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Using TRMM rainfall estimates in hydrologic and hydrodynamic modelling of the Amazon Basin

RODRIGO CAUDURO DIAS DE PAIVA[1], DIOGO COSTA BUARQUE[1], WALTER COLLISCHONN[1], MINO S. SORRIBAS[1], DANIEL GUSTAVO P. ALLASIA[2], CARLOS ANDRÉ B. MENDES[1], CARLOS E. M. TUCCI[1] & MARIE-PAULE BONNET[3]

1 *Instituto de Pesquisas Hidráulicas – IPH/UFRGS, Av. Bento Gonçalvez, 9500 – Agronomia, Campus do Vale, Setor 5, CEP 91501-970 – Porto Alegre/RS, Brazil*
rodrigocdpaiva@gmail.com

2 *Departamento de Hidráulica e Saneamento – UFSM, Av. Roraima, 1000 – Camobi, Cidade Universitária, Prédio 07, salas 518 a 523, Centro de Tecnologia, CEP 97105-900 – Santa Maria/RS, Brazil*

3 *IRD – Institut de Recherche pour le De´veloppement, UR154 LMTG, 14, Av. Edouard Belin, 31400 Toulouse, France*

Abstract Hydrological modelling of the Amazon is an enormous challenge because of its size, limited data, regional climatic diversity and particular hydraulic features, which include low gradients, back-water effects and extensive inundated areas. However, uncertainties in rainfall arising from limited ground-level measurements and low raingauge density impose severe difficulties, particularly in parts of the drainage basin lying outside Brazil. Rainfall estimation by remote sensing using satellite-derived data from the Tropical Rainfall Measuring Mission (TRMM) is a possible means of supplementing raingauge data, having better spatial cover of rainfall fields. This study reports on the use of the MGB-IPH large-scale hydrological model with rain fields obtained from TRMM. The MGB-IPH is a distributed, physically-based model using the Muskingum-Cunge formulation and a full hydrodynamic model for river routing, including backwater effects and seasonal flooding. Applying the model to the whole Amazon basin required development of several pre-processing tools to generate information about river cross-sections, flood plain extent, flood volume, and water slope from the SRTM DEM. Although TRMM under-estimates rainfall in regions with more marked relief, such as the transition region between the Amazon and the Andean regions of Peru, Ecuador and Colombia, results from the model in terms of its ability to reproduce observed hydrographs at several locations throughout the basin are encouraging.

Key words TRMM; hydrological modelling; hydrodynamic modelling; Amazon Basin

INTRODUCTION

The climate variability in the Amazon River basin and the anthropogenic pressure of economic development, coupled with population vulnerability, are factors that increase the risk from extreme hydrological events. To minimize these risks it is necessary to act preventively by improving understanding of the natural system and through reduction of vulnerability and uncertainty through the prediction of weather, climate and hydrology. In this sense, hydrological modelling in the Amazon River is an interesting challenge because of its size, limited data, regional climatic diversity and particular hydraulic features which include low gradients, back-water effects and extensive inundated areas. However, uncertainties in rainfall arising from limited ground-level measurements and low raingauge density impose severe difficulties, particularly in parts of the drainage basin lying outside Brazil, and is a major source of uncertainty in studies of hydrological processes, hydroclimatic variability, biogeochemical analysis and drainage basin response (e.g. Coe *et al*., 2008; Collischonn *et al*., 2008; Beighley *et al*., 2009).

