Large-Scale Hydrodynamic Modeling of a Complex River Network and Floodplains

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Abstract: This paper presents a one-dimensional hydrodynamic modeling of a large-scale river network and floodplains. The study site comprises the Upper Paraguay River and its main tributaries (a total of 4,800 km of river reaches) in South American central area, including a complex river network flowing along the Pantanal wetland. The main issues are related to preparing input data for the hydraulic model in a consistent and georeferenced database and to representing different flow regimes. Geographic information systems-based automatic procedures were developed in order to produce cross-sectional profiles that encompass the large floodplains and to link hydraulic data and spatial location. The marked seasonal flow regime and relative smooth hydrographs of Paraguay River were quite well reproduced by the hydraulic model. For the tributaries, it must be mentioned the model's ability to simulate both cases when the hydrograph does not present a marked peak flow, due to water loss for the floodplain, and when the hydrograph presents a more common shape, with recession and peak flows well defined.

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Introduction

In recent years there is an increasing demand for large scale hydrologic studies, primarily aiming to understand the hydrologic functioning of river drainage network for ecologic purposes and also to investigate the impacts of climatic variability and land use changes in flow regime. One-dimensional (1D) hydraulic models are often used to mathematically represent flow routing along a river reach. In this case, simplified schemes, such as linear reservoirs, Muskingum-Cunge or kinematic wave methods may be applied. When dealing with large scale rivers, however, backwater effect and floodplain inundation may become governing factors for flood wave routing, and a 1D-hydrodynamic model is a more suitable method. The application of more complex approaches such as 2D- and 3D-hydrodynamic modeling for large scale sites may be infeasible due to data requirements, computational cost and numeric instabilities (Bates and De Roo 2000; Verwey 2005; Werner 2004).

The representation of main channel morphology and floodplain topography is important for a correct flow routing modeling. Hydrodynamic models require river cross-sectional profiles that must comprise both main channel and floodplain in order to better represent the river hydraulics, the floodplain commonly being several times larger than the main channel when dealing with large rivers.

For large-scale river drainage systems, data requirement and preparation of inputs into the hydrodynamic model may be the main challenge. Cross-sectional profiles are obtained by in situ measurements and this survey is a very cost-effective task. Thus, the availability of this kind of data for large river reaches is scarce and the available profiles rarely cover the full extent of the floodplain. Additionally, the available data may be from different sources, each one of them in a specific format and with different vertical and horizontal datum. Even when using hydraulic models which provide a user-friendly graphical interface for entering input data, such as the Hydrologic Engineering Center-River Analysis System (HEC-RAS) [Brunner 2002], input data preparation may be a tedious and time-consuming process when manually dealing with hundreds of cross-sectional profiles. Automatic procedures may be developed to accomplish this task, reducing the time needed to run the model, as well as assuring the coherence among the data. In this sense, the use of geographic infor-

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mation systems (GIS) provides a valuable tool. The use of GIS allows the linkage of the hydraulic data to spatial location (Yang et al. 2006; Sui and Maggio 1999) and assists modeling applications by handling a special form of data that would otherwise be compromised to store in an aspatial database (Miles and Ho 1999). GIS is currently recognized as an emerging and beneficial technology for water resources professionals and, more than linking GIS and models (i.e., manual data exchange between model and GIS), one may combine them (i.e., automatic data exchange) or even integrate them (inserting GIS into the model environment or the model into a GIS) (Martin et al. 2005).

Some writers have developed computational tools that facilitate the input of geometric river data into hydrologic or hydraulic models, such as: the GIS-based framework developed by Djokic and Maidment (1991) for storm drainage analysis; the PREPRO preprocessor proposed by Hellweger and Maidment (1999) for the HEC-HMS, which was further developed by Olivera (2001) as CRWR-PREPRO; the HEC-GeoRAS, which is an ArcGIS extension specifically designed to process geospatial data for using within HEC-RAS (Ackerman 2005) and may be useful for extracting cross-sectional profiles from digital elevation model (DEM) (Remo and Pinter 2007); the ArcGis-SWAT proposed by Olivera et al. (2006) to assist SWAT simulations into the ArcGis environment; the Arc Hydro tool developed to provide terrain processing functions in ArcGis (Maidment 2002); and more recently the NRCS GeoHydro, developed for preparing basin and river characteristics including river cross-sectional profiles (Merkel et al. 2008). However, each one of these procedures has its own input data format requirement, which may still demand for intensive data handling in order to convert a large amount of available data from different sources and formats.

This paper presents a hydrodynamic modeling of a complex large-scale river drainage network. The main issues are related to preparing input data for the hydraulic model in a consistent and georeferenced database and to representing different flow regimes. GIS-based automatic procedures were developed in order to deal with the large amount of data provided by several different sources, to produce cross-sectional profiles that encompass the full extent of the large floodplains, and to link hydraulic data and spatial location.

The study site comprises the Upper Paraguay River and its main tributaries, summing up 4,800 km of river reaches in an intricate drainage system. It is located in a very low and flat relief area in the South American central region, known as the Pantanal, which is one of the largest wetlands of the world. This region has great global importance for its ecologic value (Junk et al. 2006; Pott and Pott 2004), albeit several anthropogenic activities currently threatening its integrity (Da Silva and Girard 2004; Junk and Cunha 2005; Pott and Pott 2004). Modeling the flow regime of the Paraguay River and its tributaries provides a valuable tool for assisting ecosystem conservation projects, as well as for predicting impacts of human induced changes and of climate variability. Earlier studies developed for studying the Pantanal hydrodynamics were too simplified or did not comprise the full extent of its drainage network (Miguez 1994; Vila da Silva 1991; Hamilton et al. 1996; Pfafstetter 1993; Hamilton 1999; Paz et al. 2007; Maathuis 2004; Kappel and Ververs 2004). This study shows the effort of hydrodynamic modeling the whole Pantanal's rivers network and floodplains in a very consistent approach, despite the data scarcity, complexity, and the intricate river drainage network of the region. More detailed analysis, such as the analysis of predictive uncertainty and of the influence of errors and uncertainty in input data are not treated in this paper.

Study Site

The Paraguay River is a 2,612-km tributary of the Prata River with a drainage area of $1,095,000\ \mathrm{km}^2$, partially extending over four South American countries (Fig. 1): Brazil (34% of the basin), Paraguay (32%), Bolivia (19%), and Argentina (15%). The Paraguay River basin may be divided into the upper and lower parts. The study site comprises the Pantanal region ($140,000\ \mathrm{km}^2$), located in the Upper Paraguay River Basin (UPRB). The UPRB also includes two other regions classified according to its topographic and hydrological characteristics: the Planalto ($260,000\ \mathrm{km}^2$) and the Chaco ($200,000\ \mathrm{km}^2$).

The Pantanal region is located in the central portion of the UPRB and presents very low and flat relief, with a complex drainage system and seasonally flooded. Rivers inundate the floodplains and flood waters create an intricate drainage system, including vast lakes, divergent and endorreic drainage networks. Annual rainfall is less than the potential evaporation and drainage is very slow because of shallow gradients (Tucci et al. 1999; Bordas 1996).

As one of the largest wetlands of the world and presenting an extraordinary biodiversity both in terms of terrestrial and aquatic biota (Harris et al. 2005), the Pantanal is a wetland of great global importance for its ecologic value (Junk et al. 2006; Pott and Pott 2004). However, several anthropogenic activities, such as agriculture and cattle raising, as well as dam building and other hydraulic condition changes, are threatening the Pantanal ecological balance (Da Silva and Girard 2004; Junk and Cunha 2005; Pott and Pott 2004; Harris et al. 2005; Ponce 1995; Hamilton 1999; Hamilton 2002; Damasceno-Júnior et al. 2005).

Rivers flowing from the Planalto region enter the Pantanal and flow with gentle slopes and low margins. As a result, large areas are flooded and most of the water spreading over the floodplain remains there, enclosed in shallow lakes or along a divergent drainage system formed over alluvial fans (Bordas 1996; Assine and Soares 2004; Assine 2005). Annually, an average area of $50,000\ \mathrm{km}^2$ is flooded (Hamilton et al. 1996). This flood pulse strongly regulates the ecosystem integrity and conservation (Junk et al. 2006; Oliveira and Calheiros 2000; Hamilton 2002), making the Pantanal very vulnerable to human induced changes (Junk et al. 2006). The flow regime of the Paraguay River tributaries is mainly governed by this flooding process, which reduces peak discharges to more than one-half (Bravo et al. 2005) and strongly modifies the shape of hydrographs from upstream to downstream along each river (Fig. 2).

