Coupled Hydrologic-Hydraulic Modeling of the Upper Paraguay River Basin

J. M. Bravo¹; D. Allasia²; A. R. Paz³; W. Collischonn⁴; and C. E. M. Tucci⁵

Abstract: This paper presents a detailed modeling of rainfall-runoff processes and flow routing along a complex large-scale region, the Upper Paraguay River Basin (UPRB), encompassing a drainage area of approximately 600,000 km², which extends over Brazil, Paraguay, and Bolivia. Within the UPRB lies the Pantanal, the world’s largest wetland, with extraordinary biodiversity and great ecologic value, but which currently is threatened by anthropogenic activities. A conceptual model was applied with two main components: (1) simulation of the basin and part of the Paraguay River tributaries by means of the distributed large-scale hydrological model MGB-IPH using simpler flow routing methods; and (2) simulation of the main drainage network, approximately 4,800 km of river reaches, with a one-dimensional hydro-dynamic model. Despite the data scarcity, complexity, and the intricate river drainage network of the region, the coupled model was able to represent the hydrological regime of the basin. Comparisons between observed and calculated hydrographs showed a good model skill in representing the flow regime of the upper Paraguay River and its tributaries, highlighting its value as a tool for understanding and predicting the system behavior. The proposed modeling of the hydrological processes of the UPRB, with a detail never presented before, provides a valuable tool for understanding ecosystem functioning and assessing its resilience to anthropogenic pressure, climate change, and climate variability.

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Introduction

There is currently an increasing effort for studying climate variability and climate change and its effects on biodiversity, water resources, food production, and other social, economic, and political aspects (Gedney et al. 2006; Heimann and Reichstein 2008; Barrios et al. 2008; Steele-Dunne et al. 2008; Jarvis et al. 2008). Inbetween the major effects predicted because of climate change (natural or human induced) are the changes in global and regional precipitation, food production, and other social, economic, and political aspects (Gedney et al. 2006; Heimann and Reichstein 2008; Barrios et al. 2008; Steele-Dunne et al. 2008; Jarvis et al. 2008). Inbetween the major effects predicted because of climate change (natural or human induced) are the changes in global and regional precipitation patterns and the consequent modification of flow regime in rivers (Betts et al. 2007; Gedney et al. 2006). Land-use changes caused by human activities have also significantly altered the hydrological processes related to the rainfall-runoff transformation in some parts of the world (Stohlgren et al. 1998; Galdino and Clarke 1997).

The investigation of these kind of effects over the water resources has required hydrologic studies encompassing large areas in which specific approaches must be employed (Overgaard et al. 2006; Xu 1999). In this sense, several distributed hydrologic models have been developed or adapted to deal with large-scale watersheds (Singh and Frevert 2002; Xu 1999; Wood et al. 1997; Croke II and He 2005; Croke II et al. 2005; DeMarchi et al. 2011). These models have been used to analyze the modifications in hydrological processes basically through sensitivity analysis of its parameters or using predicted precipitation and other climatic variables provided by meteorological models in estimating future flows (Benoit et al. 2000; Habets et al. 2004; Collischonn et al. 2005; Yu et al. 1999).

In general, large-scale distributed hydrologic models are composed of modules for calculating the soil water budget, evapotranspiration, flow propagation inside each discretization element, and flow routing through the drainage network. Relative simplified schemes are often used for streamflow routing, such as linear reservoirs, Muskingum-Cunge, or kinematic wave methods. When dealing with large-scale rivers in relative flat areas, however, backwater effect and floodplain inundation may become governing factors for flood wave routing. The floodplains may be several times larger than the main channel and act as important storage areas during the floods, dashing, and delaying peak flows. In this case, a one-dimensional (1D) hydrodynamic model may be coupled with the hydrologic model to provide a better representation of flow routing (Lian et al. 2007) as the application of more complex approaches such as two-dimensional (2D) and three-dimensional.
(3D) hydrodynamic modeling for large-scale sites may be infeasible because of data requirements, computational cost, and numeric instabilities (Bates and De Roo 2000; Verwey 2005; Werner 2004).

The main difficulties for combining hydrologic and hydrodynamic models for large-scale studies are related to numerical instabilities and data requirements and preparation. An off-line coupling of these models may weaken the first issue but not eliminate it as some care is still required when applying a full hydrodynamic model in terms of numerical instabilities (Cunge et al. 1980). The question of data requirements for hydrodynamic models, however, may be more critical, first because of scarcity of data availability for large areas, especially in developing countries (Patro et al. 2009), and secondly because it may involve data from different sources and formats. Data analysis and preparation may thus become an excessive time-consuming task.

