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Abstract: A rainfall–streamflow model featuring a unit hydrograph component is applied to four Brazilian catchments to characterise and quantify their quite different dynamic rainfall–streamflow behaviours. Using only catchment size (km^2) and time series of daily rainfall, streamflow and air temperature, six dynamic response characteristics (DRCs) are estimated for each catchment. The DRCs include decay time constants for dominant quick- and slow-response components of streamflow, a time-averaged relative volumetric contribution to streamflow from slow flow (i.e. a slow flow index, SFI) and the size of a conceptual catchment wetness store. The six DRCs are compared for the four catchments in the context of their broad hydroclimatological features. Regionalisation of DRCs with respect to physical catchment descriptors (PCDs) is mentioned in terms of the prospect of continuous streamflow simulation at ungauged sites in Brazil from rainfall and PCDs.

Keywords: Catchment characterisation; unit hydrographs; modelling; continuous flow simulation; regionalisation; Brazil.

1. INTRODUCTION

The modelling approach used in this paper is IHACRES (Identification of unit Hydrographs And Component flows from Rainfall, Evaporation and Streamflow), which was first introduced by Jakeman et al. [1990]. An IHACRES software package developed by Croke et al. [2006], referred to hereafter as ICP (IHACRES Classic Plus), was used for the rainfall–streamflow modelling.

The initial motivation for the work was to assess the efficacy of IHACRES for forecasting daily river inflows to hydropower reservoirs, using rainfall forecasts issued by the Brazilian Centre for Weather-Forecasting and Climate Studies (CPTEC, Centro de Previsão de Tempo e Estudos Climáticos). A broader context is an investigation, encouraged by the Brazilian ONS (Operador Nacional do Sistema Elétrico), of different rainfall–streamflow models and modelling approaches to assist with hydropower planning and operations.

Section 2 of the paper outlines the spatially lumped modelling approach adopted, and Section 3 gives details of the four catchments analysed and their datasets. Details of the model calibrations and a comparison of the results are given in section 4. For the four catchments, Section 5 briefly compares the performances of IHACRES models and corresponding, more complex, spatially distributed, models for the same catchments presented elsewhere [Collischonn et al. 2001; Allasia et al. 2005]. Sections 6 and 7 discuss main points arising from the work and give some brief concluding comments respectively.

2. THE MODEL

The model structure and procedures for selecting its parameters have been described in detail elsewhere [e.g. Jakeman and Hornberger, 1993; Littlewood, 2003], and therefore only brief details will be given here. The IHACRES model comprises essentially two parts: (i) a component that divides rainfall into effective rainfall and the remainder which is assumed to be lost only by evapotranspiration; and (ii) a linear transfer-function (or unit hydrograph, UH) component that transforms the effective rainfall to streamflow. Here, these two parts are called the "loss" module and the "transfer-function" (or "UH") module

respectively. The loss module accounts for all of the non-linearity in the catchment-scale rainfall–streamflow process; the transfer function module is based on linear systems theory [e.g. Box and Jenkins, 1970; Dooge, 1973]. Conceptually, the transfer function module can represent different configurations of linear stores but the configuration used here is two linear stores in parallel, in which case the whole model has just six parameters (or catchment-scale dynamic response characteristics, DRCs), three in each of the loss and UH modules.

Equations (1) to (5) in Table 1 define the model: superscripts *(q)* and *(s)* denote quick and slow flow respectively; r_k is rainfall (mm) over time step k; u_k

and $v^{(s)}$ (dimensionless) given by equations (6), (7) and (9) in Table 2. (Equation (8) in Table 2 is given for completeness. By definition, $v^{(q)} + v^{(s)} = 1$, so the UH is completely defined by any three of the four attributes $\tau^{(q)}$, $\tau^{(s)}$, $v^{(q)}$ and $v^{(s)}$.) As indicated by equation (10) and discussed later, $v^{(s)}$ is a Slow Flow Index (SFI).