The seasonal flooding of Pantanal also influences the flow regime of the Paraguay River. There are three main river reaches along the Upper Paraguay River, in which the flow is relatively constricted by its morphological characteristics, forming large natural reservoirs. These flow constrictions are located where the Paraguay river runs close to the mountains of the Serra do Amolar, Serra do Urucum (near Corumbá), and upstream of Porto Murtinho (Assine and Soares 2004; Bordas 1996). At these river reaches, the sedimentary layers are shallower than elsewhere, and the river is unable to further erode its bed. As a result, each of these flow constrictions plays the role of a reservoir outlet. Upstream of them, the slope of the water surface is small, decreasing drainage efficiency. Earlier studies have shown that backwater effects can be propagated up to 100 km upstream of each of these points, influencing the whole Pantanal flooding (Tucci et al. 2005).

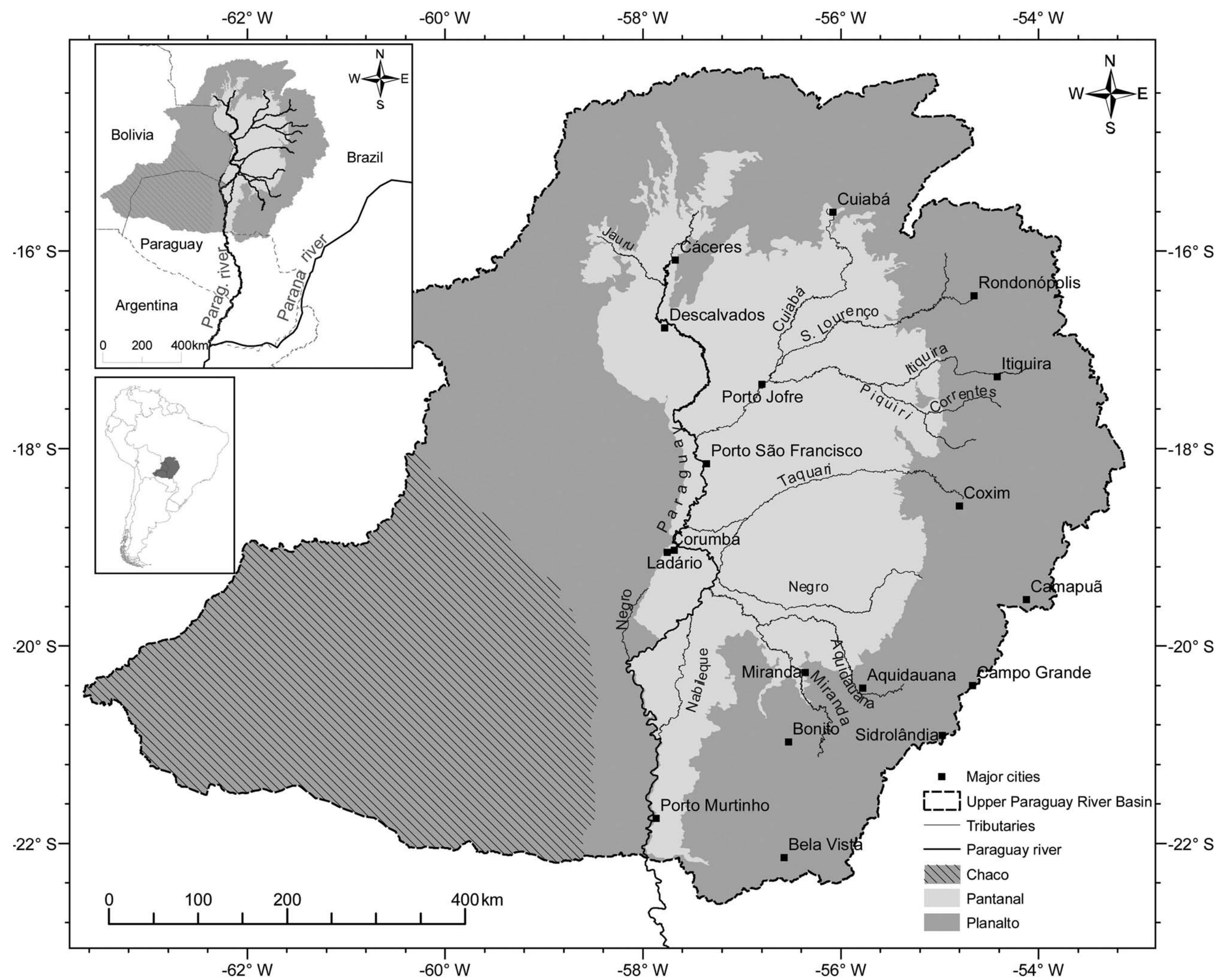

Fig. 1. Location of Upper Paraguay River Basin and its division in the Planalto, Chaco, and Pantanal regions

Available Data Sets

The data used in this study were primarily composed by freely available data sets, such as the SRTM-90m DEM, LANDSAT images, and hydrological data provided by the Brazilian Water Agency (ANA). This last data set includes daily discharge time series at 25 gauging stations in the Brazilian portion of the Upper Paraguay River Basin, as well as cross-sectional data of the Paraguay River and its main tributaries. The limited amount of available cross-sectional profiles provided by this data source contrasts with the length of the modeled rivers: three profiles for about 1,300 km of the Upper Paraguay River, and 52 cross-sectional profiles for all the tributaries together, summing up 3,500 km of river length.

An additional and fundamental data set used in this study is an extensive survey of 288 cross-sectional profiles of the Upper Paraguay River. The distance between consecutive cross sections varies from 0.5 and 10 km, and all of them cover just the main channel (i.e., there are not surveyed points along the floodplains). Further information concerning river morphology and physical characteristics of the basin are also available in former studies (Brasil, Ministério do Meio Ambiente, dos Recursos Hídricos e da Amazônia Legal 1997; DNOS 1974). These studies, however, present detailed description of the Upper Paraguay River Basin primarily based on older field expeditions and on hydraulic conditions estimated for some river reaches by kinematic wave method, which may not be suitable due to gentle slopes of these reaches.

Hydraulic Model

The well-known HEC-RAS 1D hydrodynamic model was used for river flow routing along the main river reaches. It solves the full Saint Venant equations using an implicit Preissmann four-point scheme of finite differences (Cunge et al. 1980). The finite differences equations are linearized and solved through Gaussian elimination using the Skyline storage scheme (Brunner 2004). Manning roughness coefficients are used to represent the resistance to flow. Also, contraction and expansion losses are evaluated as a function of velocity head multiplied by coefficients.

The HEC-RAS software presents a user-friendly interface for data input and visualization of results. In spite of it, due to the different data sources and formats of the available data as well as the large amount of data, some specific procedures were developed to prepare river geometry input data to the hydraulic model, as presented in the following sections.

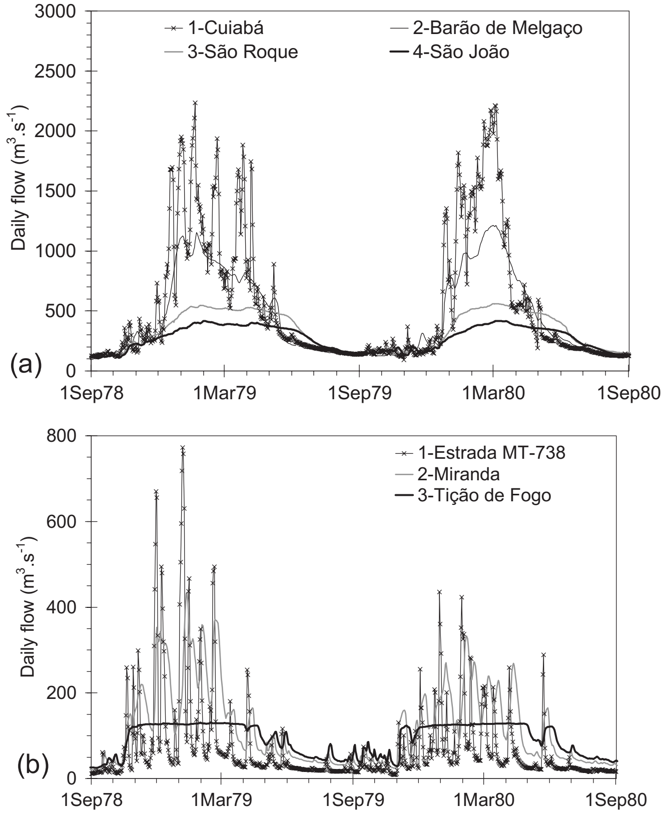

Fig. 2. Hydrographs from September 1978 to September 1980 at different gauging stations of the Rivers: (a) Cuiabá; (b) Miranda: in each graph, the gauging stations are sequentially numbered from upstream to downstream