In the Upper Paraguay River Basin (UPRB), located in three South American countries, Brazil, Bolivia, and Paraguay, in which data shortage and region complexity are a challenge, earlier hydrodynamic studies have focused on small portions of the basin or used a too simplified approach (Miguez 1994; Vila da Silva 1991; Hamilton et al. 1996; Pfafstetter 1993; Hamilton 1999; Tucci et al. 2005; Paz et al. 2007; Maathuis 2004; Kappel and Ververs 2004; Mascarenhas and Miguez 1994). The exception is the recent study of Paz et al. (2010), in which a full hydrodynamic model was applied using geographic information system (GIS)-based procedures for preparing input data and preserving spatial location of river hydraulics. In their study, a 4,800-km river drainage system was modeled, obtaining reasonable results. However, such a hydrodynamic modeling study was restricted to the Pantanal region only, which is the central portion of the UPRB with very low and flat relief and a complex drainage system and represents 25% of the basin area, using observed hydrographs as upstream boundary conditions.

As the study of Paz et al. (2010) represented only the flow routing along the river drainage system of the Pantanal region, it does not provide a way to assess land-use and climate change scenarios, for which a complete simulation of the rainfall-runoff processes in the entire UPRB is required. Modeling the rainfall-runoff transformation is extremely needed for predicting effects of several anthropogenic activities that currently threaten the region, such as agriculture, cattle raising, and dam building (Hamilton 2002; Da Silva and Girard 2004; Junk et al. 2006), beside improving the understanding of current system behavior. Nevertheless, the large dimensions of the UPRB, large diversity of biomes and topography, its peculiar hydrologic characteristics, and the lack of data to physically characterize the entire basin request a tremendous effort for developing such modeling studies.

This paper summarizes the methodology and results of the most complete and detailed coupled hydrologic-hydraulic modeling study applied for the whole UPRB. The entire drainage area of approximately 600,000 km² of the UPRB is modeled with a distributed hydrologic model coupled to the 1D-hydrodynamic model previously applied by Paz et al. (2010) for flow routing through the 4,800-km river drainage system. Results are evaluated by comparing observed and calculated hydrographs in 15 stream flow gauging stations. Analysis is also provided whether the inclusion of the rainfall-runoff processes simulation of the contributing areas of Pantanal compares with the modeling approach of Paz et al. (2010) in terms of reproducing river flow regime along Pantanal.

### Study Site

The Paraguay River is one of the main tributaries of the La Plata River, with a drainage area of 1,095,000 km² extending partially over four South American countries: 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 UPRB, which is the contributing area upstream of the affluence of the Apa River into the Paraguay river, with a drainage area of approximately 600,000 km². The UPRB may be further divided in three distinct regions (Fig. 1) according to topographic and hydrological characteristics: the Planalto (260,000 km²), the Chaco (200,000 km²) and the Pantanal (140,000 km²) regions.

The Planalto region consists of land lying above the 200-m elevation contour, primarily situated in the east and north parts of the basin, and presents a relatively rapid drainage. The annual rainfall exceeds 1,400 mm, with distinct seasonal distribution, and the land is used primarily for cattle raising and agriculture. In this region, the major part of the runoff of the entire UPRB originates; approximately 80% of the streamflow at the UPRB outlet comes from the Planalto.

The west portion of the UPRB belongs to the Chaco biome, which is characterized by very low rainfall and an endoreic drainage network, thus without significant contributions to the Paraguay River (MMA 1997).

The Pantanal region is located in the central portion of the UPRB and receives contributions from the basins draining the Planalto. The Pantanal, the world’s largest wetland, is classified as a sandy wetland on the basis of the grain size of its sediments (Iriondo 2004). Because of the gentle slope and low margins of the rivers in the Pantanal, the drainage system of this region is not able to convey the flood waters flowing from the Planalto, and extensive areas are flooded. Also, the tributaries of the Paraguay River exhibit a distributary drainage pattern responsible for reduction of channel

![Fig. 1. Location of Upper Paraguay River Basin and its division in the Planalto, Chaco, and Pantanal regions](image-url)
capacity and diversion to the floodplains (Assine and Soares 2004). The flow regime of the Paraguay River tributaries is primarily governed by this flooding process, which reduces peak discharges to more than a half (Bravo et al. 2005) and strongly modifies the shape of hydrographs from upstream to downstream along each river. This "loss to floodplain" behavior is also presented by the Paraguay River, as discussed by Assine and Silva (2009) for the reach of this river along the north border of the Pantanal.

