Predictions in Ungauged Basins: Promise and Progress (Proceedings of symposium S7 held during the Seventh IAHS Scientific Assembly at Foz do Iguaçu, Brazil, April 2005). IAHS Publ. 303, 2006.

Large basin simulation experience in South America

DANIEL GUSTAVO ALLASIA,
BENEDITO CLÁUDIO DA SILVA, WALTER COLLISCHONN & CARLOS EDUARDO MORELLI TUCCI
Institute for Hydraulic Research, Federal University of Rio Grande do Sul, PO Box 15029, 91501-970, Porto Alegre, RS, Brazil
hidrologia@gmx.net

Abstract This paper presents some applications of the Large Basin Hydrological Model developed in the Instituto de Pesquisas Hidraulicas of the Federal University of Rio Grande do Sul, Brazil (MGB-IPH) in the simulation of different South American basins. The MGB-IPH is a large scale hydrological model, distributed in square grid cells, which represents the processes of interception, soil water storage, evapotranspiration, runoff generation by surface, groundwater and subsurface processes, and flow propagation through the river network. Spatial variability is represented by the distribution of the physical characteristics through the cells all over the basin, relating it to readily available data, mainly from remote sensing. Applications of this model in South America include real time flow forecasts, seasonal flow forecasts, estimation of water availability in places with scarce data, analysis of impacts of multiple hydraulic structures on the hydrological regime and water quality assessment. The paper describes the experience the authors have achieved in large-scale hydrological modelling in South America, highlighting some challenges, successes and failures that were encountered while simulating river basins that are among the largest in the world, and where data availability may be so low as to classify them as ungauged basins.
Key words large basins; rainfall–runoff model; South America

INTRODUCTION

Large-scale hydrological modelling in basins with scarce data is needed in order to address several problems in water resources management. From an historic point of view this interest stems from the need to have modelling tools for the Earth phase of the hydrological cycle in Global Circulation Models (Wood *et al.*; 1992; Sausen *et al.*, 1994; Evans, 2003), and also because of the necessity of models for managing international conflicts related to water in transboundary basins (Andersen *et al.*, 2001); perform hydrological forecasting (Wood *et al.*, 2002); assess the effects of widespread land cover change on streamflow (Matheussen *et al.*, 2000); and estimate climate change effects on streamflow (Guo *et al.*, 2002).

There are several examples of macro-scale hydrological models developed in recent years, including the VIC family of models (Wood *et al.*, 1992; Liang *et al.*, 1994), ISBA-MODCOU (Habets *et al.*, 1999), WATFLOOD (Soulis *et al.*, 2004), and LARSIM (Bremicker, 1998). Other distributed models, like SHE (Refsgaard & Storm, 1995), originally developed as a small-scale model, have been also applied at larger scale as originally intended (Andersen *et al.*, 2003).

We developed a large-scale distributed hydrological model, based on the LARSIM (Bremicker, 1998) and VIC (Liang *et al*., 1994; Nijssem *et al*., 1997) models, in which land use, topography, vegetation cover and soil types data are used as guides to obtain the parameter values. During the last several years the model was tested and used in South American basins (Fig. 1) from the sub-tropical, rapid response basins of southern Brazil, to the basins in the Pantanal region, marked by seasonal rainfall, and, in some cases, slow response hydrographs (Collischonn & Tucci, 2001). Ongoing applications include the São Francisco River, whose basin lies partly in the semiarid region of northeast Brazil (Tucci *et al*., 2005), the Madeira River, one of the most important tributaries of the Amazon (Ribeiro *et al*., 2005), and the Tapajos River, also an important tributary of the Amazon, where satellite derived rainfall information is being used to run the model.

Fig. 1 South American basins simulated using the large scale model MGB-IPH.

Through short descriptions of model applications in South America, this paper highlights challenges, successes and failures that were encountered while simulating large river basins. Some of these basins present a situation of large data scarcity and could be classified as ungauged basins.

OVERVIEW OF THE MGB-IPH MODEL

The model is called MGB-IPH and it is composed of modules for calculation of soil water budget, evapotranspiration, flow propagation within a cell, and flow routing through the drainage network. The drainage basin is divided into elements of area (square cells), with vegetation and land use within each element categorized into one or more classes, the number of vegetation and land use types being at the choice of the user. To reduce the intensity of computation, the Grouped Response Unit (GRU) (Kouwen *et al*., 1993) approach is adopted. The GRU approach consists of grouping all areas with a similar combination of soil and land cover, such that a cell contains a limited number of distinct GRUs. Soil water budget is computed for each GRU, and runoff generated from the different GRUs in the cell are then summed and routed to the river network. This approach has been used by several large-scale hydrological models, such as VIC (Wood *et al*., 1992; Liang *et al*., 1994; Nijssem *et al*., 1997), WATFLOOD (Soulis *et al*., 2004).

