Water Resources Systems—Water Availability and Global Change (Proceedings of symposium HS02a held during IUGG2003 at Sapporo, July 2003). IAHS Publ. no. 280, 2003.

Comparison of flow forecasts by runoff models: a case study from southern Brazil

CARLOS E. M. TUCCI[1], PEDRO DIAS[2], ROBIN CLARKE[1], WALTER COLLISCHONN[1] & GILVAN SAMPAIO[3]

1 *Institute for Hydraulic Research, Federal University of Rio Grande do Sul, Brazil*
cemtucci@ig.com.br

2 *Institute for Atmospheric and Geophysical Research (IAGCA), University of São Paulo, Brazil*

3 *Center for Climatic Research (CPTEC), Brazilian Agency for Space Research (INPE), Cachoeira Paulista, Brazil.*

Abstract Over 80% of Brazil's energy demand is supplied at present by hydropower. It is therefore essential for purposes of future planning to have good estimates of reservoir inflows, and the longer the lead time of streamflow forecasts, the more distant is the planning horizon for decisions concerning the costing, production and distribution of power. Whilst it is relatively easy to forecast river basin response to precipitation that has already fallen, forecasts for periods beyond this immediate response time must be based upon estimates of future precipitation. This paper describes the results of work which combines forecasts of future rainfall given by a model of global climate with a detailed, distributed model of river basin response in the Brazilian part of the River Uruguay basin, an area of intensive hydropower production. Comparison of predicted and observed rainfall over the period of model calibration showed that it was necessary to apply a statistical correction to eliminate a spatial trend in predicted rainfall. Data from a two-year period were set aside for model validation. Results show that the combined use of models of climate and river-basin response has been successful for the River Uruguay basin, in that the root mean square error (RMSE), between observed flows and flows predicted by the combined model, is substantially less than the RMSE between observed flows and the historic mean monthly flows.

Key words climate models; flow forecasts; rainfall–runoff models; River Uruguay

INTRODUCTION

The many purposes for which forecasts of flow in Brazilian rivers are required include planning hydropower production, flood control, irrigation planning, navigation, and water supplies for industrial and domestic use. Management of water resources is more efficient where reliable flow forecasts can be calculated for long lead times, and, whilst it is often not too difficult to forecast river basin response to rain that has already fallen, forecasting for lead times greater than the basin response-time requires forecasts of future rainfall and weather conditions, and this adds additional uncertainty to forecasts of river flow. Whilst it is always possible to use mean values calculated from past rainfall and meteorological records as estimates of what might happen in the future, these estimates generally have low precision, particularly where the length of record and the time interval between forecasts, are short. A further factor is that the use of historic climate means as estimates of future conditions assumes that the historic record is statistically stationary, but in South America there is a growing body of evidence that climate regimes—and, in consequence, hydrological regimes—are either changing (Berri *et al.*, 2002; Genta *et al.*, 1998) or exhibit long-term fluctuations (Robertson & Mechoso, 1998). Whilst these effects may not be too important where flow forecasts are required for a few weeks or a few months ahead, they have greater importance where the frequencies of extreme events are to be calculated.

It is convenient to distinguish between short-term forecasts, with lead times of hours or days, and long(er)-term forecasts, with lead times of, say, up to nine months (Georgakakos & Hudlow, 1984). Forecasts of seasonal runoff are particularly needed for regions such as the Brazilian Northeast where rainfall is not only uncertain in terms of the amount falling and its spatial distribution, but also has a strongly seasonal distribution. Good long-term forecasts are also important to decrease the uncertainties in costing future energy prices, a matter of particular importance to Brazil where more than 80% of the national energy demand is met from hydropower, and the energy required for industrial development and to support rising living standards continues to increase.

Long-term flow forecasts can be obtained by statistical methods such as time-series analysis of flow sequences, or by correlating river flow with measures of oceanic behaviour such as sea surface temperatures (SSTs); a variant on the latter approach is to correlate rainfall with SSTs and use a rainfall–runoff model to obtain forecasts of river flow. In a basin where rainfall has a clearly-defined seasonal distribution, dry-season flow can also be estimated, often with good accuracy, from the hydrograph recession curve (Villanueva *et al.*, 1987). Where rainfall has no marked seasonal distribution, statistical forecasting methods can also perform reasonably well, sometimes for lead times of a few months, for drainage basins where storage is large and basin response consequently delayed; a Brazilian example is the Upper Paraguay River downstream from the extensive wetland (extending up to 140 000 km^2) known as the Pantanal. However, in drainage basins with little storage, the system "memory" is short and, if long-term forecasts are required, forecasts of future rainfall and other climate-related variables are needed, and flow forecasts must be found by using them as input variables to a hydrological model of rainfall–runoff processes.