The water that spills over the main channels may remain stored in large floodplains and shallow lakes during months or spreads over a divergent drainage system formed over alluvial fans (Bordas 1996; Assine 2005). This flood pulse process is seasonally marked, with an average flooded area of 50,000 km² each year (Hamilton et al. 1996), and strongly regulates the entire ecosystem integrity and conservation (Junk et al. 2006; Hamilton 2002).

As a result of the complex hydrologic regime of the UPRB, which governs much more complex sediment dynamics, there is an intricate drainage system in the Pantanal, including vast shallow lakes and divergent and endorreic drainage networks. In summary, as the annual rainfall is less than potential evaporation and drainage is very slow because of shallow gradients (Tucci et al. 1999; Bordas 1996), the Pantanal functions as a large natural hydrologic controller of the Paraguay River and its tributaries (Tucci et al. 2005; Bravo et al. 2005; Paz et al. 2010).

According to the Köppen climate classification, the region’s predominant climate is of the type tropical savanna, with rainfall concentrated in the summer. The rainy season begins in October and ends in April. Over most of the region, rainfall in the six wettest months accounts for more than 80% of the annual total. The wettest 3-month period is from November to January, whereas the dry season extends from May to September. In most of the basin, average temperatures range from 18 to 22°C. September and October are the hottest months, with mean temperatures ranging from 16 to 18°C. July is the coldest month, with mean temperatures ranging from 16 to 18°C.

An important climatic characteristic of the UPRB is the spatial variability of the annual rainfall, with a very strong east-west gradient, more than 1,500 mm to the east of the basin, less than 700 mm in the central region, and higher rainfall rates in a small region to the west. The Paraguay River itself runs from north to south following a path more or less aligned to the meridian 58°W. This line also approximately follows the 1,000-mm isohyets, with more rainfall to the east of the river and less than 1,000 mm west of it (Fig. 2). This rainfall distribution has a strong influence on regional hydrology. Because rainfall is higher to the east, tributaries of the east margin of the Paraguay River commonly contribute with more runoff than those to the west.

**Coupled Model Description and Data Preparation**

**Hydrologic and Hydraulic Models**

The conceptual model presented in this study has two main components: (1) simulation of the basin and part of the Paraguay River tributaries by means of a rainfall-runoff model with a simplified flow routing method; and (2) simulation of the main drainage network by a full 1D hydrodynamic model.

The large-scale, distributed hydrological model MGB-IPH was used as the first component of the conceptual model. It was developed for use in large South American basins with scarce data, and is fully described in Collischonn et al. (2007a). The drainage basin is represented by square-grid elements connected by channels, each one of these elements contains a limited number of distinct grouped response units (GRUs), i.e., areas with similar combination of soil and land cover (Kouwen et al. 1993), similarly to the hydrological response unit presented by Beven (2001). Each element has dimensions of 0.1 x 0.1° (approximately 10 x 10 km) in general; however, it depends on the basin size and model spatial discretization adopted. The MGB-IPH model consists of modules for calculating soil water budget, evapotranspiration, flow propagation inside an element, and flow routing through the drainage network. A soil water budget is calculated for each GRU, and runoff generated from the different GRUs in the element are then summed and propagated to the stream network using three linear reservoirs:

![Fig. 2. Isohyets map for the Upper Paraguay River Basin](image-url)
base flow, subsurface flow, and surface flow. Streamflow is routed through the river network using the Muskingum-Cunge method, considering different length and slope for each river reach representing the connection between two given elements, which are automatically derived from digital elevation model (DEM) processing (Paz and Collischonn 2007; Paz et al. 2006).

The MGB-IPH model has been typically applied with a daily time step as this is commonly the time discretization of available rainfall data, although smaller time steps could also be used. Precipitation data are interpolated to the center of each model grid element at each time step using the inverse-distance-squared method, whereas a nearest neighbor method is applied for other meteorological variables. The calibration of the MGB-IPH model is achieved by changing parameters values while maintaining relations between them and landuse. The multiobjective evolutionary algorithm MOCOM-UA (Yapo et al. 1998) is employed for MGB-IPH automatic calibration considering three objective functions: volume bias ($\Delta V$); Nash-Sutcliffe efficiency index for streamflow (NSS); and Nash-Sutcliffe efficiency index for the logarithms of streamflow (NSSLOG). Several applications of the MGB-IPH model for hydrological modeling and streamflow forecasting at large basins have been carried out with acceptable results (Allasia et al. 2006; Bravo et al. 2009; Collischonn et al. 2007b; Collischonn et al. 2005; Tucci et al. 2003).