Soil water budget is calculated following the variable contributing area of the ARNO model (Todini, 1996). Evapotranspiration is calculated separately for each GRU in each cell following the model by Wigmosta (1994). Routing through the river network is calculated using the Muskingum-Cunge method (Miller & Cunge, 1975).

The time step that is normally used is one day, because rainfall is often only available in South America on a daily basis, although the model was adapted to receive input and perform simulations in smaller time steps when rainfall data is available (Collischonn *et al*., 2005).

Due to the large scale of the applications, globally available data sets are used as much as possible. Soil type maps are obtained from sources such as FAO (1988), the Soil and Terrain Digital Database for Latin America and the Caribbean (SOTERLAC) (FAO, 1998) and RADAM Brazil project. Digital elevation models (DEMs) are now obtained from the Shuttle Radar Topography Mission (SRTM) and until 2001, from the Global 30 Arc-Second Elevation Dataset (GTOPO30). LANDSAT images are classified to obtain vegetation cover and land use for each basin, and climate data comes from NOAA, METeorological Aerodrome Report (METAR) and the Brazilian National Water Resources Agency (ANA).

For the calibration of the model it is assumed that a relationship exists between its parameter values and characteristics that could be obtained all over the basin, such as soils, vegetation and topography (Kite & Kowen, 1992).

APPLICATIONS OF THE MODEL

Completed and ongoing applications of the hydrological model cover a large part of South America, spanning from latitudes south of 30°S to 5°S, and including humid temperate, tropical with dry winter and tropical rainy climates (Fig. 1). Differences in soil properties and geological characteristics are also large between the basins, with shallow soils and impervious rocks in the southern basins, that lead to surface runoff dominated streamflow, and deep soils over porous rocks more common in some of the northern basins, leading to relatively large base flow.

Most of the basins lie entirely inside Brazil, but some comprise territories of neighbour countries, including Paraguay, Bolivia, Peru and Argentina. Some of these applications, as well as its main results and experiences, are presented in the following sections.

Taquari–Antas River basin

The Taquari–Antas River drains a 27 000 km^2 large basin in a humid temperate and mountainous region where mean annual rainfall is close to 1500 mm. Due to its relief, shallow soils and basalt bedrock, this basin is mainly drained by surface runoff.

The basin was divided in square cells of 10 × 10 km, and a daily time step was used. Five different GRUs were considered in the basin following the main classes of land cover and vegetation that were identified in LANDSAT images. The model was manually calibrated during a five year period (1971–1975) by checking for closeness of calculated and observed hydrographs at 11 gauging stations, with larger attention given to the station with the largest drainage area (15 800 km^2). The same relationship between GRU and parameter values was used for the entire basin, which means that all sub-basins have been simulated with the same parameter set. Volume bias (ΔV), Nash-Sutcliffe model efficiency for streamflow (R2), and the same coefficient for the logarithms of streamflow (R_{log}) were used as performance criteria and results are presented in Table 1, which includes the verification period (1976–1980).

As can be observed in Table 1, results tend to be better when evaluated at gauging stations controlling larger drainage areas. Differences in performance between calibration and verification periods are relatively small for some basins, and results may be even better during the verification period for others, although at the two

Table 1 Performance criteria of calculated streamflow in the Taquari Antas River basin.

River	Station	Área (km^2)	Calibration			Verification		
			R2	R_{log}	ΔV (%)	R2	R_{log}	ΔV (%)
Forqueta	Coimbra	780	0.66	0.73	–4.11	0.77	0.77	–1.14
Jacaré	Jacaré	432	0.68	0.71	–2.54	0.68	0.75	–4.52
Guaporé	Colombo	1980	0.80	0.79	–1.18	0.81	0.84	–2.69
Guaporé	Santa Lúcia	2382	0.87	0.85	1.62	0.79	0.82	–2.51
Carreiro	Migliavaca	1250	0.86	0.85	1.15	0.69	0.84	–3.84
Turvo	Guaiaveira	2839	0.83	0.81	3.07	0.81	0.86	1.43
Prata	Prata	3622	0.85	0.85	3.48	0.84	0.85	–2.49
Tainhas	Tainhas	1107	0.82	0.81	4.89	0.80	0.79	1.31
Antas	Gabriel	1725	0.76	0.82	–5.10	0.40	0.76	5.71
Antas	Ponte	12298	0.90	0.85	–1.11	0.83	0.81	–6.07
Taquari	Muçum	15826	0.90	0.86	1.24	0.82	0.84	–1.01