Conceptually, $1/C$ can be considered to be the depth (mm) of a catchment wetness store [Post *et al.*, 1998]. The DRCs $\tau^{(q)}$ and $\tau^{(s)}$ are exponential decay time constants for separate quick and slow response UHs respectively. There is a pure time delay (δ, days) in equations (4) and (5), e.g. when δ is one day the rainfall data are simply shifted forward by one day before modelling commences.

Table 1. The IHACRES model

Loss module		UH module	
$u_k = r_k s_k$ $s_0 = 0$	(1)	$x_k = \left[\left(\dfrac{b_0^{(q)}}{1+a_1^{(q)} z^{-1}} \right) + \left(\dfrac{b_0^{(s)}}{1+a_1^{(s)} z^{-1}} \right) \right] u_{k-\delta}$	(4)
$s_k = Cr_k + \left(1 - \dfrac{1}{\tau_w(t_k)} \right) s_{k-1}$	(2)	$x_k = \left(\dfrac{b_0 + b_1 z^{-1}}{1 + a_1 z^{-1} + a_2 z^{-2}} \right) u_{k-\delta}$	(5)
$\tau_w(t_k) > 1$			
$\tau_w(t_k) = \tau_w \exp(f(R - t_k))$	(3)		

is effective rainfall (mm); s_k is a dimensionless catchment wetness index ($0 < s_k < 1$); t_k is air temperature (°C); R is a reference temperature (°C); x_k is modelled streamflow (m^{3}s^{-1}); the a and b terms are transfer function parameters; and z^{-1} is the backward shift operator ($z^{-1}x_k = x_{k-1}$). In equation (3), parameter τ_w is a catchment wetness drying time constant (days), and f (°C^{-1}) modulates $\tau_w(t_k)$ according to temperature. Parameter C (mm^{-1}) in equation (2) is calculated to equate volumes of effective rainfall and observed streamflow over the model calibration period. The six DRCs are the three loss module parameters τ_w, f and C in equations (1) - (3), and the three UH DRCs $\tau^{(q)}$ (days), $\tau^{(s)}$ (days)

3. THE CATCHMENTS AND THE DATA

The 1657 km^2 Rio Preto at Quirinópolis (station 60870000), the 11,483 km^2 R. Meia Ponte at Ponte Meia Ponte (60680000) and the 30,491 km^2 R. dos Bois at Barra do Rio Verde (60805100) are catchments in the Paranaiba basin. Further downstream the Paranaiba becomes the River Paraná. The 34,414 km^2 R. Ivaí at Novo Porto Taquara (64693000) flows to the River Paraná.

Soils in the catchments are mainly dark-red lattosols with some red-yellow podzols. Depending on the depth and proportion of sand

Table 2. Unit hydrograph dynamic response characteristics (DRCs)

DRC	Quick flow		Slow flow	
Characteristic decay response times for data time step Δ, e.g. 1 day	$\tau^{(q)} = \dfrac{-\Delta}{\ln(-a_1^{(q)})}$	(6)	$\tau^{(s)} = \dfrac{-\Delta}{\ln(-a_1^{(s)})}$	(7)
Relative volumetric throughflow, where $V = \dfrac{b_0^{(q)}}{1+a_1^{(q)}} + \dfrac{b_0^{(s)}}{1+a_1^{(s)}}$	$v^{(q)} = \left(\dfrac{b_0^{(q)}}{1+a_1^{(q)}} \right) \left(\dfrac{1}{V} \right)$	(8)	$v^{(s)} = \left(\dfrac{b_0^{(s)}}{1+a_1^{(s)}} \right) \left(\dfrac{1}{V} \right)$	(9)
			$v^{(s)} = \text{SFI}$	(10)

and clay in the lattosols, infiltration rates may vary considerably. The original vegetation cover has been greatly altered by timber extraction, agriculture and ranching, and soils are easily cultivated. The whole region is underlain by Cretaceous basalt formations that largely confine the extensive Guaraní Aquifer System comprising Triassic–Jurassic sandstones [Tujchneider et al., 2003].

