended itself downstream.

Banks 3 and 5 represent intermittent movable deposits, common on some Brazilian rivers of the *Amazonas* and *Prata* Basins, which arise during some years, generally after flood seasons, but are gradually eroded on the subsequent periods, with lower water levels. Bank 3 was only present in 1990 and 1991, while Bank 5 emerged in 1987, 1989, of 1993 to 1996, and again in 1998, 1999 and 2001. A great challenge, and, consequently a great motivation to continue the morphodynamic studies on the *São Francisco* River, consists in explaining analytically the formation and disappearances of these movable banks. Certainly, the application of the methodology sketched in Figure 2 will allow the progress in this direction.

PHYTOSOCIOLOGIC PROBLEMS CARRIED OUT IN THE *GUAPI* ESTUARY, *RIO DE JANEIRO* STATE (CASE IV)

The *Guapi* River crosses one of the few remnant mangrove areas in the *Rio de Janeiro* State. This estuarine flow was formed by the *Guapimirim* River, after receiving the *Macacu* River. It crosses the *Atlântica* Forest (an ecosystem of altitude fields, riparian forest, marshes and mangroves).

The *Macacu* River has its sources in the *Órgãos* Mountains, *Rio de Janeiro* State. It covers 74.0 km until joining *Guapi* River and more 20.0 km from this point to *Guanabara* Bay. The *Macacu* and *Guapi* Rivers watershed drainage surface is 1,640 km^2 (Figures 16 and 17).

Originally, *Guapimirim* and *Macacu* Rivers did not have any connection each other, and flowed independently into the *Guanabara* Bay. At the end of 40 decade, the National Works and Sanitation Department – DNOS, carried out several works in this region including the rectification of meanders; the opening of drainage channels; the buildings of dykes and floodwalls (Pires, 2010). A particular work was the *Imunana* Channel construction, which connected the *Macacu* with the *Guapimirim* River, an estuarine region that until this work remained flooded. Subsequently, a water intake system was installed into this channel to supply neighboring cities

and a submerged dam was built to elevate the water level and restrain the salt-water intrusion. The downstream flow was called *Guapi* River.

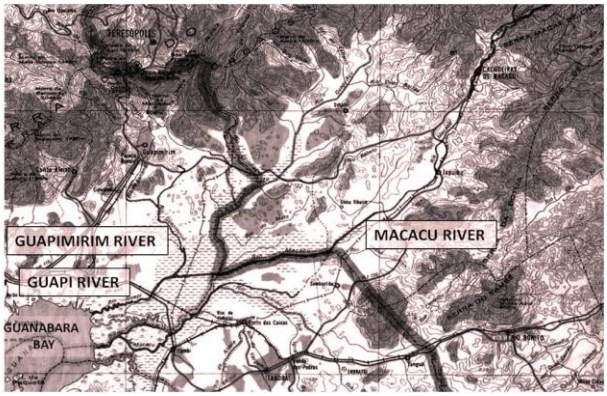

Figure 16. Macacu, Guapimirim and Guapi Rivers

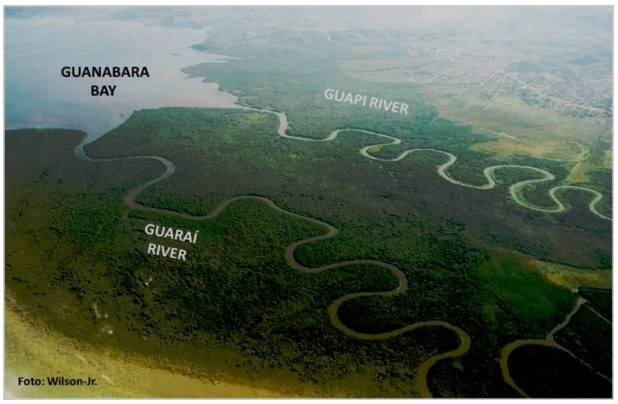

Figure 17. Guaraí and Guapi estuaries

Nowadays, the soil predominant usage is rural: agriculture and castle-raising. The vegetation presents some fragments from the *Atlântica* Forest and a considerable industrial development due to the *Rio de Janeiro* Petrochemical Complex – COMPERJ installation is predictable.