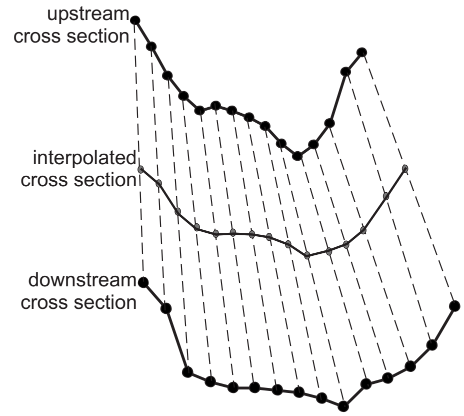

Fig. 3. Linear point-to-point scheme for interpolating cross-sectional profiles

Data Preparation and Model Application

Composing River Cross-Sectional Profiles

Even with the availability of the detailed cross-sectional survey of the Paraguay River, this data set is insufficient to represent the river hydraulics, as the cross-sectional profiles are limited to the main channel and do not extend along the floodplains. Composed profiles were created using elevation data from SRTM DEM to represent the floodplains combined with the main channel cross sections. For the tributaries of the Paraguay River, an additional step was needed due to scarcity of available main channel profiles. An interpolation procedure was performed aiming to generate main channel cross-sectional profiles, distant by about 5 km of each other in each tributary. The interpolation of cross sections between two available sections was achieved through a simple linear scheme (Fig. 3). The first step consisted of determining an equal number of intermediate points between the left and right banks along both upstream and downstream sections. For each intermediate section to be created, the horizontal and vertical location of the *i*th point is determined through linear interpolation of the ith upstream and downstream points. To obtain the composed profiles, both original and interpolated main channel profiles were combined with the floodplain topography extracted from SRTM DEM.

An automatic procedure was developed for combining detailed cross-sectional data related to the main channel and the elevation values from the SRTM DEM, in order to extend the profiles along the floodplain. Although it is recognized that the SRTM DEM fails in capturing terrain elevation values for vegetated areas (Kellndorfer et al. 2004; Sun et al. 2003; Valeriano et al. 2006) and despite its relative coarse horizontal and vertical resolutions, this data source provides enough information for the modeling purposes of this study.

An initial effort was made for converting the different vertical datum of all the available data for the same reference value, including geoid-ellipsoid corrections. The SRTM-DEM values have as vertical datum the Earth Gravitational Model 1996 or EGM96 geoid, while the available cross sections have no reliable definition concerning vertical datum, supposed to be the WGS84 ellipsoid. The undulation of the EGM96 geoid in relation to the WGS84 reference ellipsoid shows a clearly increasing trend along the Paraguay River (Fig. 4). A very similar trend was observed for the discrepancy between the measured water levels at the 288 surveyed cross sections of the Paraguay River and the corresponding SRTM-DEM values. It confirmed the WGS84 ellipsoid as the vertical datum of that extensive cross sections survey, and thus each cross-sectional profile was corrected by subtracting the respective geoid undulation value. As a result, a consistent agreement between both data sets was achieved. The reminding differences between the profiles are due to vegetation canopy effect in SRTM-DEM and mainly because the cross-sectional data refer to the water level instead of the overbank.

For composing the river cross-sectional profiles, the floodplain transect extent along each margin of the main channel was defined by manually digitized vector lines, according to the Landsat7 ETM+ images and the SRTM DEM. In general, the width of the desired floodplain varies from 5 to 30 km in both margins. Elevation values of the floodplain were extracted from the SRTM DEM at several points along a straight transect, adopting a distance of 50 m for the first four points, 200 m for the next five points and of 500 m for the last successive points up to a maximum distance of 30 km from the river margin (Fig. 5). Depending on the location of the vector data for the channel boundary, some of the first 50-m points can land on the same 90-m SRTM pixel.

The procedure was developed aiming to automatically locate the transects, extract the correspondent DEM values in each point, and then combine this information and the main channel data, producing the georeferenced composed profile for each river cross section. Additionally, information concerning the downstream distance between two cross sections and the definition of the left/right bank stations were also produced.

For each cross-sectional profile, two transects of floodplain

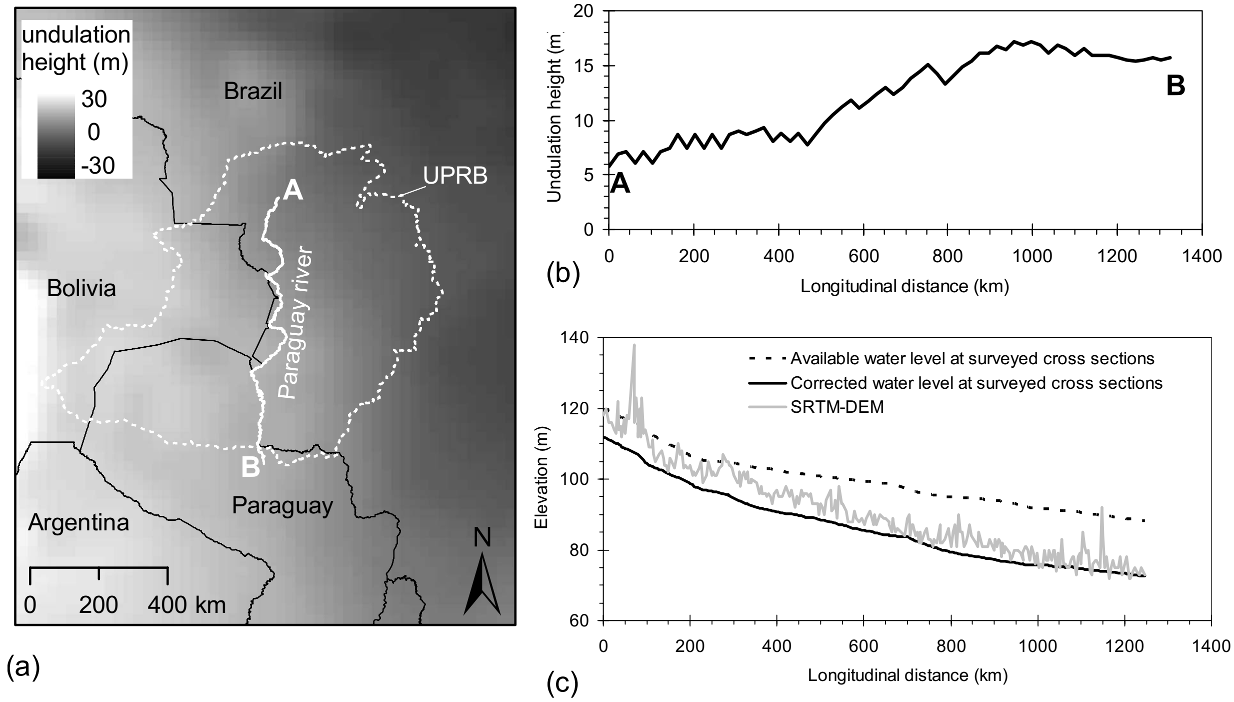

Fig. 4. (a) Undulation height of EGM96 geoid in relation to WGS84 ellipsoid for the region of the Upper Paraguay River Basin; (b) undulation height profile along Paraguay River between Cáceres gauging station (point A) and Apa River (point B); (c) water level at surveyed cross sections of Paraguay River before and after vertical datum correction, in comparison with SRTM-DEM values

elevation values were extracted: in the first one, the floodplain points were located following an alignment orthogonal to the main channel flow (i.e., maintaining the alignment of the main channel profile); and in the other one, this alignment was established orthogonally to a predefined guideline (Fig. 6). Although the concept of a river cross section means a transect orthogonal to the main channel flow, in some cases this procedure may lead to unrealistic floodplain topography in the profile [for instance, see cross section S2 indicated in Fig. 6(a)]. This problem occurs primarily due to the floodplain large extent and the river meandritic course. On the second approach, however, as the guideline was manually traced following the general orientation of the river and disregarding the sinuosity of small meanders, a more coherent floodplain representation was achieved in terms of cross-sectional profile [Fig. 6(b)].