This paper presents results of some comparisons between forecasts obtained using a statistical approach to the problem, and forecasts obtained using the latter procedure in which forecasts of rainfall obtained from a climate model were used as input to a rainfall–runoff model of that part of the River Uruguay drainage basin (75 000 km^2) lying within Brazilian territory. The Uruguay rises in Brazil, and also drains parts of Uruguay and Argentina; the basin has marked relief and little soil storage capacity, whilst aquifers linked to the drainage network exert little control over flow. The climate is characterized by cool winters, little variation in seasonal rainfall, and with annual rainfall ranging between 1500 and 2000 mm year^{-1}. The most important characteristics of relevance to this paper are the small variation in flow of different seasons, the short "memory" of the drainage basin, and the large variation in monthly flow about the historic monthly mean and median values.

MODELLING PROCEDURES

Empirical (statistical) model

The empirical model used in the comparison was based on the correlation between the time series of flow in the Uruguay River and the time series of principal components of SSTs in the Pacific and Atlantic oceans. The justification for correlating flow directly with SST principal components, rather than correlating the time series of observed rainfall with SSTs, is that SSTs determine not only the total depth of rain falling on a given region during a period of (for example) a month, but also the spatial and temporal distribution of rainfall. The mean monthly SSTs were obtained from the COADS database at a spatial resolution of 1° × 1° for the period 1950–1999. Flow records in the River Uruguay were available for a number of gauging sites.

Principal components (PCs) were calculated for each season (DJF, MAM, JJA, SON) using SST data from both the Pacific and Atlantic Oceans: the components are also known as empirical orthogonal functions (EOFs) and constitute a set of linear transformations of the SSTs corresponding to the decreasing sequence of eigenvalues of the data matrix in which the rows are months and the columns are the SSTs in a degraded 5° × 5° resolution grid (original data in a 1° × 1° grid). Thus the variance of the first (second, ...) PC is the largest (second largest, ...) eigenvalue of this data matrix. The PCs were calculated separately for the SSTs in the Atlantic and Pacific Oceans, and were related to the time series of monthly flow in the River Uruguay by multiple regression.

Flow forecasts given by combined use of a climate and rainfall–runoff models

Forecasts of monthly flow in the Uruguay River were also obtained by using outputs from a climate model developed by CPTEC, a component of the Brazilian Space Agency, INPE, as input to a distributed model of rainfall–runoff processes developed by the Institute for Hydraulic Research (IPH) for modelling flows in large drainage basins.

Climate model

The CPTEC climate spectral model is essentially a low-resolution weather prediction model with equivalent grid spacing of about 180 km with 28 vertical levels between the surface and the top of the model atmosphere at 1 mb. The model is based on the code used by the Center for Ocean and Land Studies (COLA) (Marengo *et al.*, 2002). It predicts five variables: zonal and meridional windspeed, virtual temperature (i.e. allowing for water vapour effects on air density), specific humidity and surface pressure. Vertical motion is obtained from the continuity equation and knowledge of wind divergence. Derivatives in the horizontal are calculated using the spectral method which represents each variable as a sum of spherical harmonics.

Hydrological model

Collischonn & Tucci (2001) described a distributed hydrological model for use in large drainage basins, which uses information from satellite images, digital elevation models and digitized maps of land use, vegetation cover, relief and soils. The model uses a daily time step and is similar to the LARSIM (Bremicker, 1998) and VIC-2L (Liang *et al.*, 1994; Nijssen *et al.*, 1997) models. The basin area was divided into 681 square