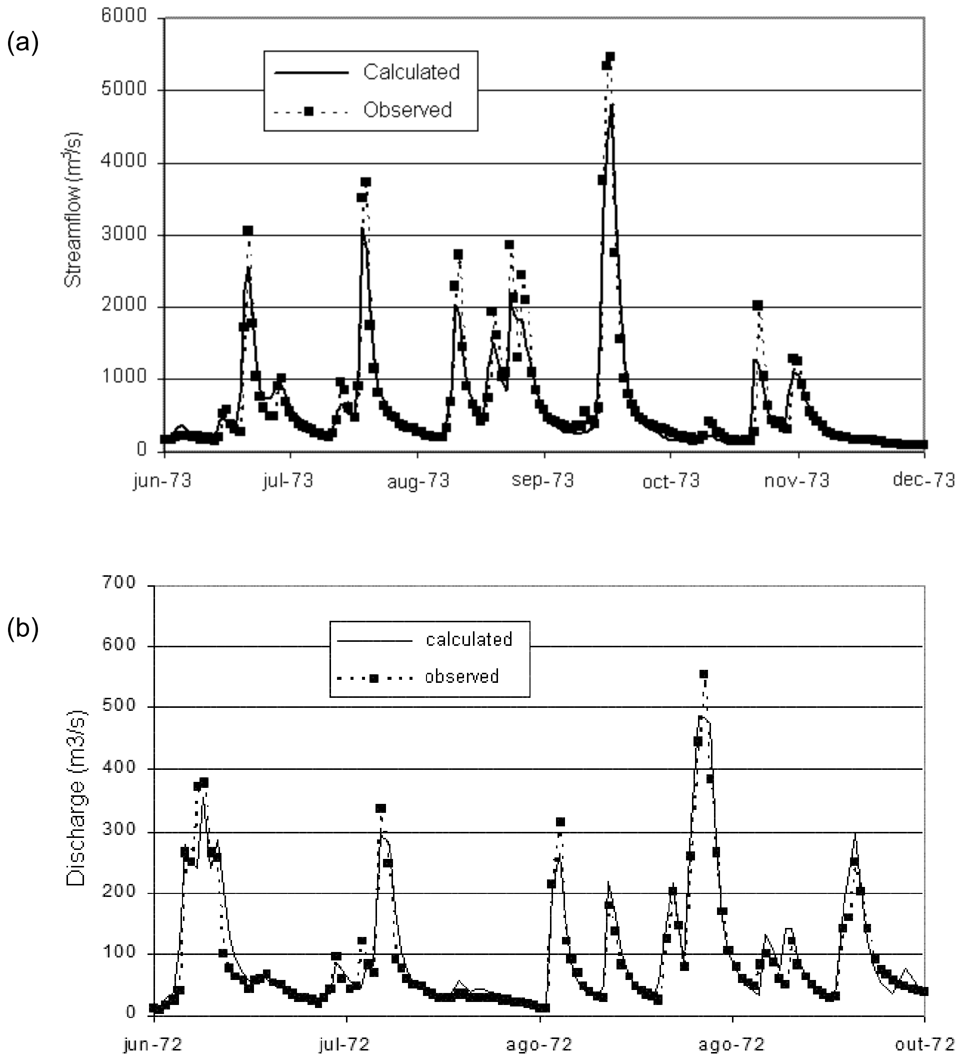

Fig. 2 Calculated and observed hydrographs during calibration period: (a) Taquari–Antas River at Muçum (15 826 km^2); (b) Carreiro River at Passo Carreiro (1250 km^2).

stations with the largest drainage area there is a relatively strong decrease in performance.

Calculated and observed hydrographs during parts of the calibration period are presented in Fig. 2, where it is possible to see that there was a good agreement in the observed hydrographs, even though the model tends to underestimate peak flows. Partly, this behaviour can be related to the little importance that was given to peak flows during the calibration period due to the low reliability of the rating curves at high stages in some gauging stations in this basin (Collischonn & Tucci, 2001).

After this calibration, the hydrological model was used as a basis for a water quality simulation model, including both diffuse and point sources of Biochemical Oxygen Demand (BOD), Total Nitrogen (TN), Total Phosphorus (TP), and faecal coliforms. This model was shown to be capable of reproducing the main patterns of spatial and temporal variability of water quality along the main river, as could be observed by comparison to data measured at three-month intervals (Larentis, 2004).