Daily rainfall, streamflow and air temperature for each catchment, 1980 to 2001, were used. For the R. dos Bois, R. Preto and R. Meia Ponte, mean daily temperature varies seasonally by approximately only 2°C, with an annual mean of about 23°C. For the R. Ivaí, temperature varies by about 3.5°C, with an annual mean of approximately 20.5°C. The flow data are from the national archive for which the Brazilian agency ANA (Agência Nacional de Águas) is responsible, and were checked for internal consistency by

Figure 1. Daily rainfall and streamflow for (top to bottom) R. dos Bois, R. Ivaí, R. Preto and R. Meia Ponte

ONS. Fig. 1 shows that R. Preto streamflow data are missing for January 1991 to March 1993, and for April and May 1998. March and April 1998 flow data are missing for the R. Meia Ponte. Rainfall data were provided by the ONS. The methods for deriving daily areal rainfall and representative air temperature for the catchments are given elsewhere [Collischonn et al., 2005; Littlewood et al., submitted]. Mean annual rainfalls (1980-2001) for the R. dos Bois, R. Ivaí, R. Meia Ponte and R. Preto are 1447, 1607, 1572 and 1422 mm respectively, and corresponding streamflows are volumetrically about 31%, 44%, 25% and 28% of rainfall respectively; it appears from these percentage runoffs that a substantial amount of the rain that falls on the R. Meia Ponte and R. Preto catchments could be leaving those

catchments as groundwater. Strongly seasonal rainfall for the R. dos Bois, R. Meia Ponte and R. Preto catchments produce strongly seasonal patterns of streamflow. The R. Ivaí catchment rainfall is not so seasonal, and streamflow is relatively flashy. The R. Preto exhibits a remarkably high baseflow as a proportion of streamflow (Fig.1), indicating that its flow is largely sustained from groundwater.

The four catchments therefore exhibit quite different rainfall–streamflow behaviours. Bearing in mind that the spatially lumped, 6-parameter, IHACRES model does not explicitly represent groundwater flow to or from a catchment, the extent to which it can characterise and quantify the catchment-scale rainfall–streamflow dynamics of the four catchments is addressed in the remainder of the paper.

4. MODEL CALIBRATIONS AND COMPARISONS OF DRCs

ICP models for the R. dos Bois and R. Ivaí had been calibrated previously over the period 1 January 1981 to 2 January 1996, using 1980 as a model warm-up period [Littlewood et al., submitted]. The gaps in the R. Preto streamflow record precluded using the same calibration period for that catchment (ICP requires unbroken, concurrent, time series for rainfall, streamflow and temperature). The longest period of available streamflow record for the R. Preto was 1 January 1980 to 31st December 1990.

The ICP package allows a model warm-up period, i.e. a sub-period at the start of the calibration period not used for assessing model-fit. Although one year was a sufficient model warm-up period for the R. dos Bois, R. Ivaí and R. Meia Ponte, the large baseflow component of the R. Preto meant that a much longer model warm-up period was required for that catchment. Using the model
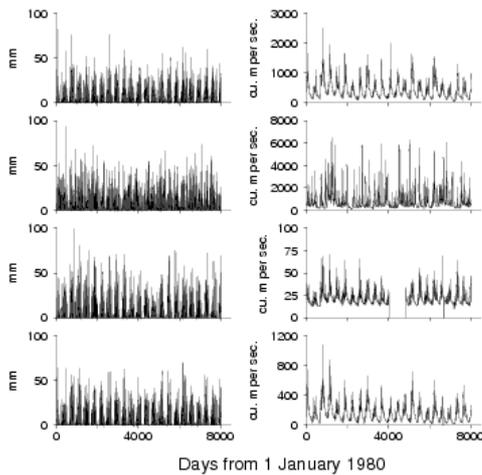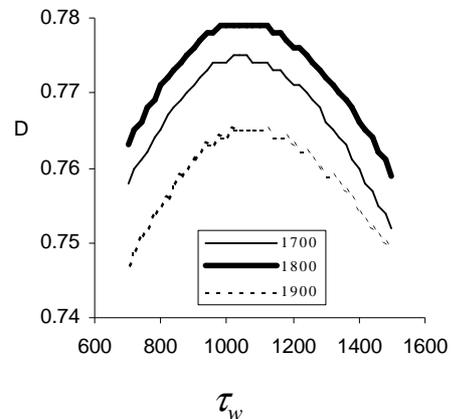