The second component of the conceptual model is a 1D hydraulic-hydrodynamic model, which was used to perform river flow routing along the main drainage network of the Pantanal region. The well-known Hydrologic Engineering Center–River Analysis System (HEC-RAS) hydraulic model (USACE 2004) was used. It solves the full Saint Venant equations using an implicit Preissmann four point scheme of finite differences (Cunge et al. 1980), and Manning roughness coefficients are used to represent the resistance to flow.

**Application of the Hydrologic Model**

The MGB-IPH model was applied to the entire Upper Paraguay River Basin with a spatial discretization of square-grid elements of 0.1° resolution and a total of 5,195 grid elements, with surface area ranging from 114.5 to 120.2 km². A daily time step was used as precipitation, streamflow, and meteorological data are available in this time interval.

The river drainage network represented in the hydrologic model was automatically derived from the SRTM-90m DEM (Fig. 3), including flow direction and accumulated drainage area for each grid element and length and slope of river reaches connecting model elements. However, even using a stream burning procedure for preprocessing the DEM (Saunders 1999; Turcotte et al. 2001), manual corrections were necessary in the drainage network owing to the extreme flatness of the Pantanal.

The scarce precipitation and meteorological data (Fig. 3) were interpolated to the center of each grid element of the hydrological model at each time step. Soils were characterized using data available from the RADAMBrasil survey (Ministério das Minas e Energia 1983), PCBAP project (MMA 1997), and soil map published by the Food and Agriculture Organization of the United Nations (FAO) (1974, 1988). The soil types of the UPRB were grouped into eight classes according to their occurrence area and water storage capacity. Land-use classification was obtained by analyzing several Landsat7 ETM+ images, aiming basically at identifying areas occupied by crops, pasture, or native vegetation and seasonally flooded areas. According to available soil and land cover maps, soil types and land-use classes were combined. This...
resulted in a number of combinations, which were then grouped in 10 GRUs; this restriction in the number of GRUs aims at reducing model parameters and also to avoid representation of irrelevant or nonrepresentative physical characteristics for the scale of this study.

Table 1 summarizes the inputs and outputs of the hydrologic model for its application to the UPRB.

Application of the Hydraulic Model

The hydrodynamic model was applied for flow routing along the Paraguay River and its main tributaries, representing its vast shallow lakes and divergent and endorheic drainage networks through a combination of reaches and storage areas approach.

As described in Paz et al. (2010), input data for the hydraulic model was prepared in a consistent and georeferenced database through GIS-based automatic procedures developed for dealing with the large amount of data provided by several different sources, with distinct formats and horizontal and vertical datum. Detailed cross-section profiles of the main channel were combined with elevation values extracted from SRTM-90m for characterizing the floodplains, maintaining the link between hydraulic data and spatial location. Following these procedures, all the geometric data relative to 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.

Model calibration consisted in the setup of Manning’s coefficients ($n$). In this study, the coefficients calibrated by Paz et al. (2010) were used. These authors defined distinct values of $n$ for the main channel and floodplain for each river flow segment between two streamflow gauge stations by comparing observed and calculated hydrographs. This procedure was performed from upstream to downstream along the modeled drainage network manually varying $n$, but restricting them to the range reported in literature for these kinds of channels and floodplains. In total, there were 27 distinct river flow segments to have their corresponding $n$ coefficients calibrated. They run the HEC-RAS hydraulic model with a 12 hour-to-hour time step for the period of January 1, 1996 to December 31, 2000. Manning coefficients ranging from 0.02 to 0.035 were obtained for the main channel, and from 0.04 to 0.2 for the floodplain. Table 2 summarizes the inputs and outputs of the hydraulic model for its application to the UPRB.

Coupling the Hydrologic and Hydraulic Models

A one-way and off-line coupling between the hydrologic and hydraulic models was adopted. The HEC-RAS hydraulic model fitted by Paz et al. (2010) was run with a 12-h time step for the same time period adopted by those authors (January 1, 1996 to December 31, 2000), but now using as input at the upstream boundary conditions the daily flows calculated by MGB-IPH model.

The entrance of each river into the Pantanal area was adopted as the upstream boundary condition in the hydraulic model (Fig. 4) as downstream from this point the flood wave is not correctly routed by the Muskingum-Cunge methodology used in the hydrologic model. Thus, the hydrographs calculated by the MGB-IPH model at these upstream boundary conditions were considered as the contribution of the Planalto region for the downstream river network modeled by the HEC-RAS model. In addition, streamflow generated in the Pantanal and Chaco areas through the rainfall-runoff transformation represented by the MGB-IPH model was considered as lateral inflows to the hydraulic model.