Uruguay River basin

Following the application in the Taquari–Antas River basin, the model was applied to the Uruguay River basin. River Uruguay forms in southern Brazil, and its basin is a close neighbour to the Taquari-Antas basin (Fig. 1), both basins having the same climate and very similar features in terms of topography, geology, vegetation, land use and soil types.

The basin was divided in square cells of 6 × 6 minutes (1/10 degree), and a daily time step was used. Land use and land cover data were obtained from classified NOAA AVHRR images (resolution of 1 km), resulting in 5 classes, similar to the classes found in the Taquari-Antas basin.

A first approach fixed the parameter values for each GRU at the same values encountered by calibration for the Taquari basin, and the model was run without any calibration. Results were fairly good during the period from 1985 to 1995, as can be seen in the hydrograph of year 1987, shown in Fig. 3. Nash-Sutcliffe model efficiency was evaluated at five gauging stations with values between 0.62 for the smaller basins (9870 km^2) to 0.84 for the gauging station with the larger drainage area (52 671 km^2). Model performance in terms of bias or relative volume error was poorer, showing a relatively high underestimation that raised to 7.4% in the larger drainage area (52 671 km^2) and was even higher (21.7%) for some of the smaller sub-basins. Results of this test are about to be submitted for publication in a separate paper.

After this test, the model was calibrated using the automatic multi-objective optimization method MOCOM-UA (Yapo *et al.*, 1998) and was applied to obtain streamflow forecasts using seasonal rainfall forecasts obtained by a Global Circulation Model. This application was fully described by Tucci *et al.* (2003).

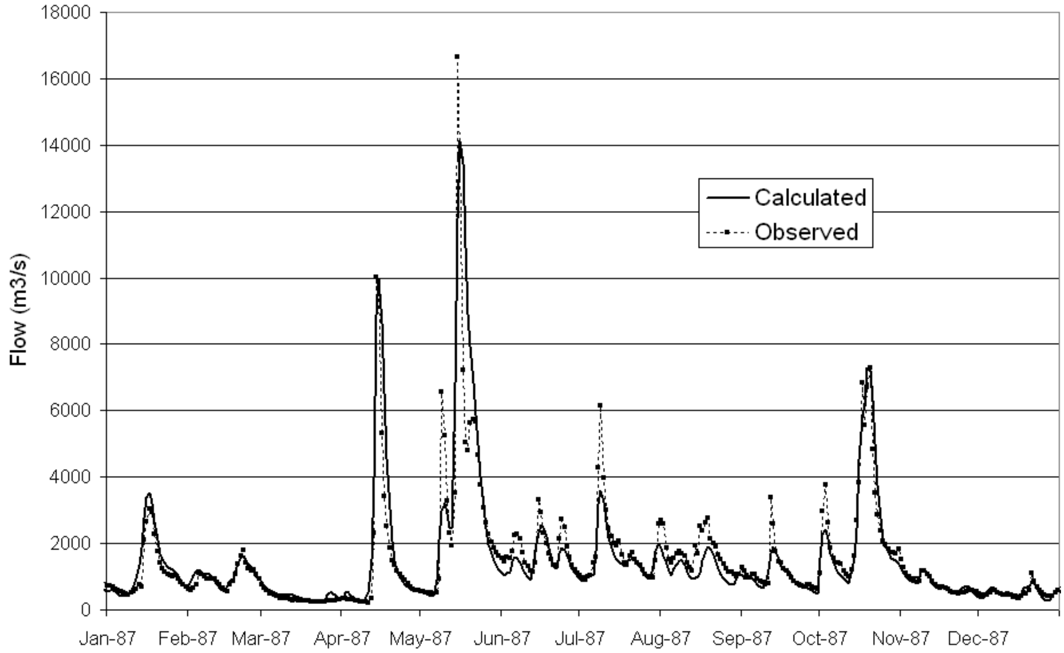

Fig. 3 Calculated and observed hydrographs of the Uruguay River in Passo Caxambu (52 671km^2) during the verification period with parameters transferred from the Taquarí-Antas Basin.

After adjustments to operate at an hourly time step the model was once more applied to the Uruguay basin, this time to generate short-term streamflow forecasts using both observed rainfall data and future rainfall forecast by a regional meteorological model. Results of this test can be found in Collischonn *et al*. (2005).