Figure 2. R. Preto: D against τ_w for three different warm-up periods

calibration period 1 January 1980 to 16 August 1990, it was found that goodness of model-fit for the R. Preto was sensitive to the length of the model warm-up period. Figure 2 shows that the coefficient of determination (D), often referred to as the Nash–Sutcliffe efficiency criterion, is higher for the R. Preto when the warm-up period is 1800 days (i.e. 1 January 1980 to 4 December 1984) than when it is either 1700 or 1900 days. Further work is necessary to investigate whether other model calibration periods would yield substantially different optimal warm-up times, i.e. with other sequences of rainfall and streamflow over the first 2000 days. As indicated in Fig. 2, a catchment wetness drying time constant (τ_w) of 1040 days was appropriate.

justifiable in the sense that if both f and τ_w were allowed in the loss module then similar highest values for D were obtained for large ranges of those two parameters. It can be seen from equation (3) that when $f = 0$ it is effectively a redundant parameter. It is therefore convenient to omit f from the model by setting it to zero, thereby reducing the number of model parameters to five. This is justifiable especially if, as for the R. dos Bois, R. Preto and R. Meia Ponte, the highest D obtained using only τ_w is not substantially less than the highest D obtained using f and τ_w. As noted earlier, the R. dos Bois, R. Preto and R. Meia Ponte catchments have a fairly subdued seasonal variation in temperature. For catchments where the seasonal temperature variation is larger, like the R.

Table 3. ICP Dynamic Response Characteristics (DRCs) and Base Flow Index (BFI)

Catchment	δ (days)	D	τ_w (days)	f (°C^{-1})	$1/C$ (mm)	$\tau^{(q)}$ (days)	$\tau^{(s)}$ (days)	$v^{(s)}$ (-)	BFI
R. Ivaí	1	0.83	20	0.112	246	4.9	128	0.34	0.63
R. dos Bois	1	0.90	52	0	912	8.7	178	0.59	0.84
R. Preto	0	0.78	1040	0	13,698	5.3	387	0.81	0.88
R. Meia Ponte	1	0.87	52	0	1104	6.5	124	0.63	0.81

Table 3 gives the DRCs for the four catchments, and Fig. 3 shows the simulation-mode R. Preto model-fit over the whole period from 1980 to 2001 (providing estimates of flow where there are gaps in the record and a measure of validation over non-calibration periods). The warm-up time can be seen at the start of the period in Fig. 3; the modelled flows climb from zero (ICP initiates s_k at zero) to reach the level of mean observed streamflow at about 1800 days. Table 3 also gives the Base Flow Index (BFI) [Gustard et al., 1992] for each catchment, calculated solely from the shape of the relevant hydrograph and representing an arbitrary baseflow proportion of streamflow. It can be noted that parameter f was set to zero for the R. dos Bois, R. Meia Ponte and R. Preto. In those cases, non-zero (>0) values of f were not

Ivaí, it is more likely that the additional loss module parameter f will be justifiable.

