Evaluation of Streamflow Predictions by the IHACRES Rainfall-Runoff Model in Two South African Catchments

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Abstract: In many South African catchments, water is an increasingly limited and highly fluctuating resource. Accurate prediction of low flows is especially vital if water resource managers are to successfully balance the growing needs of agriculture, industry, and rural and urban populations, while maintaining the ecological health of aquatic and riparian ecosystems. Existing hydrological models in use in South Africa suffer from a number of disadvantages. They are complex, over-parameterised, data-demanding, and expensive to use. IHACRES, a lumped conceptual model requiring minimal input data, is less limited by these problems, and has the potential to advance our understanding of streamflow patterns and predict how these may be altered by land-use change. The purpose of this paper is to evaluate IHACRES performance for two South African catchments: Lambrechtsbos A (a 31 ha research catchment), and Groot-Nylrivier (74 km^2). IHACRES predicted streamflow at Lambrechtsbos A with useful accuracy (pre-afforestation period, $R^2 > 0.81$; bias < 26 mm; post-afforestation period, $R^2 = 0.81$, bias = 8.4 mm). With prior knowledge of changes in annual evapotranspiration, predictions of land-use impacts on flow regime may be satisfactorily predicted. Simulations of flows in the Groot-Nylrivier catchment were found to be of useful accuracy for relatively short periods of 2-3 years, but performance over longer time periods was reduced by poor predictions in certain years. We ascribe this primarily to poor catchment-average rainfall estimation following certain storms in some years. Our simulations highlighted a tendency for IHACRES to underestimate quickflow events, especially at times when the greater part of a catchment is dry. Further model development is required to overcome these problems. IHACRES shows great potential in linking proposed land-use change to altered flow regimes, and efficiently describing the flow characteristics within catchments. However, poor estimation of average rainfall in larger catchments is a limitation that needs to be overcome before long-term flow regimes of non-research catchments may be predicted with confidence.

Keywords: Streamflow; IHACRES; Land-use; Rainfall-Runoff model; South Africa

1. INTRODUCTION

South Africa is a relatively dry country, and limited water resources are set to become increasingly valuable as demand for water by agricultural, industrial and urban sectors increases. Supply in rivers fluctuates widely because of large variation in the amount and distribution of rainfall, both within and between years. Periodic droughts, especially when associated with consecutive years of below average rainfall, have a major detrimental effect on the national economy.

Land use changes have the potential to greatly alter catchment water yields. The best known example in South Africa follows the conversion of grasslands to forest plantation, when water yields may be reduced by up to 600 mm per year [Dye and Bosch, 2000]. However, the hydrological impacts of a wide range of other land-use conversions in watershed areas is increasingly in contention, as water resource managers prepare to implement a new water law involving a more holistic approach to water resource planning. This planning will increasingly require scenario analyses of different land use options, with great attention being paid to water availability in years of greatest shortage.

Several physically-based hydrological models are already in use, or are currently being evaluated for their ability to assist planners in assessing different land-use scenarios. Foremost are the ACRU, Pitman, VTI, HSPF, SWAT and MACAQUE models. They all, however, share certain problems that reduce their effectiveness:

- They are data demanding, and much time is required to gather, check, patch and format the necessary input data. The cost of setting up a simulation, especially for large catchments, is high.
- Estimation of certain parameter values, especially those controlling the flow of soil water and ground water to the stream channel, is difficult.
- The success of these models is often influenced by the calibration skills of the user. Those with the necessary skills and experience can often afford only limited time to assist others in setting up simulations.
- Such models are often criticised for being over-parameterized [Jakeman and Hornberger, 1993]. There is widespread consensus that simple modelling approaches, using as few parameters as possible to represent the key identifiable catchment runoff response, is a promising strategy in rainfall-runoff modelling [Nash and Sutcliffe, 1970; Beven, 1989; Beven, 1993; Jakeman et al., 1990; Young and Beven, 1994; Jakeman and Hornberger, 1993].