Estimation of rainfall using satellite-mounted instrumentation, on the other hand, avoids the problems of limited spatial coverage of ground-based raingauge networks, although the lengths of record obtainable from such sources are, as yet, fairly short. CMORPH (Joyce *et al*., 2004), giving 30-min rainfall at a spatial resolution of 8 km at the equator, began in late 2002, whilst the Tropical Rainfall Measurement Mission (TRMM) algorithm 3B42 (Huffman *et al*., 2007), giving 3-hour rainfall at a spatial resolution of 25 km, dates from 1998. Despite this, compared with raingauge data, the rapidity with which remote-sensed precipitation estimates become available is attractive. In this sense, where the density of ground-level networks of hydrologic instruments is sparse, as is true in the Amazon basin, rainfall estimation by remote sensing using satellite-derived data is a possible means of supplementing the limited data available from surface sites, having better spatial cover of rainfall fields. Several studies have been reported which explored aspects of remote-sensed rainfall in the Amazon, in particular using TRMM data sets (Collischonn *et al*., 2008; Condom *et al*., 2010; Getirana *et al*., 2010; Tian & Peters-Lidard, 2010; Paiva *et al*., 2011).

As part of a wider project to apply a large-scale, distributed and process based hydrological-hydrodynamic model, named MGB-IPH (Collischonn *et al*., 2007; Paiva, 2009; Paiva *et al*., 2011), the present work reports results on the use of this model for the whole Amazon basin (including Amapá State and the Tocantins River basin, as shown in Fig. 1) with rain fields obtained from TRMM 3B42.

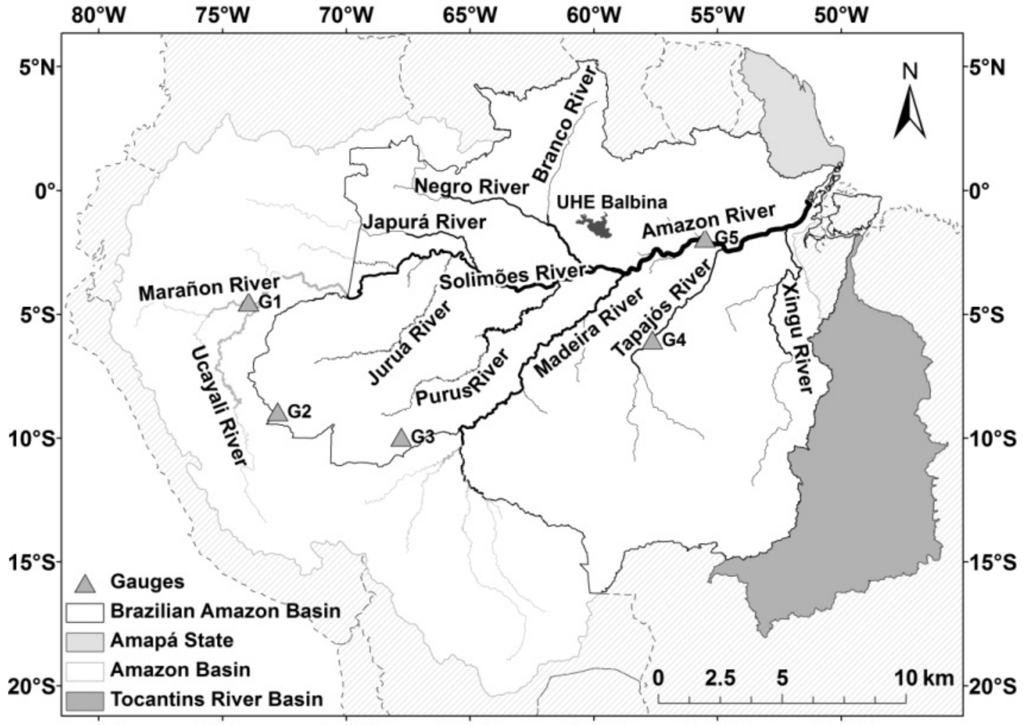

Fig. 1 Amazon River basin with main tributaries and streamgauges (grey triangles) used for analysis of model results.