Broad similarities and differences between flow regimes become more apparent when streamflow hydrographs (m^3s^{-1}) are plotted as equivalent daily runoff (mm) hydrographs, as shown in Fig. 4. The R. dos Bois and R. Meia Ponte drain adjacent catchments and have similar runoff hydrographs, so it is as expected (but reassuring) that their DRCs in Table 3 are similar, particularly τ_w, $1/C$ and $v^{(s)}$ (= SFI). However, the R. Preto, which is located in the same region, has a relatively subdued runoff hydrograph, and its much higher τ_w, $1/C$ and $\tau^{(s)}$ are consistent with that difference
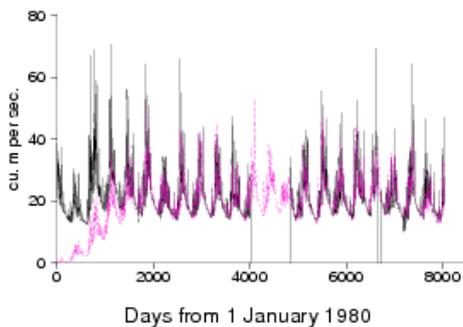

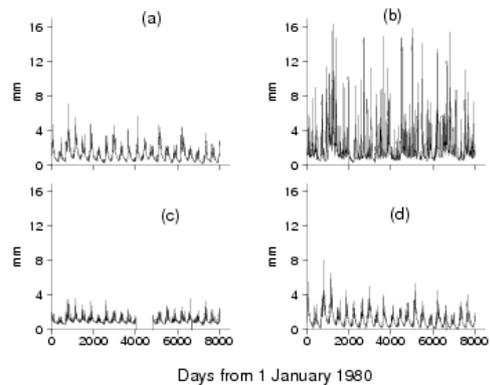**Figure 3.** R. Preto: simulation-mode model-fit, 1980 to 2001

Figure 4. Daily runoff hydrographs 1980 to 2001 (a) R. dos Bois, (b) R. Ivaí, (c) R. Preto, (d) R. Meia Ponte

(the remarkably high catchment wetness storage, $1/C$, of more than 13m for the R. Preto is discussed later). Figure 4 confirms the relative flashiness of the R. Ivaí flow regime, and this is reflected in its relatively low τ_w, combined relatively low $\tau^{(q)}$ and $\tau^{(s)}$, and low $\nu^{(s)}$. It is interesting to note that BFI and $\nu^{(s)}$ (= SFI) are similar only for the R. Preto, and substantially different for each of the other three catchments, where BFI varies by only about 5% for the quite different R. dos Bois and R. Preto flow regimes. It appears that SFI, which differs by about 27% for the same two catchments, is better able than BFI to discern these flow regimes.

5. COMPARISON WITH SPATIALLY DISTRIBUTED MODELS

For the R. dos Bois and R. Ivaí, Littlewood et al. [submitted] compared IHACRES and the spatially distributed model MGB (Modelo de Grandes Bacias) developed at the Instituto de Pesquisas Hidráulicas (IPH) of the Brazilian Federal University UFRGS [Allasia et al., 2005; Collischonn et al., 2005]. In terms of D and bias (the difference between mean observed and mean modelled flows), structurally less complex IHACRES models for the R. dos Bois and R. Ivaí were almost as good as, or indistinguishable from, corresponding MGB models for those catchments.

The additional ICP models for the R. Meia Ponte and R. Preto presented in this paper gave values for D of 0.87 and 0.78 respectively, compared with 0.80 and 0.58 respectively for MGB models calibrated over shorter periods of record, which may partly explain the somewhat higher value of D for the R. Meia Ponte ICP model. However, a considerable amount of caution needs to be exercised when assessing the relevance of the much higher D for the R. Preto ICP model. Two main points will now be discussed.

6. DISCUSSION

First, as the paper has shown, a warm-up time of 1800 days (nearly five years) was applied to obtain the ICP model for the R. Preto. The other ICP models, and the MGB models, referred to above were all calibrated using a warm-up time of one year. An MGB model for the R. Preto calibrated using a warm-up time of about 1800 days may yield a D comparable to that obtained using IHACRES; work is underway to test this idea.