Simulation and Discussion

Hydrologic Model Results at Planalto

Model parameters were primarily set according with each GRU’s characteristics, but some of them were adjusted by the automatic calibration process available for the MGB-IPH, restricting the parameter search between realistic physical limits. In spite of being a physical distributed model, as the number of distinct GRUs was set to a maximum of 10, because of computational limitations,

<table>
<thead>
<tr>
<th>Data type</th>
<th>Description</th>
<th>Digital format</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input; basin physical characteristics</td>
<td>Soil type and land use, which are combined into GRUs; topography; parameters related to land use: leaf area index, surface resistance, albedo, and vegetation height</td>
<td>Raster; raster; ASCII</td>
</tr>
<tr>
<td>Input; discretization and drainage network</td>
<td>Basin division into elements; drainage network connecting model elements; length and slope of river reaches connecting model elements; surface area and contributing drainage area for each element</td>
<td>Raster; raster</td>
</tr>
<tr>
<td>Input; hydro-meteorological data</td>
<td>Precipitation time series; meteorological information: air temperature, atmospheric pressure, solar radiation, wind speed, and relative humidity</td>
<td>ASCII; ASCII</td>
</tr>
<tr>
<td>Output</td>
<td>Streamflow at the boundary conditions of the hydraulic model</td>
<td>ASCII</td>
</tr>
<tr>
<td>Output</td>
<td>Lateral inflow to reaches of the hydraulic model</td>
<td>ASCII</td>
</tr>
</tbody>
</table>

Table 2. Description of Input and Output Data for Applying the HEC-RAS Model to the UPRB

<table>
<thead>
<tr>
<th>Data type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input; geometry</td>
<td>River reaches and system network; composed (channel-floodplain) cross-section profiles; distance between cross sections; characteristics of storage areas (location and elevation-volume curves)</td>
</tr>
<tr>
<td>Input; parameter</td>
<td>Manning’s roughness coefficient in channel and floodplain for each river flow segment between two streamflow gauge stations estimated by the MGB-IPH model</td>
</tr>
<tr>
<td>Input; boundary conditions</td>
<td>Streamflow at the boundary condition estimated by the MGB-IPH model; lateral inflow into several river reaches estimated by the MGB-IPH model</td>
</tr>
<tr>
<td>Output</td>
<td>Streamflow at the several control points inside the Pantanal region</td>
</tr>
</tbody>
</table>
some regions of the basin were not represented with enough details to correctly characterize the local hydrological processes. Consequently, slight differences among subbasins were allowed for varying the MGB-IPH model parameters related to GRU characteristics.

Different time periods were considered for calibrating each of the subbasins at the Planalto according to data availability. A total of 15 parameters of the MGB-IPH model was calibrated. The description of each parameter and its influence on distinct aspects of hydrological processes representation are described by Collischonn et al. (2007a). As a result of the calibration process, several Pareto optimal solutions were found for each gauging station, and a single solution was chosen among them, aiming at providing an acceptable tradeoff in fitting of the different parts of the hydrograph (Bastidas et al. 2002).

In general, the model fitted well as the NSS and NSSLOG coefficients were approximately 0.80 in most catchments in both calibration and validation periods (Table 3). The errors in volume between observed and calculated hydrographs were also acceptable, being close to 2–4% in most cases. Examples of the fit between calculated and observed hydrographs are presented.

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**Table 3. Statistics Showing Goodness of Hydrologic Model Fit in the Planalto Region of the Upper Paraguay River Basin**