Upper Paraguay basin

The Rio Paraguay is one of three main tributaries of the La Plata drainage basin, the second largest in South America and the world's fifth largest (Fig. 1). The Upper Paraguay basin contains parts of Brazil, Paraguay and Bolivia, and extends to the Apa River on the border between Paraguay and Brazil. The drainage area of the Upper Paraguay is about 600 000 km^2. Within the Upper Paraguay basin lies the Pantanal, the world's largest wetland, with a very rich ecology which attracts valuable tourism. The Pantanal is the area where altitudes are lower than roughly 200 m, located in the centre of the Upper Paraguay basin. It is enclosed by highlands up to 1000 m, drained by several rivers, the Paraguay itself, and major tributaries such as the Cuiaba, Taquari and São Lourenço, which form alluvial fans and seasonally inundate the Pantanal, forming permanent and temporary lakes, which constitute an excellent refuge for a varied fauna.

Hydrological modelling of this basin poses major challenges due to the complexity of the drainage network in the low lying areas, the scarce rainfall and streamflow data, and the variability of soil types, geological characteristics and topography. Precipitation alone varies from >1800 mm $year^{-1}$ in the north to <900 mm $year^{-1}$ in the west.

The model was applied using a spatial resolution of 6 × 6 minutes and daily time steps, using raingauge rainfall data (we were only able to get data from gauges inside Brazil) and using land use and vegetation cover obtained by classification of LANDSAT images. A map of soil types was obtained from the Brazilian RADAM BRASIL survey, which was completed with data from FAO (1988) in Bolivia and Paraguay. Ten combinations of soil types and land use or vegetation cover were identified to compose the model GRUs.

In the application to the whole basin, including the low lying areas of the Pantanal, where river slopes are as low as a few centimetres per kilometer, and where strong river–flood plain interactions exist, the relatively uncomplicated Muskingum-Cunge flow propagation method did not work well, as expected. At the moment we are changing the propagation method, using a raster based simplified hydrodynamic model following the approach of Bates & De Roo (2000) and Bates *et al*. (2005). No results are available at this time using this propagation model, so results shown here are taken from the river Taquari, one of the main tributaries of the Paraguay, at the Coxim gauging station (27 000 km^2), upstream of its main entrance to the Pantanal (Fig. 4(a)).

As can be seen in Fig. 4(a), calculated and observed hydrographs are not as close as to consider the results good, but these results have to be seen in the context of low data availability, particularly rainfall data. On average there is one raingauge every 2800 km^2 in the region. An interesting feature of the hydrological behaviour of this river, as well as of several rivers that drain to the Pantanal, is the large amount of natural regulation provided by the water storage capacity of soils and geology, leading