THE MGB MODEL

The MGB-IPH is a large-scale hydrological model, which has been applied before to several other large-scale basins in South America. The MGB-IPH is a distributed and process-based hydrological model, which uses a catchment based discretization and a Hydrological Response Units (HRU) approach. It uses physical based equations to simulate the hydrological processes, such as the Penman Monteith model for evapotranspiration, and the Moore and Clarke approach for soil infiltration. River routing is done either using the Muskingum-Cunge method or a full hydrodynamic model, or a combination of both. The hydrodynamic model uses the full Saint Venant equations, a simple flood plain storage model and GIS based parameters extracted from Digital Elevation Models, and is capable of simulating backwater effects and seasonally flooded flood plains. The application of this model to the whole Amazon basin demanded the development of several pre-processing tools, aimed at generating the necessary data for the hydrodynamic model from the SRTM DEM, based on relatively poor information, as river cross sections, flood plain extent and volume, and river slope was developed. Details concerning the model structure can be found in Collischonn *et al*. (2007), Paiva (2009) and Paiva *et al*. (2011).

DATA SET and model discretization

The study area is the whole Amazon River basin including the Tocantins River Basin as presented in Fig. 1. We used the SRTM DEM (Farr *et al*., 2007) with 15″ resolution (approximately 500 m) for model discretization. The Amazon basin was discretized into 6863 catchments, in which 92% has areas between 100 and 5000 km^2. An HRU map with 12 classes was developed using soil and vegetation maps from the Brazilian database RADAMBrasil Project (RADAMBRASIL, 1982), SOTERLAC/ISRIC (Dijkshoorn *et al*., 2005) and the "Vegetation Map of South America" developed by Eva *et al*., (2002). Discharge data from 172 streamgauges was provided by the Brazilian agency for water resources ANA (Agência Nacional das Águas) and model results were analysed in all of those gauges, but analysis for only five streamgauges (Fig. 1 and Table 1) are shown here. Meteorological data were obtained from the CRU CL 2.0 dataset (New *et al*., 2002). We used the TRMM precipitation data provided by algorithm 3B42 (Huffman *et al*., 2007), with spatial resolution of 0.25° × 0.25° and daily temporal resolution, for the 8-year period 1998–2005. Data sets from TRMM were than interpolated to each catchment centroids, providing more reliable daily rainfall time series than can be achieved with the sparse ground-based raingauge networks existent due to its spatial cover of rainfall fields.

The MGB-IPH parameters related to soil water budget were calibrated, using discharge data from the 1998–2005 period from 172 streamgauges, with the MOCOM-UA algorithm (Yapo *et al*., 1998), as described in Collischon *et al*. (2007).

Table 1 Streamgauges used for analysis of model results.

Code	Name	Latitude	Longitude	Point
10070500	San Regis	–4.51000	–73.95000	G1
12370000	Taumaturgo	–8.93985	–72.77709	G2
13600002	Branco River	–9.96061	–67.78580	G3
17500000	Fortaleza	–6.04031	–57.63946	G4
17050001	Óbidos	–1.92322	–55.51858	G5

RESULTS AND DISCUSSION

Figures 2 and 3 present simulated and observed discharges in the gauges shown in Fig. 1 and described in Table 1. Results in the figures are shown only for the 2001–2004 period. The model performance using TRMM 3B42 data is very good near the outlet of the Amazon River basin in the Óbidos streamgauge (Fig. 3(c)). In this site, the Nash and Suttcliffe index is $E_{NS} = 0.89$ and the error in the volume equals $\Delta V = -5.6\%$, showing that the timing of the flood wave in the Amazon mainstream is well represented by the model and the error in the volume is small. Results are also promising in the Amazon main tributaries, exemplified here using results in the Purus and Tapajós rivers. The MGB-IPH model using TRMM 3B42 presented very good results in the Tapajós River, representing very well the peaks of the flood, the flow recessions and total volume ($E_{NS} = 0.95$ and $\Delta V = 0.1\%$). In the Purus River we selected a streamgauge in the upper part of the basin to show model performance in a smaller river basin. Hydrographs in small basins are noisy, with several peaks related to intense rainfall events, different from the lower part where the flood waves are attenuated and delayed due to river and flood plain effects. Results for this selected basin were also good ($E_{NS} = 0.84$ and $\Delta V = 2.7\%$) and the model with TRMM 3B42 was able to simulate mean discharge, low and high flows, although some of the peaks were not well represented.