<table>
<thead>
<tr>
<th>Reference</th>
<th>River</th>
<th>Station name</th>
<th>Time period</th>
<th>Drainage area (km²)</th>
<th>NSS</th>
<th>Volume error (%)</th>
<th>NSSLOG</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>Cuiabá</td>
<td>Rosario Oeste</td>
<td>1980–1990</td>
<td>14,688</td>
<td>0.81</td>
<td>0.00</td>
<td>0.84</td>
</tr>
<tr>
<td>(b)</td>
<td>Cuiabá</td>
<td>Cuiabá</td>
<td>1980–1990</td>
<td>22,037</td>
<td>0.80</td>
<td>1.70</td>
<td>0.82</td>
</tr>
<tr>
<td>(g)</td>
<td>Taquari</td>
<td>Porto Pedro Gomes</td>
<td>1978–1984</td>
<td>9,300</td>
<td>0.49</td>
<td>2.40</td>
<td>0.65</td>
</tr>
<tr>
<td>(h)</td>
<td>Taquari</td>
<td>Coxim</td>
<td>1978–1984</td>
<td>27,040</td>
<td>0.81</td>
<td>–1.30</td>
<td>0.84</td>
</tr>
<tr>
<td>(o)</td>
<td>Upper Paraguay</td>
<td>Barra do Bugres</td>
<td>1993–1999</td>
<td>10,120</td>
<td>0.80</td>
<td>0.18</td>
<td>0.80</td>
</tr>
<tr>
<td>(q)</td>
<td>Upper Paraguay</td>
<td>São José Sepotuba</td>
<td>1993–1999</td>
<td>8,640</td>
<td>0.73</td>
<td>–0.20</td>
<td>0.76</td>
</tr>
<tr>
<td>(r)</td>
<td>Upper Paraguay</td>
<td>Cáceres</td>
<td>1993–1999</td>
<td>33,890</td>
<td>0.88</td>
<td>–0.45</td>
<td>0.91</td>
</tr>
<tr>
<td>(d)</td>
<td>Itiquira</td>
<td>Itiquira</td>
<td>1975–1981</td>
<td>2,872</td>
<td>0.65</td>
<td>–0.60</td>
<td>0.71</td>
</tr>
<tr>
<td>(e)</td>
<td>Itiquira</td>
<td>BR 163</td>
<td>1975–1981</td>
<td>5,100</td>
<td>0.74</td>
<td>4.10</td>
<td>0.78</td>
</tr>
<tr>
<td>(c)</td>
<td>Vermelho</td>
<td>Rondonópolis</td>
<td>1992–1999</td>
<td>11,995</td>
<td>0.56</td>
<td>1.50</td>
<td>0.71</td>
</tr>
<tr>
<td>(j)</td>
<td>Aquidauana</td>
<td>Ponte do Grego</td>
<td>1992–1997</td>
<td>6,830</td>
<td>0.74</td>
<td>–3.00</td>
<td>0.74</td>
</tr>
<tr>
<td>(k)</td>
<td>Aquidauana</td>
<td>Aquidauana</td>
<td>1992–1997</td>
<td>15,200</td>
<td>0.83</td>
<td>–2.00</td>
<td>0.84</td>
</tr>
<tr>
<td>(l)</td>
<td>Miranda</td>
<td>MT 738</td>
<td>1994–1999</td>
<td>11,820</td>
<td>0.66</td>
<td>1.10</td>
<td>0.71</td>
</tr>
</tbody>
</table>
in Fig. 5 for eight control points in the Planalto region, in which six of them represent the outlet sections of rivers flowing from Planalto to Pantanal.

The statistics presented previously should be understood in the context of data scarcity. The study used data from 86 streamflow and 92 rainfall gauges, which indicates a density of one discharge gauge every $2.953 \text{ km}^2$ and one rainfall information every $2.760 \text{ km}^2$ in the best and rare situation of having available data in a given day at all the stations simultaneously. These densities are too far from the World Meteorological Organization's recommended ones for regions characterized by difficult data acquisition. Consequently, worst (best) results were achieved in the least (best) monitored basins. For example, it was not uncommon to have only one working rainfall station in the Aquidauana basin during most of the period, resulting in a density close to one rainfall information every $10,000 \text{ km}^2$. In light of this, results obtained were considered acceptable.

**Coupled Model Results at Pantanal**

The first interesting analysis of the results at Pantanal is the comparison to the results obtained in the former study of Paz et al. (2010), which used observed streamflow as an upstream boundary condition instead of coupling a distributed hydrological model. The statistics obtained after comparing observed and calculated hydrographs along the Paraguay River and tributaries were similar in both studies in terms of NSS and root-mean-square error (RMSE) (Fig. 6). Overall, the better the fit obtained by Paz et al. (2010), the smaller the difference between the statistics of those authors and this paper's. In other words, the difficulties in reproducing the observed flow regime at some streamflow gauge stations found by the discussed study, in which the Manning coefficients of the 1D hydrodynamic model were adjusted, were enlarged when the modeling of the rainfall-runoff processes over their contributing areas was included. This was expected because the uncertainties in precipitation estimates and in the rainfall-runoff modeling are now incorporated in the modeling. However, the similarity between the results achieved by this study relative to that obtained by the simplified approach of using observed discharges as upstream boundary conditions highlights the very reasonable results of the effort to model the entire UPRB.

The coupled model satisfactorily reproduced the observed flow regime at the tributaries, as illustrated by visual inspection of the hydrographs (Fig. 7) and according to the statistics obtained and showed in Table 4, in which MAE means mean absolute error.
**Fig. 6.** Comparison between the performance measures NSS and RMSE obtained in this study, coupling hydrologic-hydrodynamic models, and those reported by Paz et al. (2010), which used observed streamflow as an upstream boundary condition to the hydrodynamic model; circles refer to stations along Paraguay River; triangles refer to tributaries.