A reasonable and coherent agreement was achieved between main channel data and floodplain elevation from SRTM-DEM, although in some cases there was a difference of up to 5 m between the right/left most points of main channel profile and the following points of the floodplain transect. Fig. 7 shows two actual examples of composed cross sections of Paraguay River. The altitude differences between the nearby points of main channel and floodplain at Section i is 1 m at the left margin and 3 m at the right margin. For Section j, these differences are around 5 and 4 m. The occurrence of this kind of artificial step in the transition from main channel to floodplain is mainly due to vegetation canopy effect over the SRTM-DEM. However, the vegetation effect in the Pantanal is not as harmful as in the Amazon, where the rivers are surrounded by forest. The vegetation adjacent to the Pantanal rivers is composed of patches of forests and grassland. Taller vegetation is usually found only on higher terrain. A typical river and floodplain cross section shows that larger trees are con-

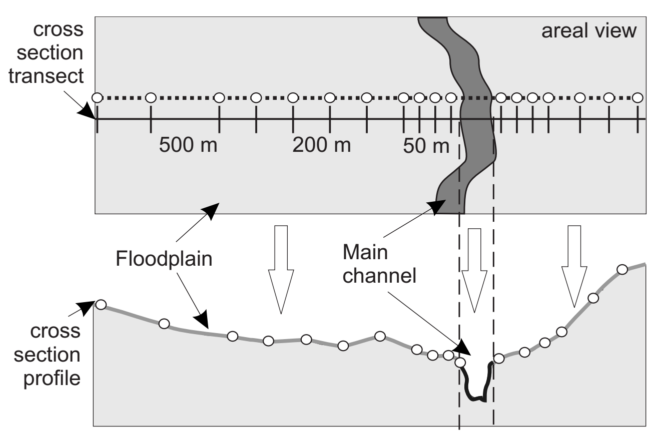

Fig. 5. Procedure of composing a river cross-sectional profile based on detailed data of the main channel and elevation values extracted from DEM for floodplain characterization

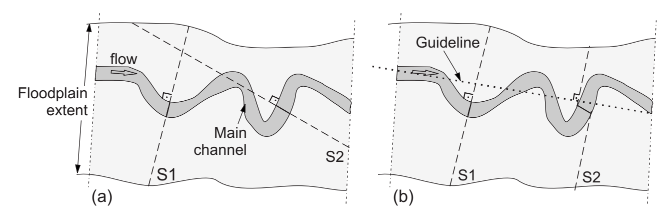

Fig. 6. Floodplain transects traced: (a) following the alignment of main channel cross sections; (b) orthogonally to a predefined guideline

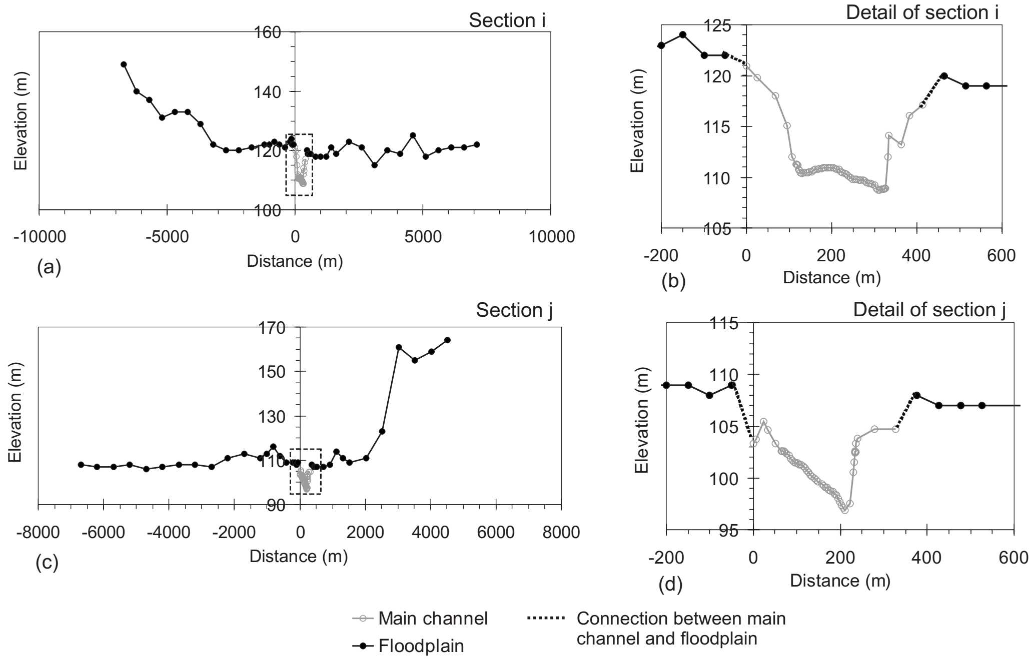

Fig. 7. [(a) and (c)] Actual examples of full composed cross sections; [(b) and (d)] detailed view of connection between main channel and floodplain [regions indicated by dashed rectangles in (a) and (c), respectively]

centrated on the natural levees, along the river margins. Afar from the close vicinity of the river, shorter vegetation proliferates. Therefore, SRTM elevation errors due to the presence of the trees will be a minor problem, because connectivity of the river channel with the floodplain can be simulated by the hydrodynamic model even when the cross section have those errors along both margins. Owing to the large scale of the cross sections, such artificial steps have minimal influence over its hydraulic properties.

For the tributaries of Paraguay River, due to the very small quantity of available cross sections, the channel slopes were defined trying to follow the main trend observed in river profiles extracted from SRTM-DEM. Thus, the average channel slope for each river is quite similar to the average slope of the floodplains. As expected mainly due to vegetation effects over DEM, the range of floodplain slopes is larger than that for the channel slopes. Table 1 presents the minimum, average and maximum values of channel and floodplain slopes considering individual reaches between each two cross sections for the tributaries and the Paraguay River.

For the Paraguay River, there was an extensive cross-sectional survey available, but it was limited to the main channel. As mentioned in the paper, a vertical datum correction was necessary to provide the agreement between these data and the floodplain extracted from SRTM-DEM. The channel slope ranges from 0.02 to 0.09 m/km, with an average value along the entire Paraguay River of 0.04 m/km. The average value of the floodplain slope is similar (0.05 m/km), but the range is larger, varying from −0.10 to 0.17 m/km.

Application of the Hydraulic Model

Flow routing along the modeled river network was simulated with the HEC-RAS hydraulic model. The inlet section of each river in

Table 1. Average, Minimum, and Maximum Channel and Floodplain Slopes of Individual Reaches of the Paraguay River and Its Tributaries

	Channel botton slope (m/km)			Floodplain slope (m/km)		
River	Minimum	Average	Maximum	Minimum	Average	Maximum
Aquidauana	0.15	0.15	0.15	−0.01	0.16	0.34
Cuiabá	0.06	0.09	0.12	−0.13	0.10	0.33
Itiquira	0.10	0.18	0.29	−0.03	0.17	0.51
Jauru	0.12	0.19	0.25	−0.03	0.19	0.33
Miranda	0.10	0.14	0.17	−0.04	0.13	0.31
Nabileque	0.02	0.02	0.02	−0.11	0.03	0.14
Negro (Bolivia)	0.03	0.03	0.04	−0.08	0.05	0.13
Negro (Brazil)	0.08	0.17	0.36	−0.07	0.17	0.61
Piquiri	0.09	0.10	0.12	−0.09	0.10	0.30
Taquari	0.22	0.26	0.29	0.11	0.26	0.54
São Lourenço	0.18	0.22	0.43	−0.04	0.21	0.54
Paraguay	0.02	0.04	0.09	−0.10	0.05	0.17

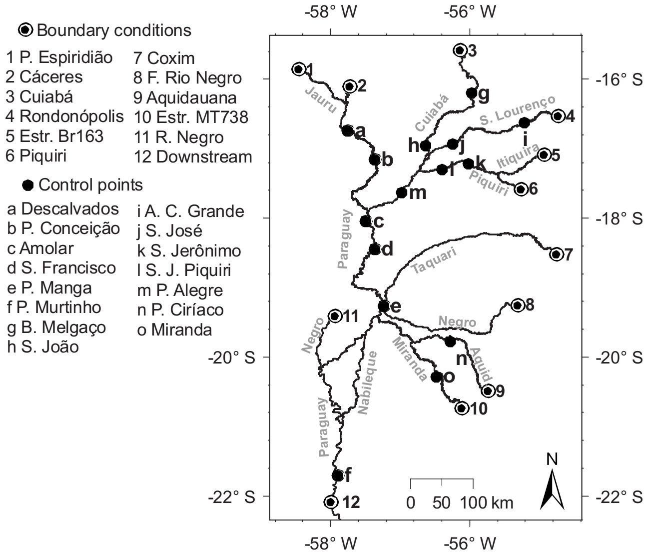

Fig. 8. Location of boundary conditions and streamflow gauging stations selected for comparison of results (control points) of the hydraulic model of Paraguay River and its tributaries

the Pantanal region was considered as the upstream boundary conditions (Fig. 8 and Table 2). The Paraguay River section upstream of the affluence of Apa River, about 60 km downstream from Porto Murtinho, was taken as the downstream boundary condition of the modeled network, considering the energy slope parallel to average bed slope.

A vector data set of the whole modeled river network was obtained by manually digitizing over Landsat7 ETM+ satellite images, comprising a total of 4,800 km of river length. This georeferenced and detailed vector data was used to represent the river reaches in the hydraulic model, maintaining the coherence of geographic location of the boundary conditions and of the river cross sections.

An automatic procedure was developed to assemble the river drainage network in the geometric data file of the HEC-RAS hydraulic model together with cross-sectional profiles and other data required by this model to characterize the modeled system (Fig. 9).