Although model results were good for most of the streamgauges used for comparisons, poor agreements with observations were found in some regions such as small or headwater catchments, and areas outside Brazil. Figure 3 shows results in parts of the basin where the MGB-IPH with TRMM 3B42 presented some errors. In small river basins such as in upper Jurua River basin (e.g. gauge 12370000, Fig. 3(a)), the MGB-IPH with TRMM data could not resolve intense rainfall events, the peaks in the hydrograph were not represented by the model and the model performance was low (E_{NS} = 0.45 and $\Delta V = -30.6\%$). These errors are perhaps related to the spatial resolution of TRMM 3B42 (~ 25 km), that may be too coarse to represent these intense rainfall events in small catchments.

Model results also presented relevant errors in the Solimões River basin outside Brazil. TRMM data seemed to underestimate rainfall in this region. As a result, in the Marañon River (Fig. 3(b)) the MGB-IPH underestimated streamflow ($\Delta V = -18.2\%$) and model performance was low (E_{NS} = 0.08); even though the timing of flood waves have been represented. This may be related to errors in satellite rainfall estimates in the Amazon basin outside Brazil, mainly in the Andean region, that were also shown by Tian & Peters-Lidard (2010) in a global map of uncertainties of satellite precipitation estimates and by Condom *et al*. (2010).

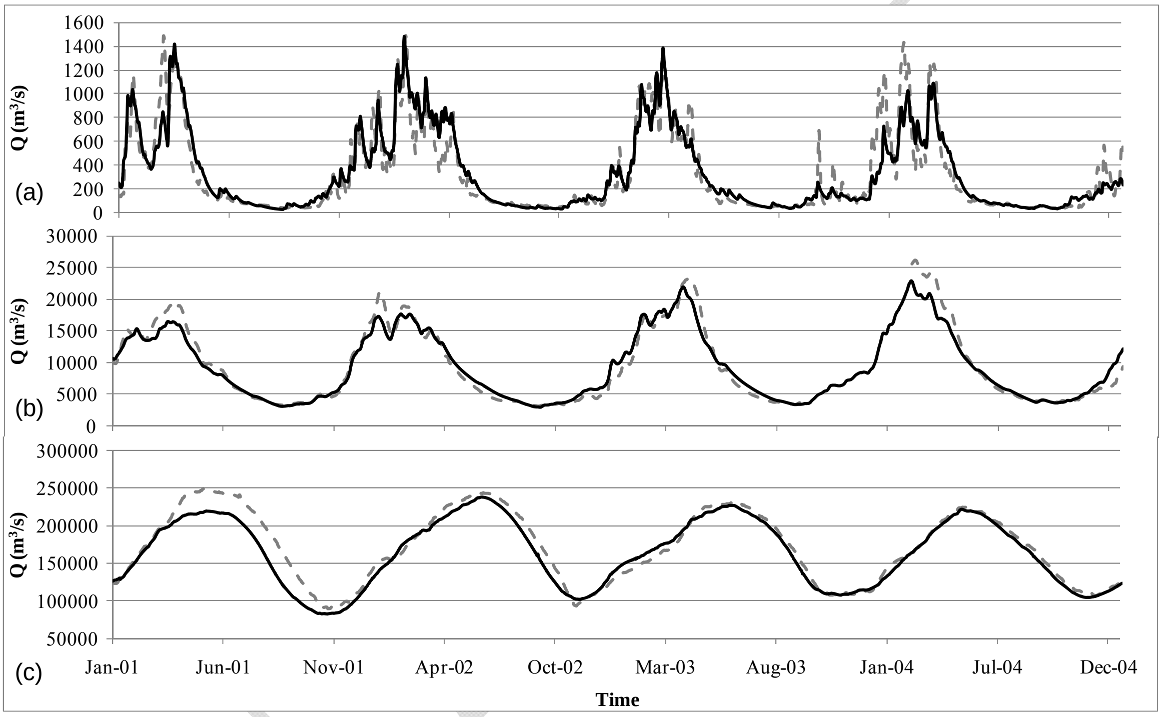

Fig. 2 Observed (dashed grey line) and simulated (black line) daily streamflow in the gauges 13600002 (a), 13500000 (b) and 17050001 (c) in the 2001 to 2004 time period.