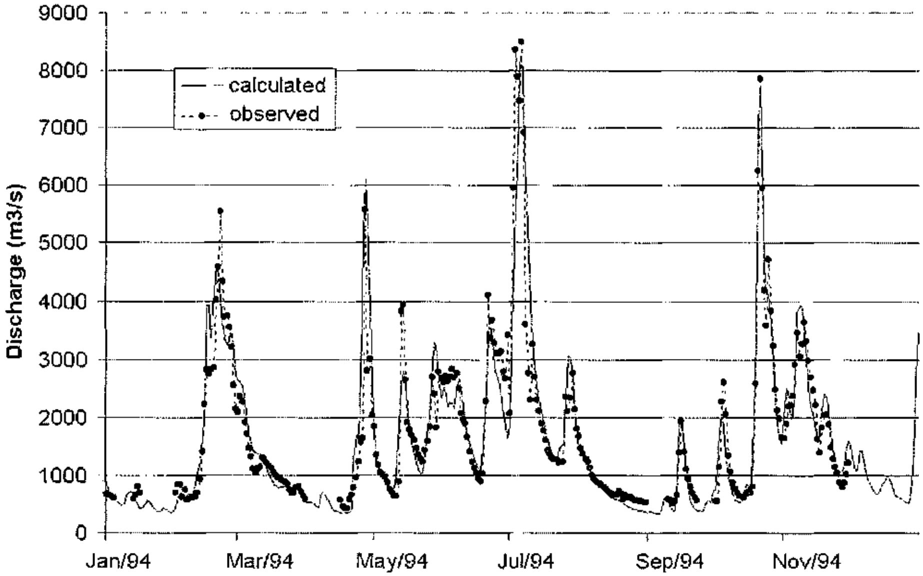

Fig. 1 Recorded and fitted discharge at Passo Caxambu, River Uruguay; basin area of 54 000 km^2.

cells of size 0.1° × 0.1°, which were further divided into blocks according to the combination of soils, land use and vegetation cover. Soil water balance was computed independently for each block of each cell, considering only one soil layer. Processes of flow routing and storage included in the model were canopy interception, evapotranspiration, infiltration, surface runoff, subsurface flow, baseflow and soil water storage. Evapotranspiration from the soil, vegetation and the canopy, to the atmosphere, was estimated through the Penman-Monteith equation as described by Wigmosta *et al.* (1994). Streamflow was propagated through the river network using the Muskingum-Cunge method with time steps of one day or less, depending on the stream reach length and slope. Within each cell, flow was propagated using three linear reservoirs to represent baseflow, sub-surface flow and surface flow.

The model was calibrated using streamflow and rainfall data from 1985 to 1995 and verified with data from 1977 to 1985. A multi-objective calibration method based on a genetic algorithm (Yapo *et al.*, 1998) was used to calibrate the model parameters in each block defined by soil type, land use and vegetation cover. Data from five gauging stations within the basin were used simultaneously for model calibration. An example of the fitting is presented as Fig. 1.

RESULTS

The basin of the Uruguay River has very little storage and very little memory, and so runoff generated from rainfall emerges from the basin rapidly. As a consequence, regression models, in which flow in any month is forecast from flow and rainfall recorded in preceding months, perform poorly. These models were explored but their results are not reported here.

The CPTEC climate model gave forecasts of rainfall which, when compared with observed rainfall over the same periods, showed a systematic error, and this was corrected statistically by transforming the empirical probability distribution of rainfalls forecast by the CPTEC model, into the empirical probability distribution of observed rainfalls, using a method similar to that of Wood *et al.*(2002).

Comparisons between the empirical model and the climate–hydrological model were effected using two periods. Period 1, from December 1995 to December 1998, was used to obtain model forecasts and to derive the probability distributions needed for the statistical correction described in the preceding paragraph. Period 2, from June 1999 to October 2001, was used as a verification period, with forecasts corrected using the probability distributions obtained with data from Period 1. During this verification period, construction of two new reservoirs (Itá and Machadinho) was completed in the Uruguay basin and they began to fill; this introduced some distortion into the flows observed. The tables below therefore give results for periods in which the periods of reservoir filling were both included and excluded.

Table 1 (fourth column) shows the root mean square error (RMSE, $m^3 s^{-1}$) calculated from the observed monthly flows and the monthly flows as forecast by the combined climate and rainfall–runoff models. Column 3 of the table shows the RMSE obtained when monthly flows calculated from the historic record are used as forecasts of future monthly flows; the RMSE is considerably greater than the RMSE given by

Table 1 Summary of comparisons between forecasts in terms of root mean square error, RMSE, ($m^3 s^{-1}$) of monthly runoff, using historic means and the combined climate and hydrological models. (Tucci *et al.*, 2002).

Period	Type	RMSE ($m^3 s^{-1}$): Historic means	Climate–hydrological model	Rainfall known
Dec. 1995–Dec. 1998	Forecast	2069	1331	558
Jun. 1999–Oct. 2001	Verification	1299	1198	–
	*Excluding**	*1369*	*1087*	–
Dec. 1995–Oct. 2001	Complete	1785	1276	–
	*Excluding**	*1839*	*1245*	–

* Excluding months when Itá and Machadinho reservoirs were filling.

Table 2 Summary of comparisons between forecasts in terms of RMSE calculated from three-monthly flows: using historic means, climate and hydrological models, the hydrological model with future rainfall known, and the empirical model with three-monthly flows regressed on principal components of SSTs.