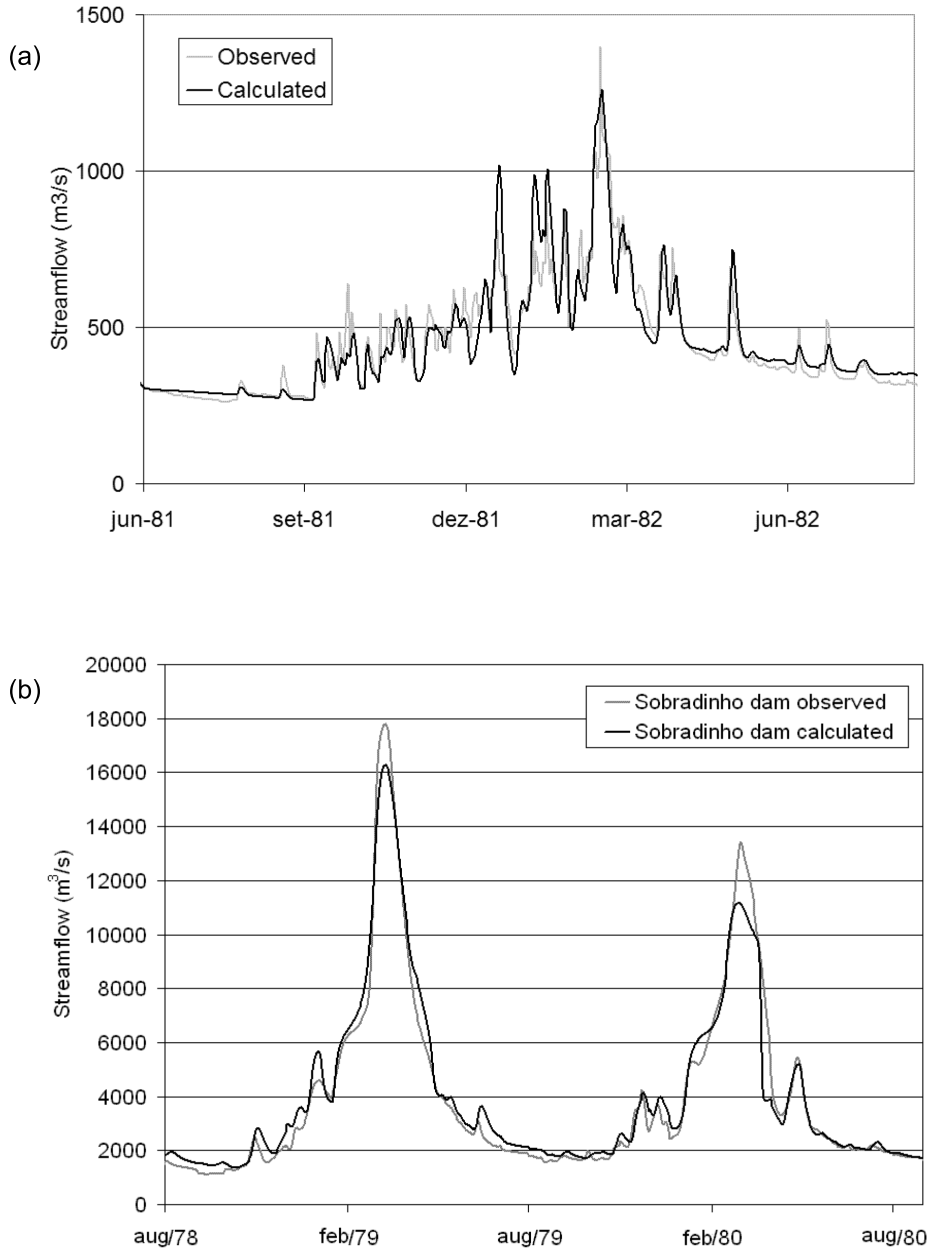

Fig. 4 Observed and calculated hydrographs in: (a) the Taquari (Upper Paraguay) river at Coxim; and (b) the São Francisco river at Sobradinho Dam (504 000 km^2).

to relatively little differences between high and low flows, even though nearly 90% of annual rainfall is concentrated during the six months from October to March. In fact, our local inspections revealed that there are huge areas in this region, which were originally covered by cerrado (a woody savannah), and that are now largely converted to agriculture, which do not show any traces of surface runoff, and seem to constitute important aquifer recharge areas. Contrasting to this, there are some spots with shallow Lithosols, where most of the rainfall is converted to surface runoff. The result of this combination are hydrographs that typically show seasonal flood peaks overlaid on a high baseflow, as can be seen in Fig. 4(a). This feature was relatively well preserved in the model simulation because soil type maps were used while defining the GRUs, and parameters were calibrated separately for each GRU considering typical runoff generation behaviour expected for each soil.

Relating to model application in ungauged basins, one of the most interesting things we observed during the application in the Paraguay River basin was that parameter transferability between basins is lower than in the southern basins. In our opinion this may be related to the high base flow in the northern basins, mainly due to the presence of deeper soils, with larger contents of sand and also due to frequent presence of sedimentary rocks beneath the soil. According to our experience, it seems to be easier to calibrate a hydrological model in impervious basins than in more pervious ones. This may be related to the fact that, in pervious basins, there are more paths that water may take, and more complexity involved in the representation of hydrological processes especially evapotranspiration, which becomes more important in this case. On the other hand, in the case of impervious basins, it seems to be more or less sufficient to have good rainfall data and a reasonable method for flow routing to get good results with a hydrological model.

São Francisco River basin

In the Sao Francisco River basin, the MGB-IPH model was applied within a runoff forecast research project (Tucci *et al.*, 2005). The aim of this project was to test both short-term (10 days) and long term (6 months) runoff forecasts for hydroelectric reservoirs based on precipitation forecast by atmospheric models. The drainage area of the Sao Francisco River at its outlet in the Atlantic is close to 640 000 km^2, and the northern part of the basin is located in the driest region in Brazil, where mean annual rainfall falls below 700 mm $year^{-1}$. Almost 70% of its streamflow is generated in the upper São Francisco (near 190 000 km^2), to the south, where rainfall is as high as 1800 mm $year^{-1}$.

If applied in a spatial resolution of 6 × 6 minutes cells the model processing would be very time consuming, so a hybrid spatial resolution was adopted for this huge basin. In the southern upstream part of the basin (near 190 000 km^2), where rainfall is more intense and a larger number of raingauges is available, the MGB-IPH model was applied using cells 6 × 6 minutes. In the northern part (450 000 km^2) the model was applied using a coarser resolution (12 × 12 minutes).