The model IHACRES (Identification of unit Hydrographs And Component flows from Rainfall, Evapotranspiration and Streamflow data) is a simple model designed to avoid the problems described above. First described by Jakeman et al. [1990], its subsequent development and application has demonstrated the following advantages and capabilities:

- It is simple, parametrically efficient, and statistically rigorous.
- Results are data-based, and require no subjectively- estimated parameter values.
- Input data requirements are simple, comprising only precipitation, streamflow and temperature.
- Simulations are quickly set up, and computational demand is low.
- The model efficiently describes the dynamic response characteristics of catchments [Jakeman et al., 1992; Sefton and Howarth, 1998].
- Statistical relationships may be developed relating these dynamic response characteristics to physical catchment descriptors [e.g. Sefton et al. 1995; Sefton and Howarth, 1998; Post and Jakeman, 1996]. Such relationships provide a basis for regionalising results of sample catchments.
- It can also be used to assess changes in streamflow following a change of land use in a catchment [e.g. Post et al., 1996].

The purpose of this paper is to report the results of tests of the model against data from two South African catchments, and to explore the potential of IHACRES to meet some of the information needs of South African water resource managers. Lambrechtsbos A is a small research catchment (31.2 ha) situated in the high rainfall forestry region of South Africa, which has undergone a radical land-use change from indigenous Macchia-type vegetation (Fynbos) to *Pinus Radiata* plantation. The Groot-Nylrivier is typical of larger non-research catchments where streamflow records may exist for extended periods, but where rain gauge density is low. The aim of this catchment study was to explore if useful long-term simulations are possible for such catchments.

2. MODEL DESCRIPTION

The IHACRES model used in this study is based on the catchment moisture deficit (CMD) model of Evans and Jakeman [1998]. This model uses a non-linear module to estimate the effective rainfall, and a linear routing module representing transport lags is used to convert the effective rainfall to streamflow. The non-linear module uses a constant multiplier (c) to estimate the potential evapotranspiration (ET) from temperature (T). The CMD is then used to determine the effect of drying on the catchment on the actual ET. These relationships are defined in equations 1 and 2:

$$ET = c\,T \quad \text{for } CMD < d \qquad (1)$$
$$= c\,T\,exp(2(1-CMD/d)) \quad \text{otherwise} \qquad (2)$$

The effective rainfall (U) is estimated from observed rainfall (P) and CMD using the drainage equation:

$$dU/dP = 1 - CMD/a \quad \text{for } CMD < a \qquad (3)$$
$$= 0 \quad \text{otherwise} \qquad (4)$$

Further details of this non-linear module can be found in Croke and Jakeman (in preparation). The non-linear module parameters were varied systematically in the optimisation process to get a best fit of observed and modelled flows.

In the case of Groot-Nylrivier, the parameters for the linear routing module were determined by a simple refined version of the instrument variable technique [Young, 1984; Jakeman et al., 1990]. In the case of Lambrechtsbos A, the implementation of the instrument variable method used for calibration was unsuccessful due to the combination of an hourly timestep, and a very long time constant needed for the slowflow component. To overcome this, the unit hydrograph response curve was determined directly from observed flow [Croke, 2001].

3. CATCHMENT DESCRIPTIONS

3.1 Lambrechtsbos A

This research catchment (33^0 57' S; 18^0 55' E) is situated in the Jonkershoek valley, a short distance northeast of the town of Stellenbosch in the Western Cape Province of South Africa. It is 31.2ha in extent. Slopes are steep (average 45%) and the altitude varies from 360 to 1067 m.a.s.l. The geology comprises sandstone and quartzite with intermittent thin shale bands of the Table Mountain Group, occurring mostly in the upper slopes and cliffs of the scarp. The soils are complex, derived primarily of mixed colluvial material, with major forms being Hutton, Magwa and Nomanci [McVicar et al., 1977]. The soils have a low bulk density, high infiltration capacity and are well drained. Soil depths range from approximately 1-2 m, but are underlain by unconsolidated or decomposed material that allows free drainage of water as well as exploration by tree roots.