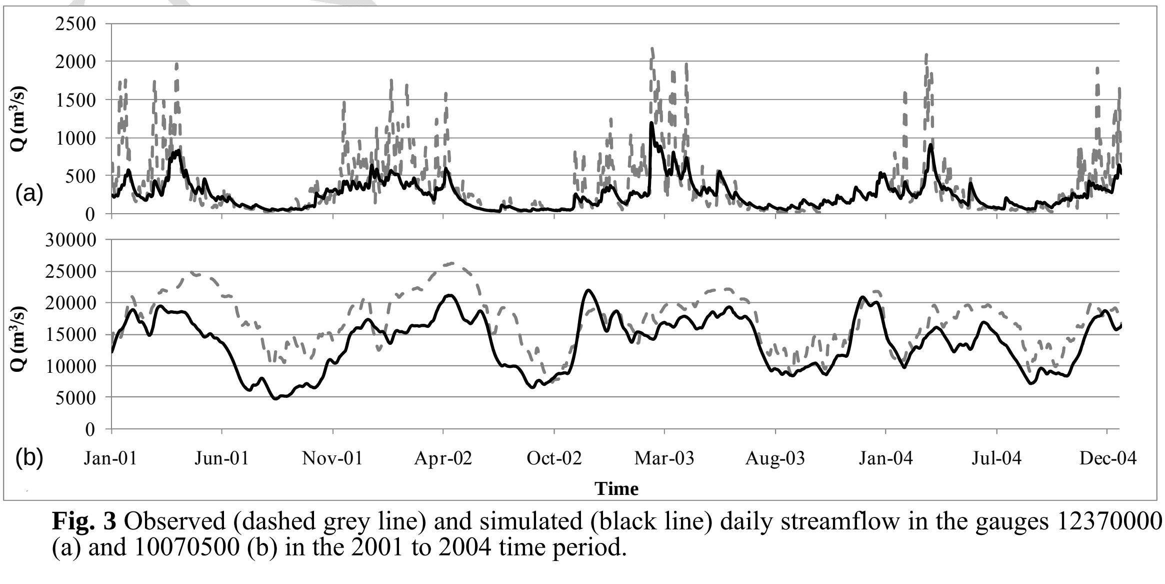

Fig. 3 Observed (dashed grey line) and simulated (black line) daily streamflow in the gauges 12370000 (a) and 10070500 (b) in the 2001 to 2004 time period.

In this paper, we preferred to validate the TRMM data set by comparing the MGB-IPH model outputs with discharge measurements because: (i) the spatial coverage of the ground-based raingauge network is limited in the Amazon, mainly outside Brazil, (ii) the objective of our study is to apply a hydrological model to get discharge estimates in a region with a lack of raingauge data, and (iii) when comparing rainfall fields obtained by satellites with raingauge data several difficulties arise, such as the irregular spatial coverage of the raingauges and differences between point (raingauge) and areal averaged (satellite based) rainfall estimates. Although there are other sources of model errors such as uncertainty in input data, parameters and model structure, uncertainty in rainfall data is one of the greatest importance, and the above-mentioned difficulties can be reduced by integrating TRMM rainfall fields within a catchment using hydrological modelling and comparing the model results with observed discharges.

CONCLUSION

The MGB-IPH model using TRMM 3B42 data was shown to be able to reproduce observed hydrographs in the Amazon River and main tributaries well. TRMM 3B42 data under-estimates rainfall in the Amazon River basin outside Brazil, in the transition region between the Amazon and the Andean regions of Peru, Ecuador and Colombia, and as a result the model underestimates discharge in parts of such regions. However, comparisons of model results with discharge observations at several locations throughout the basin showed that model performance using TRMM 3B42 data is encouraging.

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