In this application the river flow routing was adapted to allow simulation of rivers with flood plains, since the main course of the São Francisco has nearby areas that are flooded when discharge exceeds 6000 $m^3 s^{-1}$ approximately. A nonlinear version of the Muskingum-Cunge method was adopted for the main river, in this case.

Results of the model application can be seen in Fig. 4(b), where calculated and observed inflow hydrographs to Sobradinho reservoir are shown. It can be observed that this river also has a marked seasonal behaviour, similar to the Upper Paraguay. Except for the flood peaks of the two years shown, which are among the extreme floods of the record, overall agreement between calculated and observed hydrographs is relatively good. Underestimation of the flood peaks is probably related to incorrect flood propagation representation when the flood plain is inundated.

CONCLUSIONS

We have described applications of a large scale hydrological model in South America, and some of the experiences gained in applying this model in basins spanning different climate types, geological characteristics and data availability situations.

The model is distributed in square cells and uses information of topography, land use, vegetation and soil types to further divide the cells into Grouped Response Units (GRUs). Parameters are related to the GRUs and both manual and automatic calibration methods are used. We focus on the use of data that is globally available, such as satellite images.

Challenges to the application of the model generally come from data scarcity, mainly rainfall and surface meteorological data.

Concerning possible application in ungauged basins, we observed that parameter transferability is higher for regions where surface runoff is the dominating form of flow generation. On the other hand, despite the fact that good results could be obtained in basins with more groundwater contribution to total streamflow, parameter transferability was low in these basins. We suggest that this may be related to the higher relative importance that soil–vegetation–water relations have in this kind of basin.

Among the major shortcomings that were detected in the model during these applications, are the flow routing method that is not capable of dealing with flood plains. Current work is being done to improve the model in this aspect, as well as other applications are being conducted in other basins, including the simulation of large basins using satellite estimated rainfall.

Acknowledgements The authors thank the two reviewers for their careful review and for several useful suggestions.

REFERENCES

Andersen, J., Refsgaard, J. C. & Jensen, K. H. (2001) Distributed hydrological modelling of the Senegal River Basin—model construction and validation. *J. Hydrol.* **247**, 200–214.

Bates, P. D., Dawson, R., Hall, J., Horrit, M., Nicholls, R., Wicks, J. & Hassan, M. (2005) Simplified two dimensional numerical modelling of coastal flooding and example applications. *Coastal Engng* **52**, 793–810.

Bates, P. D. & De Roo, A. P. J. (2000) A simple raster based model for flood simulation. *J. Hydrol.* **236**, 54–77.

Bremicker, M. (1998) Aufbau eines Wasserhaushaltsmodells für das Weser und das Ostsee Einzugsgebiet als Baustein eines Atmosphären-Hydrologie-Modells. Dissertation Doktorgrad, Geowissenschaftlicher Fakultät der Albert-Ludwigs-Universität. Freiburg. Germany.

Collischonn, W. & Tucci, C. E. M. (2001) Large basins hydrologic simulation. *Brazilian J. Water Resour.* **6**(1), 15–35 (in Portuguese).

Collischonn, W., Haas, R., Andreolli, I. & Tucci, C. E. M (2005) Forecasting River Uruguay flow using rainfall forecasts from a regional weather-prediction model. *J. Hydrol.* **205**, 87–98.

Evans, J. P. (2003) Improving the characteristics of streamflow modelled by regional climate models. *J. Hydrol.* **284**, 211–227.

Food and Agriculture Organization (FAO) (1988) Soil map of the world. Revised legend. Reprinted with corrections. *World Soil Resources Report 60*. FAO, Rome, Italy.

Food and Agriculture Organization (FAO) (1998) *Soil and Terrain Database for Latin America and the Caribbean (1:5 million scale).* [CD-ROM]. FAO Land and Water Digital Media Series #05.

Guo, S., Wang, J., Xiong, L., Aiwen Y. & Li, D. (2002) A macro-scale and semi-distributed monthly water balance model to predict climate change impacts in China. *J. Hydrol*. **268**, 1–15.

Habets, F., Noilhan, J., Golaz, C., Goutorbe, J. P., Lacarrère, P., Leblois, E., Ledoux, E., Martin, E., Ottlé C. & Vidal-Madjar, D. (1999) The ISBA surface scheme in a macroscale hydrological model applied to the Hapex–Mobilhy area Part 1: model and database. *J. Hydrol.* **217,** 75–96.