The climate is of the humid mesothermal Mediterranean type with warm, dry summers and cool, wet winters with frequent frontal rains. The mean annual temperature is 16.1 ^{0}C with a yearly maximum of 38.1 ^{0}C and a minimum of 0.7 ^{0}C [van Lill, 1967]. Mean annual rainfall recorded from 1940 to 1998 is 1145 mm.

The native vegetation of the area is a tall (2 - 3 m), open to closed, Fynbos (Macchia) shrubland dominated by *Protea neriifolia, Protea repens, Brunia nodiflora* and *Widdringtonia nodiflora.* In 1972, 89% of the catchment was planted to *Pinus radiata*. The remaining 11% was left unafforested and included a 20-metre strip on either side of the stream, as well as rocky cliffs and steeper slopes.

3.2 Groot-Nylrivier

This 73 km^2 catchment is situated midway between the towns of Warmbaths and Nylstroom in the Northern Province of South Africa. The catchment is the source of the Groot-Nylrivier, which ultimately flows into the Limpopo River. Flow is monitored at a weir (A6H011) situated at 24° 45$'$ 40S, 28^0 20$'$ 44E. The drainage density of the catchment is 0.307 km km^{-2} [Hughes, 1997]. Four very small dams were judged to have little significant effect on flows recorded at the weir. Altitude ranges from 1180 to 1508 m, and average slope is 3.5°.

The catchment is underlain by sedimentary rock of the Waterberg and Rooiberg group and includes a wide variety of sandstone, greywacke, grit, mudstone, siltstone, shale and conglomerate. Soils are highly variable, but are predominantly acidic sands, loams or gravels with a maximum depth of 1200 mm.

Natural savanna classified as Waterberg moist mountain bushveld [Low and Rebelo, 1998] covers 90% of the catchment, while the remaining 10% consists of croplands.

The estimated mean annual precipitation of 654 mm is based on a single rain gauge situated 1.79 km from the weir. Rainfall is concentrated in the summer months from November to April, and occurs predominantly in the form of thunderstorms. Mean annual temperature averages 18°C but ranges from –6 to 39 ^{0}C [Low and Rebelo, 1998].

4. MODELLING PROCEDURE

4.1 Lambrechtsbos A

An hourly time step was considered to be appropriate for this relatively small catchment. Daily maximum and minimum temperatures recorded at a nearby weather station were disaggregated to hourly values using the USDG software package METCMP. Cross-correlation analysis showed a time delay of one hour between rainfall and streamflow response. The data record from 1967 to 1971 was judged to be representative of the pre-afforestation period. Model calibration was performed using data recorded from 1 April 1970 to 3 May 1971. The model was then tested against the remaining independent data.

A detailed paired-catchment analysis of long-term streamflow in Lambrechtsbos A revealed a relatively stable post-afforestation period from 1988 to 1991 [Scott et al. 2000]. Calibration was performed using data recorded from 1 January 1989 to 2 May 1990. The model was then tested on the remaining independent data. It was assumed that a change of vegetation would not alter the threshold (a) in catchment moisture deficit for production of flow. Consequently, the value of 200 determined for the pre-afforestation period was assumed to remain unchanged in the post-afforestation period. Dummy input data were used in each case to "warm up" the model".

4.2 Groot-Nylrivier

Rainfall, streamflow and temperature data for January 1968 to December 1978 were selected for this study, because it corresponds to a period of few missing data. A three-year calibration period (October 1971 to September 1974) was chosen since it included years of average and very low rainfall and streamflow; these are regimes of most interest. A daily time step was judged to be appropriate and from the cross correlation of rainfall and streamflow, a time lag of 1 day in streamflow response was specified. Following model calibration and parameter estimation, the model was run on the remaining independent data.

5. RESULTS

5.1 Lambrechtsbos A

Table 1 shows the model fit statistics, and the fitted parameter values for the non-linear module. Overall model performance at this site, based on calculated R^2 (proportion of discharge variance explained) and bias (average annual error in mm), was judged to be satisfactory, and comparable to results reported from many other catchments such as those in Sefton and Howarth [1998] and Chiew and McMahon [1994].