In spite of its environmental conservation organizations: (i) fluvial – *Órgãos* Mountain National Park; Environmental Protection Areas (*APA*) of *Petropólis* Municipality and of *Macacu* River watershed; and (ii) estuarine – *Guapimirim APA* and *Guanabara* Ecological Station; this region has been still submissive to the same former anthropogenic interventions. The vegetation suppression has been intensively practiced, for obtaining new sugar-cane and coffee cultivation areas; and the mangrove wood has been used to feed the brick-works industry. With the fluvial water discharge increase from the *Macacu* River, the *Guapimirim* River bordering forest, which was mainly composed of *Rhizophora* mangle *Linnaeus* (red mangrove), of *Laguncularia racemosa* (*L.) Gaertn f.* (white mangrove) and of *Avicennia schaueriana Stapf & Leechman* (black mangrove), was partially extinguished.

At 1984, when the *Guapimirim APA* was conceived, the mangrove vegetation cutting was forbidden. Nevertheless, in spite of the high resilience power of this ecosystem, the mangrove area that had already been cut did not return to its original conditions, on account of the salt-wedge regression that occurred after the *DNOS* interferences. With the salinity decrease and the hydro corium dispersion of riparian vegetation fragments from upstream, the degraded mangrove areas were gradually replaced by the *Tabebuia cassinoides ecosystem* or *caxetal* ecosystem in Portuguese. As well as the sand banks, shoals and mangrove systems, the *caxetal* system is a littoral marshland ecosystem, which is subject to a fluvial influence (Ziller, 1992). Its species, mainly the *Tabebuia cassinoides* (*Lam.*) *DC* is very resistant to an almost continuous flooding.

So, with the hydrodynamic process changes in the *Guapimirim* fluvial-estuarine system, the phytosociological process also changes, and, it is now affecting local sedimentological and morphological processes, modifying, in particular, the riparian vegetation and the sedimentological equilibrium of the flow segments.

CONCLUSIONS AND RECOMMENDATIONS

The use of topobathymetric measurements and of Remote Sensing and GIS are essential for calibration and validation studies on Sedimentological and Morphological Processes.

The morphological variations of the *Paraguay* River, in the *Ferradura* Island segment, were determined by comparing the topobathymetric curves taken in a 20-years period. Results showed that the segment presented a sedimentological disequilibrium with predominantly erosive process, estimated equal 28,750 m^3/year. However, the aggradation rate equal 7,300 m^3/year was at the entrance of a riparian farm, making the navigation and the farm's access impracticable.

Borges (2004) used high resolution IKONOS images to reproduce the bathymetric of the *Morro Grande* Reservoir in *Rio de Janeiro* State. The adopted treatment showed a great potential to be applied: (i) in the estimate and monitoring of sediments deposits in reservoirs and water streams with depths less than 10.0 m and (ii) on the management of dredging operations and maintenance of navigation channels, once the best results were obtained for aggradated shallow stretches.

It was also showed that LANDSAT-5 TM Satellite Images can be used for the morphological study of a river stretch. These images were used to describe the temporal evolution, during 27 years, of sediment banks and margins of a 10.0 km stretch in the *São Francisco* River. It is recommended that these Remote Sensing, GIS techniques and the topobathymetric measurements be introduced on the Sediment Movement Study Methodology steps, as suggested in Figure 1 of this paper, that is: (i) on the Watershed Basin Knowledge, and (ii) as special measurement of the Sedimentological and Morphological Processes. They enable the calibration and validation of qualitative and quantitative sediment transport models and the understanding of correlated phenomena, as the Phytosociological Process, e.g. the mangrove changes which are taking place on the *Guapi* Estuary borders, in *Rio de Janeiro* State.

Instead of an instantaneous vision of the measurements stations, these tools provide the observer with a wide and detailed vision of the watershed basin, the river stretch and even the bed changes.

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