**Fig. 7.** Calculated (black line) and observed (gray line) hydrographs at six control points along tributaries of the Paraguay River.
and MRE means mean relative error. The NSS coefficients ranged between 0.7 and 0.9 for half of the available gauge stations and were less than 0.5 for only three of them (São João, São Jerônimo, and Porto Ciríaco). Along the tributaries, the MRE ranged between 12 and 22%, except at the Barão de Melgaço, São João, and Miranda stations, in which this measure was greater than 30%.

The major difficulty in reproducing flow regime along the Paraguay River tributaries is mostly because of uncertainties related to scarcity of available cross-section profiles. However, the proposed coupled hydrologic-hydraulic model was capable of reproducing the distinct observed flow regimes at the tributaries of the Paraguay River. At Barão de Melgaço, the Cuiabá River presents a marked seasonal flow regime, with the flood period occurring between October and May and peak flows reaching 1,600 m³·s⁻¹, whereas the recession flows are approximately 100 m³·s⁻¹. The São Lourenço River at the São José station also presents a marked seasonal flow regime, but this is characterized by smoother raising and falling limbs in comparison to the Cuiabá River at Barão de Melgaço, which presents more nervous oscillations in response to precipitation events. At São José, peak and recession flows are typically approximately 400 and 160 m³·s⁻¹, respectively, which mean flood peaks of just 1.5 times greater than recession flows. This ratio is 10 times greater for the Cuiabá River at Barão de Melgaço. However, downstream of this station, at Porto do Alegre, the flow regime of the Cuiabá River becomes very similar to that of the São Lourenço River at São José: smooth raising and falling limbs of flood hydrographs with relative small variation between flood peaks and recession flows. At São José Piquiri in the Piquiri River, a behavior slightly similar to this is observed but with more pronounced flood peaks. In turn, the flow regime at Miranda station in the Miranda River presents weak seasonality but with rapid and very pronounced response of flows to precipitation events. Lastly, at the Porto Ciríaco station in the Aquidauana River, the flow regime is very distinct to all those discussed previously, presenting a marked maximum value of 150 m³·s⁻¹ and slight seasonality. The observed hydrograph at this station presents only small peak flows, as during the major floods a huge volume of water spills over the main channel and inundates the floodplains, resulting in a slash of the raising limb at the value of 150 m³·s⁻¹.

All the complex flow regimes described were satisfactorily reproduced by the coupled hydrologic-hydraulic model, as indicated by visual comparison of observed and calculated hydrographs and by statistics shown in Table 4. Additionally, the remarkable changes in flow regime along each river flowing from Planalto to Pantanal were also reproduced by the proposed model. These changes are a consequence of the low conveyance capacity of river channels at Pantanal and the resultant floodplain inundation. For instance, compare the hydrographs between Rondonópolis (Fig. 5) and São José (Fig. 7); at the former, which represents the São Lourenço River outlet section from Planalto, seasonal peak flows range between 900 and 1,200 m³·s⁻¹, whereas at São José, the hydrograph is much smoother and peak flows are less than 450 m³·s⁻¹. Another notable example is along the 230-km reach of the Aquidauana River between the Aquidauana (Planalto) and Porto Ciríaco (Pantalán) stations, in which peak flows reduce from 700 m³·s⁻¹ to less than 150 m³·s⁻¹.

As obtained in the study of Paz et al. (2010), the worst results were found for the São João station, located in the Cuiabá River upstream the confluence of the São Lourenço and Piquiri Rivers. Along this river reach, the main channel capacity is reduced, and floods are diverted to the floodplain even at the smaller discharges; more than 50% of the annual volume is lost to the floodplain, and the peak discharge decreases from 2,000 m³·s⁻¹ to less than 400 m³·s⁻¹. Water in the floodplain may remain up to 3–5 months stored and evaporating before return in a diffused and not very well understood way through the complex system of secondary channels, shallow lakes, and ponds. However, the good model fit obtained at the Porto de Alegre station, for instance, MRE = 18% and NSS = 0.73, located 50 km downstream of São João suggests that the bias found at São João becomes less important after the inflow of the other tributaries of the Cuiabá River.