Table 1. A summary of model fit statistics, and the parameter values for the non-linear modules applicable to the Lambrechtsbos A simulation.

	Pre afforestation		Post-afforestation	
	Non-linear module parameters			
a	200		200	
c	10		16	
d	142		132	
	Model fit			
	Calib	Verif	Calib	Verif
R^2	0.864	0.814	0.751	0.811
bias(mm)	0.7	25.8	0.0	8.4

Figure 1 shows the fit obtained for the pre-afforestation test period. The overall trend in baseflow is reproduced reasonably well but the quickflow peaks tend to be underestimated. This is particularly noticeable during the dry season (Nov-Apr), when there is often no modelled response to rainfall events that cause measurable quickflow. We believe this flow is generated from riparian zones and perhaps areas of shallow soil or exposed rock, at times when the major part of the catchment is experiencing a high soil moisture deficit. IHACRES cannot take account of such spatial variability in soil depth and moisture content, and no effective rainfall may be generated at times of high overall CMD. Discrepancies between observed and modelled flows are especially noticeable in quickflow peaks.

Figure 2 depicts a plot of observed versus modelled flows over the same test period shown in Figure 1. The data points joined by lines represent a single 32 hr period associated with the highest rainfall event. Their exclusion increases the R^2 to 0.88. Best model predictions are for the lowest flows, due to convergence of observed and modelled recession flows. A tendency for dry season quickflows to be underestimated was equally apparent in simulations of the post-afforestation period.

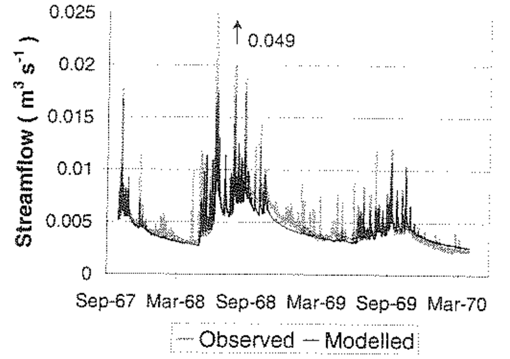

Figure 1. Observed and modelled hourly flows over a three-year pre-afforestation test period in Lambrechtsbos A catchment.

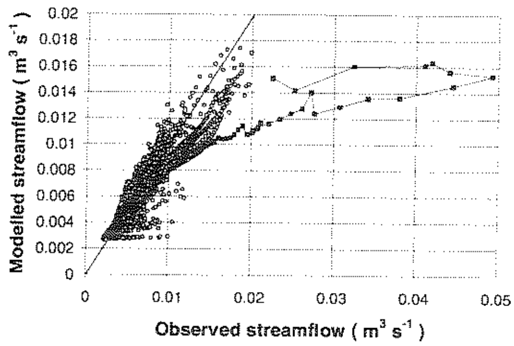

Figure 2. Observed versus modelled hourly flows for the test period, Lambrechtsbos A catchment. Joined points represent a single 32-hour high-rainfall event.

In the pre-afforestation analysis (runoff coefficient = 0.37), parameters a, c and d were allowed to vary to model-optimised values (Table 1). In the post-afforestation analysis (runoff coefficient = 0.23), we kept parameter *a* unaltered at 200, and allowed only c and d to vary. Parameter *a* was considered to be less influenced by vegetation changes, and more by the physical characteristics of the catchment. Parameters *c* and *d* are both significantly influenced by vegetation, and were expected to change in response to the land-use conversion. Annual ET from *Pinus radiata* (1059 mm) is markedly higher than the 769 mm associated with the pre-afforestation Fynbos vegetation, and is in accord with estimates based on long-term water balance data [Scott et al., 2000]. The difference in annual ET is attributed mainly to the higher maximum ET for Pinus radiata.

There is a small difference in threshold parameter d between the pre-afforestation (142) and the post-afforestation (132) period. This implies that the original Fynbos vegetation is somewhat more drought resistant than the *Pinus radiata* trees. Such a difference would not be surprising in view of the adaption of the indigenous flora to seasonal drought and high temperatures.