Second, the ICP model structure does not conceptualise groundwater imports to, or exports from, a catchment. The model defined by equations (1) to (5) makes the assumption that all of the rain on a catchment eventually leaves the catchment either as streamflow or evaporation. For the R. Preto, the combination of (a) a strongly subdued streamflow response (Fig. 4) and (b) a runoff coefficient of about 28% suggests there is groundwater export from the catchment, which is not represented explicitly in the IHACRES model structure. (The R. Meia Ponte has an even lower runoff coefficient of 25%, but its SFI is 0.59 compared with 0.81 for the R. Preto. For reasons not yet fully understood, but possibly related to their different degrees of interaction with the regional Guaraní Aquifer System, the R. Meia Ponte has a quite different flow regime from that for the R. Preto.)

The R. Preto IHACRES model is saying only that the catchment behaves approximately as if there is no export of groundwater, and that it has a catchment wetness storage ($1/C$) of more than 13m, not that there is no groundwater export, nor that it has a physically identifiable storage of that depth. The relatively large $1/C$ may be compensating for the lack of groundwater export representation in the model (but it does indicate a remarkable catchment hydrology). Thus it is possible that the ICP model for the R. Preto may represent more of a curve-fitting than a conceptual modelling exercise for that catchment. Structurally simple models like IHACRES will always have limitations of interpretation regarding the physical meaning of their parameters, especially when applied to 'exotic' catchments and, as in this paper, when there is limited knowledge about the catchments, e.g. the extent to which there is interaction with the Guaraní Aquifer System.

However, for the other three catchments the magnitudes of, and differences between, their $1/C$ DRCs (and similarly for the other DRCs) appear to be reasonably consistent with their broad hydroclimatological features. On that basis the DRCs are considered to be physically meaningful in some sense. Although a major motivation for applying IHACRES to Brazilian catchments is to assess its efficacy for streamflow forecasting in relation to hydropower planning and operations, another motivation is to investigate continuous flow simulation at ungauged (flow) sites from DRCs estimated from PCDs. It is intended to apply IHACRES to many more catchments in Brazil (and elsewhere) and to establish to what extent its DRCs can be estimated from PCDs, e.g. stream density, slopes, land-use, etc.

7. CONCLUDING REMARKS

The paper has demonstrated the utility of the IHACRES approach for modelling four Brazilian catchments ranging in size from about 1,600 km^2 to more than 34,000 km^2. Its performance, in terms

of D and bias, is comparable with that of MGB, a structurally more complex (spatially distributed) model. In three cases (R. dos Bois, R. Ivaí and R. Meia Ponte), the IHACRES model parameters (DRCs) characterise the different catchment-scale dynamic rainfall–streamflow behaviours reasonably well. In the fourth case (R. Preto), simple inspection of the runoff hydrograph (Fig. 4) indicates a large, quasi-constant, groundwater component, possibly the result of substantial interaction between the catchment and the regional Guaraní Aquifer System.

In terms of D, the R. Preto model (0.78) is a little poorer than the other three catchment models (0.83-0.90), and its DRCs should therefore be treated with more caution than the DRCs for the other catchments. Beyond that, the R. Preto DRCs should be treated with extra caution because the model structure does not incorporate any representation of groundwater imports or exports. Future modelling of the R. Preto could consider its large groundwater component separately by first subtracting a constant (or slowly varying) baseflow from the hydrograph, or by initiating the catchment wetness index, s_k, at an appropriate non-zero value.

Based on the IHACRES work presented in the paper, it has been suggested that the spatially distributed MGB might yield a better R. Preto model-fit if it were calibrated with a warm-up period of much longer than one year. This will be tried in due course and is an example of where one modelling approach can help to inform another. It makes sense to apply different modelling approaches to the same datasets. The IHACRES model results presented and discussed here, particularly those for the R. Preto, should be regarded as provisional; future work with spatially distributed models (possibly including MGB using long warm-up periods) may provide insights to help model the catchments by the IHACRES approach.

8.   ACKNOWLEDGEMENTS

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