Period	Type	RMSE ($m^3 s^{-1}$): Historic means	Climate-hydrological model	Rainfall known	Empirical model with SSTs
Dec. 1995–Dec. 1998	Forecast	1570	733	508	1153
Jun. 1999–Oct. 2001	Verification	808	771	–	1154
	*Excluding**	*900*	*638*	–	*1086*
Dec. 1995–Oct. 2001	Complete	1295	750	–	1157
	*Excluding**	*1373*	*701*	–	*1134*

* Excluding months when Itá and Machadinho reservoirs were filling.

the combined climate–hydrological model. The final column of Table 1 shows the RMSE obtained when it is assumed that the monthly rainfall was known exactly over the verification period, and was used as input to the rainfall–runoff model; there is clearly some scope for improving the performance of the climate and hydrological models.

The empirical model, in which three-monthly flows are forecast using a multiple regression of flow on SST principal components, performed as shown by the RMSEs in the final column of Table 2. This table also shows the corresponding RMSEs where historical three-monthly mean flows are used as forecasts (column 3 of the table), the RMSEs using the combined climate and rainfall–runoff models (column 4), and the RMSEs obtained assuming three-monthly rainfalls are known exactly during the verification period (column 5). Values in columns 3–5 differ from those in Table 1 because the forecast periods are of different duration (three months instead of the one month in Table 1, the three-month duration being determined by the empirical model that uses SSTs). Table 2 shows that the combined climate and rainfall–runoff models show reductions in RMSE, relative to historic means, similar to but smaller than those of Table 1. The empirical model using the SST data gave smaller RMSEs than historic means during the fitting Period 1, but larger RMSEs during the verification Period 2. The performance of the empirical model is poorer than that of the combined climate and rainfall–runoff models.

CONCLUSIONS

From the limited data used in these comparisons, and with model performance assessed in terms of the RMSE between forecasts and observed flows during both monthly and three-monthly periods, the combined use of climate and rainfall–runoff models for forecasting future flow in the River Uruguay gives a consistent improvement in performance relative to the use of historic mean flows as forecasts of future flows. The improvements in accuracy are not large, but are useful. Comparison of the RMSEs given by the combined (climate–hydrological) model with the RMSEs obtained when it is assumed that future rainfall is known exactly, suggests that there is considerable room for improvement in the accuracy of model forecasts. The empirical model, in which three-monthly flow forecasts are obtained from a multiple regression of river flow on SST principal components, always performed less well than the climate-hydrological model, and was poorer over the verification period than when historic means were used as forecasts.

REFERENCES

Berri, G. J., Ghietto, M. A. & Garcia, N. O. (2002) The influence of ENSO in the flows of the Upper Parana River of South America over the past 100 Years. *J. Hydromet.* 57–65.

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. (2001) Hydrologic simulation of large basins (in Portuguese). PhD Thesis, IPH UFRGS, Brazil.

Collischonn, W. & Tucci, C. E. M. (2001) Hydrologic simulation of large basins (in Portuguese). *Revista Brasileira de Recursos Hídricos* **6**(1).

Genta, J. L., Perez-Iribarren, G. & Mechoso, C. R. (1998) A recent increasing trend in the streamflow of rivers in southeastern South America. *J. Climate* **11**, 2858–2862.

Georgakakos, P. K. & Hudlow, M. D. (1984) Quantitative precipitation forecast techniques for use in hydrological forecasting. *Bull. Am. Met. Soc.* **65**, 1186–1200.

IPCC (2001) *Climate Change 2001: Impacts, Adaptation and Vulnerability*. Report of Working Group II of Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

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**(D7), 14415–14428.

Marengo, J., Cavalcanti, I., Satyamurty, P., Trosnikov, I., Nobre, C., Bonatti, J., Camargo, H., Sampaio, G., Sanches, M., Manzi, A., Castro, C. A. C. & D'Almeida, C. (2002) Ensemble simulation of regional rainfall features in the CPTEC-COLA atmospheric GCM: skill and predictability assessments and applications to seasonal climate prediction. Accepted for publication in *Climate Dynamics*.

Mechoso, C. R. & Robertson, A. W. (1998) Interannual and decadal cycles in river flows of southeastern South America. *J. Climate* **11**, 2570–2581.

Villanueva, A., Zamanillo, E. D. & Tucci, C. E. M (1987) Previsão de Vazão para Irrigação. In: *VII Simpósio Brasileiro de Recursos Hídricos*vol 1, 536–549.

Wood, A. W., Maurer, E. P., Kumar, A. & Lettenmaier, D. P. (2002) Long range experimental hydrologic forecasting for the eastern US. *J. Geophys. Res.* (in press).

Yapo, P. O., Gupta, H. V. & Sorooshian, S. (1998) Multi-objective global optimization for hydrologic models. *J. Hydrol.* **204**, 83–97.