The results obtained at the Paraguay River show that the applied model was able to reproduce the marked seasonal flow regime and the typical relatively smooth shape of hydrographs, as illustrated by Fig. 8. In Fig. 8, calculated and observed hydrographs at six stations along the Paraguay River are shown, depicting the changes in hydrographs according to flood routing from Cáceres up to Porto Murtinho, a reach of approximately 1,300 km. Along this flowpath, the Paraguay River receives significant contributions along its left margin, mostly from drainage basins of Cuiabá and Miranda Rivers. More importantly, these contributions occur by means of waters drained by both the main channel and floodplains, i.e., water flowing along floodplains of tributaries may contribute to channel flow along some reaches of the Paraguay River. On the
contrary, along other reaches of this river, huge volumes of water spill over the main channel and inundate the floodplain. These multifaceted lateral water exchanges between channel and floodplain strongly make the hydrodynamic modeling of the Paraguay River difficult. Thus, the results obtained are very satisfactory as the applied model reproduced the variations on time and magnitude of flood peaks and recession flows along the Paraguay River, as indicated by statistics summarizing the comparison between observed and calculated hydrographs. At the Cáceres, Descalvados, Porto Conceição, Amolar, and Porto da Manga stations, NSS was greater than 0.74. The worst results were obtained at the São Francisco (NSS = 0.50) and Porto Murtinho (NSS = 0.48) stations. Along the Paraguay River, RMSE ranged between 52 and 510 m$^3$·s$^{-1}$, and MAE ranged from 44 to 402 m$^3$·s$^{-1}$. These values are apparently too large but correspond to MREs varying from 10 to 12%, except at São Francisco (21%) and Porto Murtinho (16%). The difficulty in reproducing observed flow regime three of them (Francisco may be because of occurrence of contributions drained by Taquari River floodplains, which was not well-represented in the proposed model. At Porto Murtinho, the major reason for not achieving better results is the data scarcity for characterizing the contributions of the Bolivian part of the basin along the right margin of the Paraguay River. This was already suggested in the study of Paz et al. (2010), which indicated the secondary flood peaks in the observed hydrograph as being probably generated in the Bolivian part of Pantanal. On the contrary, an earlier study had concluded that the contribution of the Bolivian side of the basin was insignificant and could be disregarded (MMA 1997), considering the loss of water because of floodplain inundation and evaporation process and using a simplified hydrological balance procedure on the basis of available discharge data, i.e., data from streamflow gauging stations located in the Brazilian part of the basin. The study indicates, however, that for better fitting hydrograph volumes and timing along the Paraguay River downstream of Amolar, the contribution from the Bolivian part of the basin must be better quantified and represented in the model.

**Conclusions**

This paper showed the application and results of coupled hydrologic-hydraulic modeling of the entire Upper Paraguay River Basin, encompassing a drainage area of approximately 600,000 km$^2$. This is the most comprehensive study on the
hydrologic simulation of the whole Upper Paraguay River Basin and flow regime of the Paraguay River and its tributaries. This study greatly amplifies the previous one presented by Paz et al. (2010), which focused on fitting the 1D hydrodynamic model for the Paraguay River and its tributaries flowing along Pantanal. In the study, the transformation of rainfall into runoff was incorporated in the modeling, consequently bringing together the uncertainties in estimates of precipitation and of other meteorological variables and the difficulties in physically characterizing such a large area in terms of soil type and vegetation cover and representing them into the distributed hydrological model. Overall, the similarity of the results achieved by this study relative to that obtained by the simplified approach of using observed discharges as upstream boundary conditions highlights the capability of the model presented in this paper.

Despite the data scarcity, complexity, and the intricate river drainage network of the region, the coupled modeling was able to satisfactorily represent the rainfall-runoff transformation and flow routing along the basin. The distinct and complex flow regimes along each of the tributaries of Paraguay River were well-represented, including the changes in hydrograph shape as a result of the differences in slope and cross-section area between river reaches at Planalto and at Pantanal. Flood flow routing along the 1,300-km reach of the Paraguay River was also reasonable reproduced by the proposed model, both in terms of magnitude and timing of peak and recession flows. Some difficulties were encountered for reproducing flow regime downstream of the Amolar station and largely at Porto Murtinho because of data scarcity (discharges, precipitation, and other meteorological variables) to properly estimate contribution from the Bolivian part of the basin at the right margin of the Paraguay River.

The effort on modeling the hydrological processes of the entire UPRB provides a valuable tool for understanding the ecosystem’s functioning and for assessing its resilience to anthropogenic pressure, climate change, and climate variability. For instance, the applied coupled model will be able to predict how landuse, precipitation, and temperature change scenarios will affect the streamflow at major river reaches. However, the achievement of these goals is dependent on gathering more data, which, because of the characteristics of the basin, should be relied in remote sensing techniques or meteorological reanalysis.

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