Initially, a basic version of the geometric data file (a data file with extension ".g") was created using the HEC-RAS interface, containing only general information about topology and connectivity of the river drainage network. At this time, each river reach is represented by a schematic single nongeoreferenced straight line [Fig. 10(a)]. The digitized vector river network and a list of the river reaches were then used to automatically update the geometric file [Fig. 10(b)], providing the actual geospatial location and flow path of each river reach. This is achieved outside of the HEC-RAS environment, writing the information directly into the .g file.

In the next step, information concerning location, composed profiles, downstream reach length, and definition of left/right

Table 2. Streamflow Gauging Stations of Paraguay River and Its Tributaries Used in This Study

Reference		Station number	Station name	River	Drainage area (km^2)	Available data[a]
(a)	Control points	66090000	Descalvados	Paraguay	48,360	Observed
(b)		66120000	P. Conceição	Paraguay	65,221	Observed
(c)		66800000	Amolar	Paraguay	246,720	Observed
(d)		66810000	S. Francisco	Paraguay	251,311	Observed
(e)		66895000	P. Manga	Paraguay	331,114	Observed
(f)		67100000	P. Murtinho	Paraguay	581,667	Observed
(g)		66280000	B. Melgaço	Cuiabá	27,050	Observed
(h)		66360000	S. João	Cuiabá	39,908	Observed
(i)		66460000	A. C. Grande	S. Lourenço	21,800	Observed
(j)		66470000	S. José	S. Lourenço	24,989	Observed
(k)		66600000	S. Jerônimo	Piquiri	27,150	Observed
(l)		66650000	S. J. Piquirí	Piquiri	28,871	Observed
(m)		66750000	P. Alegre	Cuiabá	104,408	Observed
(n)		66950000	P. Ciriaco	Aquidauana	19,204	Observed
(o)		66910000	Miranda	Miranda	15,460	Observed
(1)	Boundary conditions	66072000	P. Espiridião	Jaurú	4,970	Observed
(2)		66070004	Cáceres	Paraguay	33,890	Observed
(3)		66260001	Cuiabá	Cuiabá	22,037	Observed
(4)		66451000	Rondonópolis	S. Lourenço	11,995	Observed
(5)		66520000	Estr. Br. 163	Itiquira	5,686	Estimated
(6)		66480000	Piquiri	Piquiri	9,097	Estimated
(7)		66870000	Coxim	Taquari	27,040	Observed
(8)		66890000	F. Rio Negro	Negro	6,091	Estimated
(9)		66945000	Aquidauana	Aquidauana	15,200	Observed
(10)		66900000	Estr. MT 738	Miranda	11,820	Observed
(11)		—	R. Negro	Negro	89,640	Estimated

[a]Data observed or estimated by a hydrological model (Tucci et al. 2005).

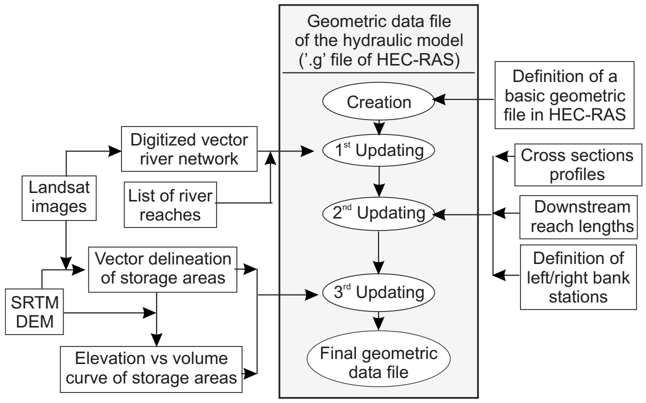

Fig. 9. Schematic description of the procedure for automatic entering geometric data into the HEC-RAS hydraulic model

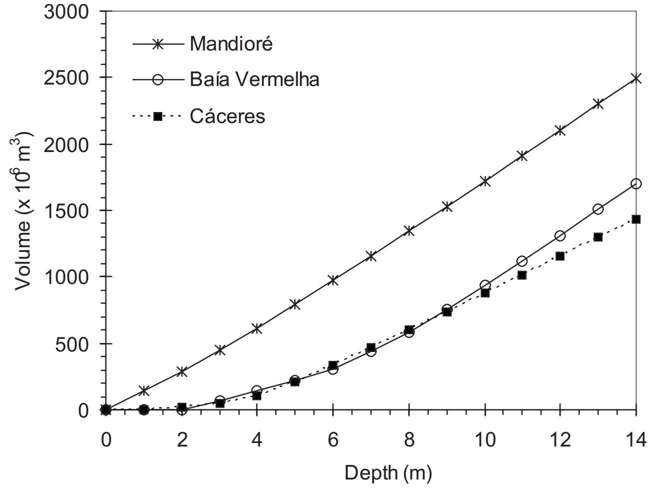

Fig. 11. Estimates of storage-elevation curves of three lakes of the study area

bank stations for all the cross sections are written in the .g geometric file (second update) [Fig. 10(c)]. After the second update, the geometric data file contains all the information required for simulating river hydraulics. In this study, the main lakes located next to the Upper Paraguay River were explicitly considered in the hydraulic modeling system as storage areas, demanding a third updating of the .g file [Fig. 10(c)]. The storage areas were used aiming to represent the process of water loss from the channel to the lakes. This volume of water is diverted from the main flux of the river and flows through a distinct and independent path. This water may return to the main channel, but with a time delay in relation to the flood wave.

Simplified estimates of storage-area-elevation curves for Lakes Uberaba, Gaiva, Mandiore, Baía Vermelha, Cáceres, and other six smaller lakes were determined based on Landsat images, SRTM DEM, and data available from Brasil, Ministério do Meio Ambiente, dos Recursos Hídricos e da Amazônia Legal (1997) and DNOS (1974).

The shape and location of each lake were determined by manually digitizing over Landsat images and printed maps available from Brasil, Ministério do Meio Ambiente, dos Recursos Hídricos e da Amazônia Legal (1997) and DNOS (1974). The polygon defining each lake's boundaries was used as a mask, and the curves were determined by an incremental flooding process. The minimum elevation value Zmin among all pixels located inside each polygon defines the starting point of the curve (with null values for area and volume). The next point of the curve is determined by a flooding level of Zmin+dz, where dz is a constant predefined incremental elevation. The corresponding area is calculated summing the superficial areas (Ai) of all the inundated pixels, while the volume is given by summing the products Ai $\times$hi, where hi is the inundation depth at pixel i. This procedure is

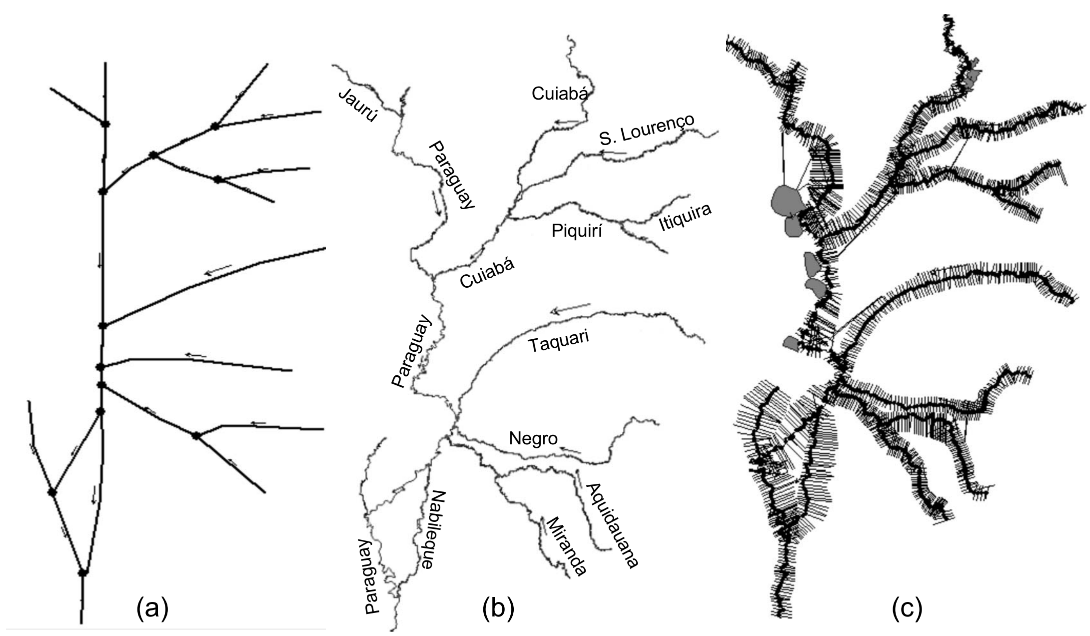

Fig. 10. Generation and updating of the geometric data file of the HEC-RAS hydraulic model applied for the Paraguay River and its tributaries: (a) topologic network of river reaches; (b) actual georeferenced river reaches; and (c) final representation of the modeled network including cross section transects and storage areas