5.2 Groot-Nylrivier

Figure 3 illustrates the comparison of modelled and observed flows over the test period. The overall fit is poorer than for the calibration period (Table 2), with discrepancies evident in both quickflow peaks and offset recession curves. The model does however reproduce a realistic decline in recession flow in all years. Quickflows that occur in response to moderate to low rainfalls in spring and winter, when the catchment is dry, are underestimated.

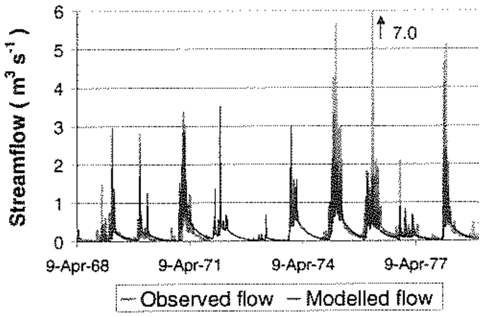

Figure 3. Time series of observed and modelled daily flows over an independent seven-year test period in the Groot-Nylrivier catchment.

Table 2. A summary of model fit statistics, parameter values for the non-linear module, and the dynamic response characteristics for the Groot-Nylrivier (the larger value for the c parameter compared with that for Lambrechtsbos A is due to running the model on a daily rather than hourly timestep).

	Non-linear module parameter values	
a	160	
c	278	
d	100	
	Model fit	
	Calibration	Verification
R^2	0.83	0.622
bias (mm)	-0.4	6.9

Figure 4 shows observed versus modelled daily flow for this catchment. There is a wider scatter of data points, even at low flows, than recorded in the smaller Lambrechtsbos A. Underestimation of highest quickflows is still evident, although less pronounced than in the Lambrechtsbos A catchment. We ascribe these differences primarily to the presence of only a single gauge in the catchment, and the greater uncertainty over the amount of rainfall falling over the larger Groot-Nylrivier catchment.

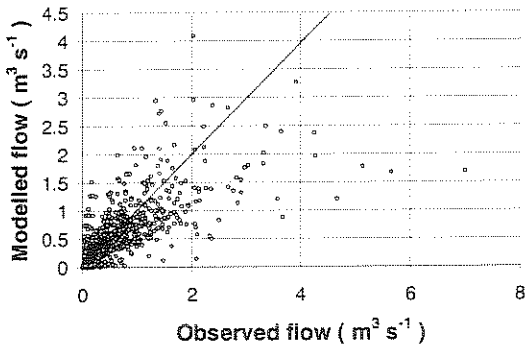

Figure 4. Comparison of daily observed and modelled flows for the calibration period in the Groot-Nylrivier catchment.

6. CONCLUSIONS

We draw the following conclusions from the results of this study:

- IHACRES is likely to generate useful flow predictions for smaller catchments with spatially representative rainfall measurements.
- Slow flows are better predicted than quickflows. Higher flows tend to be under-simulated. This is particularly marked at times when the conceptual catchment moisture deficit is large. Limited areas of low infiltration capacity such as saturated riparian soils, shallow soils and exposed rock are believed to be responsible for this phenomenon.
- The model appears to be especially suitable for predicting the effects of land use changes on low flows as seen in the application to the pre- and post-afforestation periods for the Lambrechtsbos A catchment. This capability deserves further investigation.
- Use of IHACRES to predict flows in larger non-research catchments in South Africa is feasible, but constrained by inadequate rainfall data. Radar measurement of rainfall in South Africa is currently under investigation, and improved rainfall estimates for larger catchments are envisaged with this technique [van Heerden and Steyn, 1999].

We believe that the model shows considerable promise in characterising and revealing differences in streamflow patterns and catchment functioning in South Africa.

7. ACKNOWLEDGEMENTS

We are grateful to Professor Tony Jakeman of CRES at the Australian National University for supporting collaboration between our Institutions and his comments on the manuscript. Ms Marilyn Royappen provided considerable support in obtaining and checking the necessary input data.

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