Kite, G. W. & Kowen, N. (1992) Watershed modeling using land classifications. *Water Resources Res.* **28**(12), 3193–3200.

Kouwen, N., Soulis E. D., Pietroniro A., Donald J. & Harrington R. A. (1993) Grouped response units for distributed hydrologic modeling. *J. Water Resour. Plan. Manage.* **119**(3), 289–305.

Larentis, D. G. (2004) Mathematical modeling of water quality in large river basins. MSc Dissertation. Instituto de Pesquisas Hidráulicas, Universidade Federal do Rio Grande do Sul. Porto Alegre, Brazil (in Portuguese).

Liang, X., Lettenmaier, D. P., Wood, E. F. & Burges, S. J. (1994) A simple hydrologically based model of land surface water and energy fluxes for general circulation models. *J. Geophys. Res.* **99**(7), 14415–14428.

Matheussen, B., Kirschbaum, R. L., Goodman, I. A., O'Donnell, G. M. & Lettenmaier, D. P. (2000) Effects of land cover change on streamflow in the interior Columbia River basin (USA and Canada). *Hydrol. Processes* **14**, 867–885.

Miller, W. A. & Cunge, J. A. (1975) Simplified equations of the unsteady flow in open channels. In: *Unsteady Flow in Open Channels* (ed. by K. Mahmood & V. Yevjevich). Water Resources Publications. Fort Collins, Colorado, USA.

Nijssen, B., Haddeland, I. & Lettenmaier, D. (1997) Point evaluation of a surface hydrology model for BOREAS. *J. Geophys. Res.*, **102**(29), 367–378.

Refsgaard, J. C. & Storm, B. (1995) MIKE SHE. In: *Computer models of Watershed Hydrology* (ed. by V. P. Singh), 809–846. Water Resources Publications, Fort Collins, Colorado, USA.

Ribeiro A., Collischonn, W., Vieira da Silva, R. & Tucci, C. E. M. (2005) Hydrological modelling in Amazonia—use of the MGB-IPH model and alternative data base. In: *Predictions in Ungauged Basins: Promise and Progress* (ed. by M. Sivapalan) (Foz do Iguaçu, Brazil), 246–254. IAHS Publ. 303. IAHS Press, Wallingford, UK (this volume).

Sausen, R., Schubert, S. & Dümenil, L. (1994) A model for river runoff for use in coupled atmosphere-ocean models. *J. Hydrol*. **155,** 337–352.

Soulis, E. D., Kouwen, N., Pietroniro, A., Seglenieks, F. R., Snelgrove, K. R., Pellerin, P., Shaw, D. W. & Martz L. W. (2004) A framework for hydrological modelling In Mags. In: *Prediction in Ungauged Basins: Approaches for Canada's Cold Regions* (ed. by C. Spence, J. W. Pomeroy & A. Pietroniro). CWRA ACRH Press, Ontario, Canada.

Todini, E. (1996) The ARNO rainfall—runoff model. *J. Hydrol.* **175**, 293–338.

Tucci, C .E. M., Clarke, R. T., Collischonn, W., Dias, P. L. S. & Sampaio, G. O. (2003) Long term flow forecast based on climate and hydrological modeling: Uruguay river basin. *Water Resour. Res.* **39**, n.7, 3, 1–11.

Tucci, C. E. M., Marengo, J. A., Silva Dias, P. L., Collischonn, W., Silva, B. C., Clarke, R. T., Cardoso, A. O., Juarez, R. N., Sampaio, G., Chan, C. S & Tomasella, J. (2005) Streamflow forecasting in São Francisco River Basin based in the climatic forecasting. *Technical Report ANEEL/WMO/98/00*. Porto Alegre, Brazil (in Portuguese).

Wigmosta, M. S., Vail, L. W. & Lettenmaier, D. P. (1994) A distributed hydrology-vegetation model for complex terrain. *Water Resour. Res.* **30(**6), 1665–1679.

Wood, E. F., Lettenmaier, D. P. & Zartarian, V. G. (1992) A land surface hydrology parameterization with subgrid variability for general circulation models. *J. Geophys. Res*. **97**(3), 2717–2728.

Wood, A. W., Maurer, E. P., Kumar, A. & Lettenmaier, D. P. (2002) Long-range experimental hydrologic forecasting for the eastern United States. *J. Geophys. Res.* **107**(D20), 4429, doi:10.1029/2001JD000659

Yapo, P. O., Gupta, H. V. & Sorooshian, S. (1998) Multi-objective global optimisation for hydrologic models. *J. Hydrol.* **203**, 83–97.