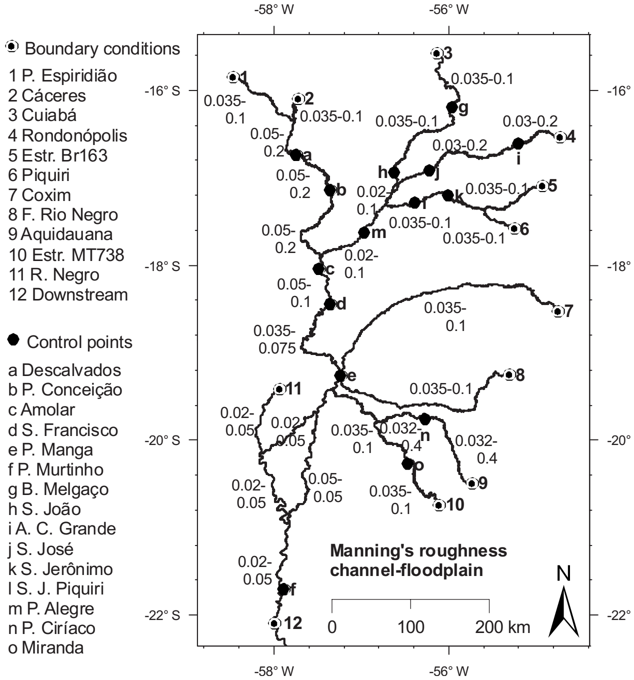

Fig. 12. Map of fitted n values for the Paraguay River and its tributaries (for each river reach, first and second n values refer to the main channel and floodplain, respectively)

repeated for several incremental elevations until reach a specified maximum elevation. Fig. 11 illustrates the resulting storage-elevation curves obtained for three lakes.

Due to SRTM-DEM limitations, including vegetation canopy effects and absence of water depth data, the simplified procedure adopted leads to rough estimates of the storage-area-elevation curves. However, these estimates are sufficient to make the hydraulic model able to represent the storage effect according with the water level rising. Shape, location, and storage-area-elevation curves of each lake were automatically added to the geometric file. These storage areas were further connected to specific river cross sections in the HEC-RAS modeling system using weir-type equations. Following these procedures, all the geometric data regarding the 24 river reaches, 12 junctions, 1,124 cross sections and 11 storage areas were entered into the hydraulic model in a coherent and not time-expensive way.

Simulation and Discussion

Several time steps were tested for running the HEC-RAS hydraulic model, ranging from 1 to 12 h, and the same results were obtained. This is mainly due to the slowly variation of stage and discharge presented by the rivers in the Pantanal region. At the upstream boundaries of the river network represented in the hydrodynamic model, the typical time of rise of flood hydrographs is of the order of several days. At the heart of the region, the river actually shows a single flow peak every year, giving a time of rise of more or less 6 months. Furthermore, as the flow data of the boundary conditions and of the control points were in a daily basis and aiming at reducing the computational cost, a 12-h time step was adopted.

For calibration purposes, each river reach between two control points (certain gauging stations with available data) or between an upstream boundary condition and a control point was considered as a homogeneous segment in terms of roughness, i.e., with a constant n value. For each homogeneous river segment, from upstream to downstream, the correspondent n values (channel and floodplain) were manually varied looking for the best agreement between observed and calculated hydrographs at the downstream control point. The agreement was achieved through Nash-Suttcliffe (NS) coefficients, by analyzing time and amount of peak and recession flows as well as error of volume, and by visual comparison of the hydrographs.

The initial n estimates were adopted as a constant value of 0.035 for the channels and of 0.1 for the floodplains. These values were set according with recommended values in literature (Chow 1959,1964) for rivers in a natural state with irregular and rough sections, and floodplains prevailing medium to dense brush and some trees. As the analysis of parameter uncertainty is beyond the scope of this paper, the tested values of the Manning coefficients were restricted for those reported in the literature for this kind of

Table 3. Performance Measures at Control Points for the Period January 1, 1996–December 31, 2000

Reference	Control point	River	RMSE ($m^3 \cdot s^{-1}$)	MAE ($m^3 \cdot s^{-1}$)	MRE (%)	NS
(a)	Descalvados	Paraguay	65.5	46.5	7.58	0.94
(b)	P. Conceição	Paraguay	49.7	40.5	11.00	0.87
(c)	Amolar	Paraguay	110.8	93.9	7.57	0.88
(d)	S. Francisco	Paraguay	309.9	264.2	16.49	0.71
(e)	P. Manga	Paraguay	153.4	134.2	7.79	0.91
(f)	P. Murtinho	Paraguay	398.3	316.3	13.07	0.68
(g)	B. Melgaço	Cuiabá	150.8	98.1	23.86	0.74
(h)	S. João	Cuiabá	95.6	74.1	28.45	0.40
(i)	A. C. Grande	S. Lourenço	31.9	18.3	4.18	0.98
(j)	S. José	S. Lourenço	38.5	30.2	11.51	0.82
(k)	S. Jerónimo	Piquirí	84.7	61.5	19.77	0.49
(l)	S. J. Piquirí	Piquirí	89.1	62.3	17.93	0.80
(m)	P. Alegre	Cuiabá	59.1	45.7	6.86	0.91
(n)	P. Ciriaco	Aquidauana	22.9	16.9	15.14	0.64
(o)	Miranda	Miranda	53.4	32.4	29.47	0.60

Note: RMSE=root-mean-square error; MAE=mean absolute error; MRE=mean relative error; and NS=Nash-Sutcliffe efficiency index.

Table 4. Mean Statistic Values Based on Observed and Calculates Hydrographs with the Initial Estimates of Manning Roughness and with the Calibrated Values at Several Control Points

		Initial estimates of n					Calibrated values of n				
River	Control point	ΔQ_{max} (%)	ΔT_{max} (d)	ΔQ_{min} (%)	ΔT_{min} (d)	ΔVol (%)	ΔQ_{max} (%)	ΔT_{max} (d)	ΔQ_{min} (%)	ΔT_{min} (d)	ΔVol (%)
Cuiabá	B. Melgaço	9.9	1	−21.2	0	−16.4	9.9	1	−21.2	0	−16.4
	S. João	6.0	8	−25.5	0	−18.0	6.0	8	−25.5	0	−18.0
	P. Alegre	0.8	2	3.0	4	−2.0	0.2	−1	−1.7	−2	1.9
S. Lourenço	S. José	−4.0	48	4.8	5	−2.5	2.0	25	4.4	4	1.4
Piquiri	S. J. Piquiri	−1.4	−5	−4.4	−1	1.5	−1.4	−5	−4.4	−1	1.5
Aquidauana	P. Ciriaco	−9.5	−1	−15.8	0	−12.1	−0.9	−1	−15.7	0	−9.4
Miranda	Miranda	−6.0	0	−13.3	1	−13.7	−6.0	0	−13.3	1	−13.7
Paraguai	Descalv.	10.0	−2	−16.1	4	−3.5	−0.2	0	−0.1	2	−1.0
	Amolar	−11.7	23	−5.9	0	−11.8	−1.4	13	−1.5	0	−2.6
	P. Manga	−4.8	3	11.7	10	0.2	0.3	8	4.2	−12	0.1
	P. Murtinho	−8.2	25	19.3	87	−3.9	2.5	2	1.3	8	−3.1

channels and floodplains. Moreover, due to data scarcity related to channel cross sections and slopes for the tributaries, the variation of roughness values of these rivers was more restricted than for the Paraguay River, for which there was extensive cross-sectionals data available.

The period from March 31, 1995 to December 31, 2000 was selected for model calibration, as the available data for this period was more reliable. However, there were not observed discharges available for all the upstream boundary conditions for the entire calibration period, and missing data was replaced by values calculated with the distributed hydrologic model MGB-IPH (Collischonn et al. 2007). This hydrologic model was previously applied and adjusted for all the subbasins in the Planalto region of the Upper Paraguay River Basin in the study reported by Tucci et al. (2005). A very reasonable fit was achieved, with NS coefficients ranging from 0.56 to 0.88. A detailed description of the hydrologic modeling and fitting of the subbasins of the Planalto region will be presented in a further paper.

The analysis of the model performance may be done separately for the Paraguay River and for its tributaries, both because of the discrepancy in the amount of available data and also because model fitting at Paraguay River is influenced by model performance at the tributaries. Following the calibration process, the final values of the Manning's coefficients for the tributaries varied from 0.02 to 0.035 for the main channel, and from 0.04 to 0.2 for the floodplain (Fig. 12). In general, the model was found to fit well, as the NS coefficients ranged from 0.40 to 0.98 for all the river reaches (Table 3). Several river reaches remained within the initial n estimates. Considering the reaches where the final n values were distinct from the initial ones, greater improvements in model performance were obtained at São José gauging station, with a 50% reduction in the difference between calculated and observed timing of peak flow, and at Porto Ciríaco gauging station, where the error in peak flow was reduced from −10 to −1%.

The proposed model satisfactorily reproduced the general shape of observed hydrographs at the tributaries (Fig. 13), with more discrepancy for the Cuiabá River upstream the affluence of the São Lourenço and Piquiri Rivers. For instance, at São João gauging station, which is located 370 km downstream of the upstream boundary condition, calculated discharges underestimate the recession flow, and during the floods the calculated hydrograph presents an untrue nervous oscillation [Fig. 13(a)]. An underestimation error of volume greater than 16% resulted for the B. Melgaço and São João gauging stations, while minimum flows were underestimated by more than 20% and the peak flow were overestimated by less than 10% (Table 4). Along this reach of the Cuiabá River there are several places where overflows occur even during relatively small floods, and there are also secondary channels which divert water during low flows, spreading out over the floodplain. Some of this water may return to the main river channels, and some part of it remains stored and eventually evaporates. Approximately more than 50% of the volume of water that flows from Planalto along Cuiabá River is loosed from the main channel to the floodplains upstream of São João gauging station (Fig. 2). On the other hand, the hydrograph comparison at the Porto Alegre gauging station, which is located downstream of São João, shows a better agreement between observed and calculated streamflows, with a small overestimation (less than 1%) of peak flows [Fig. 13(d)]. The error of volume and the error in minimum flows were reduced to less than 2%. These results suggest that the bias found in São João gauging station becomes less important after the inflow of the tributaries.

In general, for the São Lourenço, Piquiri, Aquidauana, and Miranda Rivers, the calculated hydrographs are also very similar to the observed ones, including time and amount of peak flow, rising and falling limbs, and recession flow. The errors of volume and minimum flows for the São Lourenço and Piquiri Rivers were less than 5% in absolute values, being slightly greater for the Miranda and Aquidauana Rivers. The error in peak flows varied from an underestimation of 6% for the Miranda River to an overestimation of 2% at São Lourenço River. The observed timing of peak and recession flows was quite well reproduced by the model, except for the peak flow at São José gauging station at São Lourenço River.

The hydrographs showed in Fig. 13 illustrate the complexity of the flow regime at the tributaries of Paraguay River. An important issue that must be highlighted is the model ability to simulate both cases when the hydrograph does not present a marked peak flow (e.g., at Porto Ciríaco gauging station), due to water loss for the floodplain, and when the hydrograph presents a more common shape (e.g., at Miranda gauging station), with recession and peak flows well defined.

At the Paraguay River, the flow regime presents a marked seasonal variation with relative smoothed hydrographs. The model was able to reproduce this flow regime quite well, as illustrated by the comparison between observed and calculated hydrographs at five gauging stations showed in Fig. 14—note that the

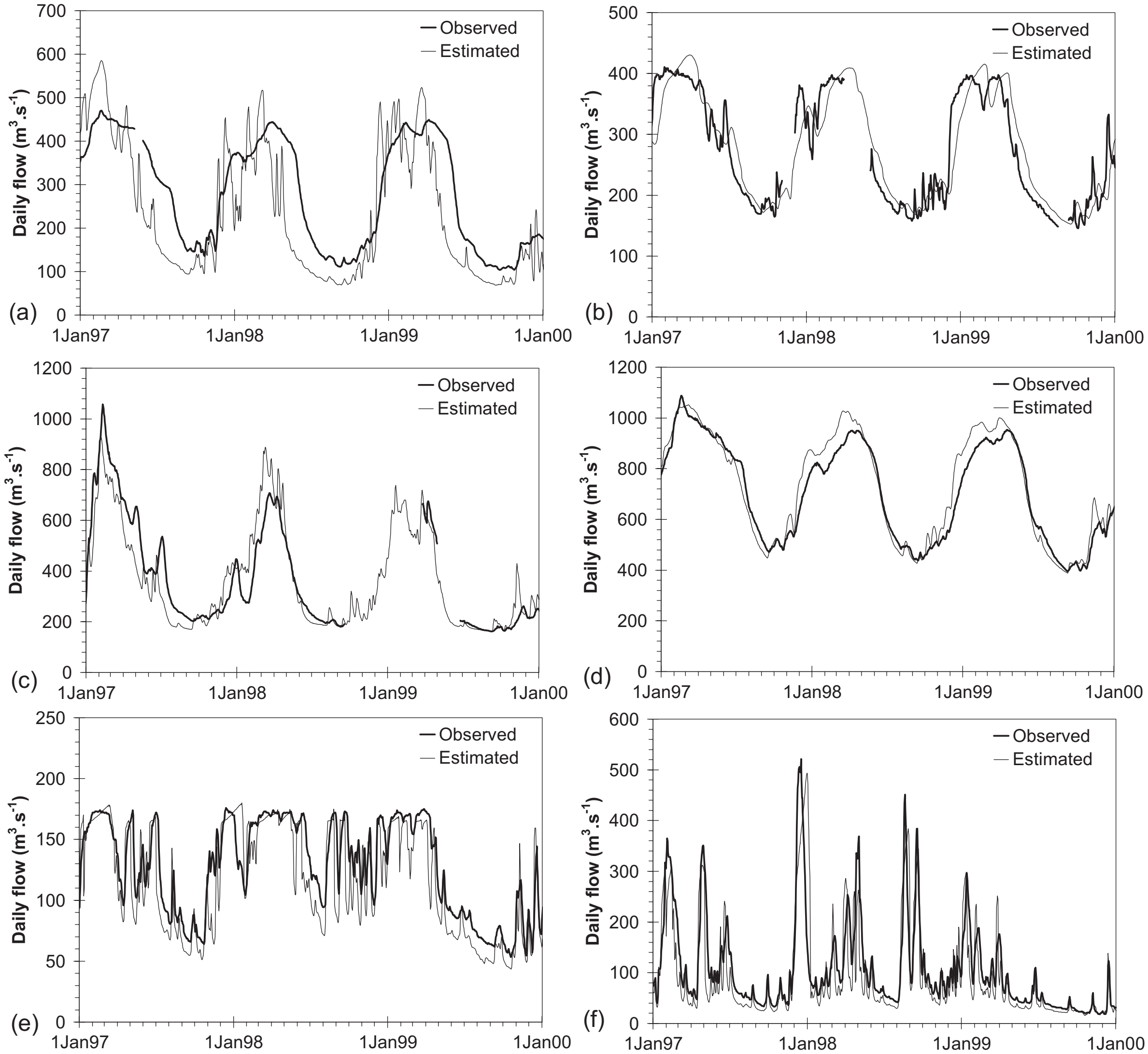

Fig. 13. Estimated and observed hydrographs at six control points along tributaries of Paraguay River during part of the calibration period: (a) São João (Cuiabá River); (b) São José (São Lourenço River); (c) S. J. Piquiri (Piquiri River); (d) P. Alegre (Cuiabá River); (e) P. Círíaco (Aquidauana River); and (f) Miranda (Miranda River)

y-axis has distinct scales among these graphs. The hydrograph at the upstream boundary condition of the Paraguay River (Caceres gauging station) is also presented in Fig. 14. Model adjustment was achieved by using Manning's coefficients ranging from 0.02 to 0.035 for the main channel, and from 0.04 to 0.1 for the floodplains (Fig. 12). In general, the fitted n values of both channel and floodplains decreased from upstream to downstream.

The NS coefficients for control points at Paraguay River vary from 0.68 to 0.94 (Table 3). The error of volume and the error in peak and recession flows were less than 4% in absolute values at Descalvados, Amolar, P. da Manga, and P. Murtinho gauging stations (Table 4). Using the initial n estimates, these errors were significantly greater, up to 19.3%. The timing of peak and recession flows was also improved by fitting n values, obtaining differences less than 13 days in relation to observed hydrographs.

The water flowing from Planalto enters into Paraguay River at Cáceres gauging station, where peak flows reached 1,200–1,600 m^3/s for the period shown in Fig. 14. About 150 km downstream, at Descalvados gauging station, the peak flow was reduced to 1,100 m^3/s, and at Porto Conceição gauging station, 120 km downstream from Descalvados, peak flow was reduced to around 700 m^3/s. There was a significant loss of water for the floodplains during the floods along this reach of the Paraguay River, and this process was reasonably represented in calculated hydrographs. The observed recession flows were also reduced by almost 100 m^3/s along the river reach between Descalvados and Porto Conceição, but this was not well represented by the hydraulic model, which overestimated the recession flow at Porto Conceição gauging station.

At Amolar gauging station, downstream the affluence of Cuiabá River, the observed peak flows are almost three times greater than the peak flows at Porto Conceição station, located 236 km upstream. This increase in peak flows and the whole flow regime at Amolar were very well represented in the calculated hydrograph, as illustrated in the three annual floods shown in Fig. 14. Further downstream in Paraguay River, at Porto da Manga gauging station, there is an important increase in observed flows again, now due to the affluence of Taquari River. A good agreement between observed and calculated hydrographs was also obtained at this control point, which has a contributing area greater than 50% of the Upper Paraguay River Basin.

About 28 km downstream of Porto da Manga, the Paraguay

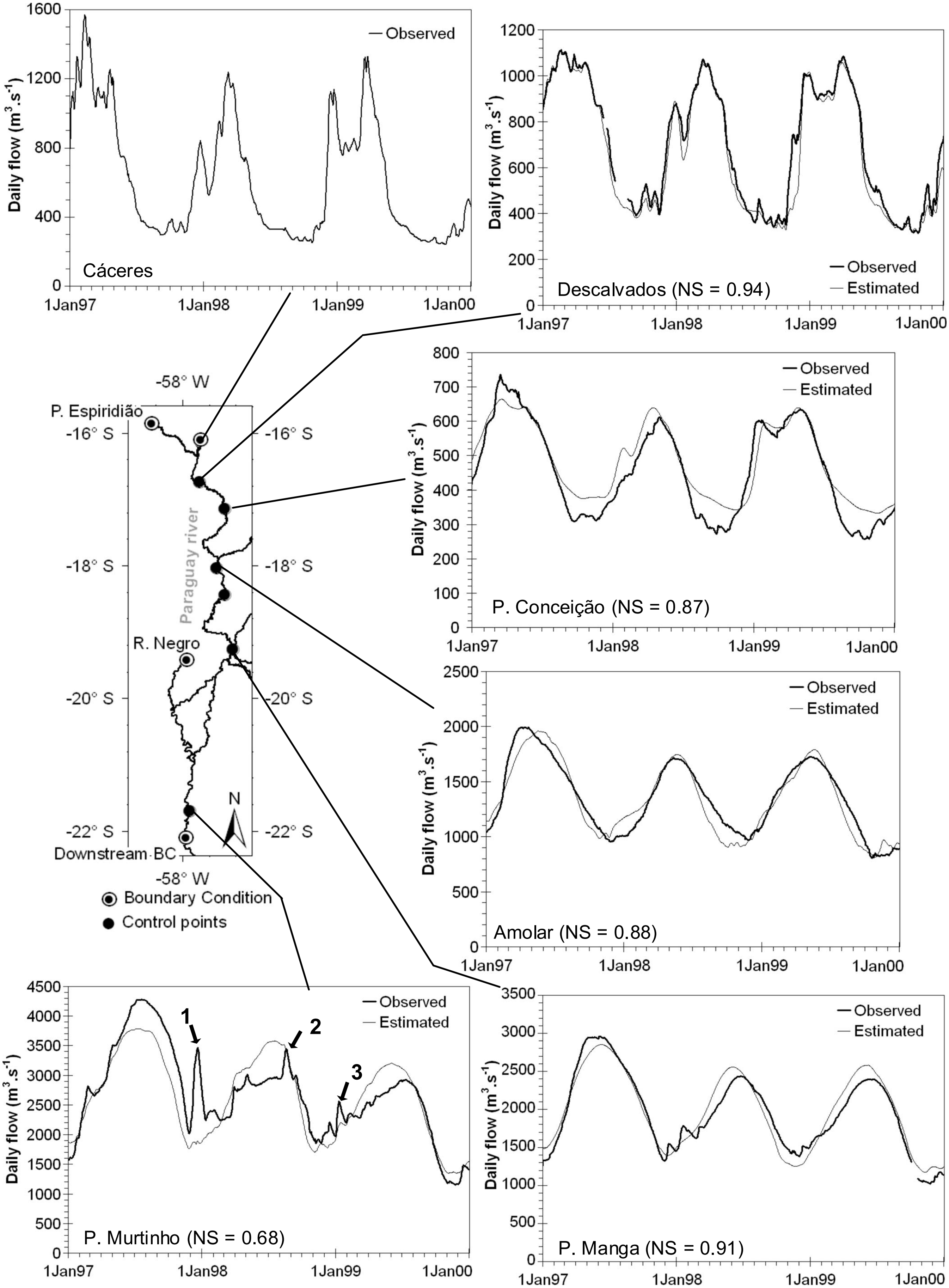

Fig. 14. Estimated and observed hydrographs at four control points along Paraguay River during part of the calibration period

River receives the contribution of the Miranda basin. In this basin, the Aquidauana and Miranda Rivers were simulated by the hydraulic model with a satisfactory agreement between observed and calculated hydrographs. Between the affluence of Miranda River and the following downstream control point at Paraguay River (Porto Murtinho gauging station), there is a 430-km river reach without reliable observed discharge time series in Paraguay River and the incremental contributing area is completely ungauged. At Porto Murtinho, the performance of the hydraulic model decreased compared to previous control points. The seasonal peak flows were underestimated by 12%, and the model was not able to reproduce secondary flood peaks that appear in the observed hydrograph (as indicated by arrows 1, 2, and 3 at Porto Murtinho observed hydrograph in Fig. 14). This result, however, is probably caused by errors in the boundary condition and lack of data for simulating the contributions of Negro River (flowing from Bolivian territory) and other lateral inflows to Paraguay River rather than by a failure of the hydraulic model in simulating the Paraguay River. The indicated secondary flood peaks in the observed hydrograph are probably generated in the Bolivian part of Pantanal, west to the main river. As there are not available observed discharges for the Negro River, the boundary conditions of the hydraulic model were estimated using a hydrological model, which was applied with severe scarcity of data (Tucci et al. 2005). Moreover, flow propagation along Negro River was strongly compromised by the absence of cross-sectional data. Despite that, the hydraulic model was able to reasonably reproduce the general shape of the observed hydrograph at Porto Murtinho, but with a performance worse than in all the upstream control points.

Summary and Conclusions

This paper presents the simulation of the flow regime of the Paraguay River and its tributaries located at Pantanal wetland, a very flat- and low-relief region. The hydraulic modeling of such large and complex drainage system was feasible because of the development of GIS-based automatic procedures for preparing input data. The 4,800-km river network was modeled in a consistent way, preserving spatial location of hydraulic data. Despite the user-friendly interface of the HEC-RAS model, manually preparing and entering all the geometric data regarding 24 river reaches, 12 junctions, 1,124 cross sections, and 11 storage areas of the modeled river network would be a tedious and time-consuming task.

For the tributaries of Paraguay River, the hydraulic model was able to reproduce both cases when (1) there is water loss for the floodplains resulting in hydrographs without well defined peak flows, and when (2) the observed hydrograph presents a more common shape, with marked peak and recession flows. The hydraulic model represented the marked seasonal flow regime along the Paraguay River, including time and amount of peak flows, as well as recession flows. The results in Porto Murtinho (which is the most downstream control point of this study) did not show a good agreement because of missing information to estimate flow contribution of a tributary of the right margin of Paraguay River in Bolivian territory, just upstream of that gauging station.

For rivers flowing at Pantanal, the floodplain is several times larger than the main channel, which strongly influences flood wave routing. The results obtained validate the approach of adopting cross-sectional profiles composed by main channel data and floodplain elevation values extracted from DEM for representing river hydraulics. Analysis concerning predictive uncertainty and the influence of errors and uncertainty in the input data over the results are being developed and may be subject of a future paper.

The actual drainage network in the Pantanal is far more complex than the one represented in the hydraulic model. Secondary channels along the floodplains connect the main rivers both during high and low flows. The importance of these secondary channels changes with time, and they may become active or inactive with siltation or clogging with vegetation. The most stable of those secondary channels is a 225-km reach parallel to the Paraguay River, known as Nabileque River, at the south part of the system. This was the only secondary channel which was represented in the model. At the other places, flow along the floodplains was represented using the active floodplain option allowed by the hydrodynamic model HEC-RAS. Probably better results will be attained in the future with a more detailed representation of the floodplain and secondary channels. Efforts have been initiated for using a different approach, coupling a 1D hydrodynamic model with a raster-based model for flood inundation simulation (Bates and De Roo 2000). However, the results shown in the present manuscript have the merit of obtaining very good results despite of all data limitations. To our knowledge, results presented here are the ones with the best skill in representing the behavior of the complex Pantanal river system.

Additionally, further studies will focus on simulating the whole Upper Paraguay River Basin, including the rainfall-runoff process in the contributing areas of Pantanal wetland. This modeling system will be able to predict land-use change scenarios, constituting a valuable tool for water resources and ecological managing purposes.

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