Verification of the *ACRU* model for forest hydrology applications[#]

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Abstract

Simulation model output must be tested for goodness of fit against observed data before the model can be utilised with confidence for any useful or decision-making purpose. Unless this is the case, a model is unlikely to be accepted by users other than the model developers. With intense competition for Southern Africa's sparse water resources, the potential impacts of afforestation, currently the only named streamflow reduction activity (SFRA) in the National Water Act of 1998, need to be assessed prior to planting.

The *ACRU* model has been used extensively in conjunction with a decision support system to assist the user in preparing input information to simulate water production from afforested areas. Verification of the output of the *ACRU* model is thus of utmost importance if it is to be accepted by the water community at large for use in this type of application.

Values of simulated streamflow were compared with observed streamflow at three locations, one each in KwaZulu-Natal, Mpumulanga and the Northern Province on forested catchments with a range of catchment sizes, forest species and ages of plantation. *ACRU* was found to perform acceptably at most sites. Some problems of temporal distribution of streamflow were, however, found to exist. It is concluded that *ACRU*, when used in conjunction with the decision support system developed to assist in the simulation of forest hydrological impacts, could be a particularly useful tool to resource managers, planners and Catchment Management Agencies in water management areas where afforestation may take place or where its impact has to be assessed.

Introduction

With intense competition for Southern Africa's sparse water resources, the potential impacts of afforestation, currently the only named streamflow reduction activity (SFRA) in the National Water Act of 1998, need to be assessed prior to planting. Increasing afforestation in Southern Africa and concern for its impact on water resources has led to increasing use of models to simulate the impacts of commercial afforestation on downstream water resources. The *ACRU* agrohydrological modelling system has been used extensively in this regard. As a result, a decision support system has been developed for use when simulating hydrological impacts of afforestation with the *ACRU* agrohydrological modelling system. This system simplifies the task of the model user a great deal by providing default values to land cover and soils input variables which may be affected by afforestation of a catchment. The user merely provides information regarding tree species and age and the method of site preparation used. The development of this forest decision support system has been described and discussed elsewhere (Jewitt and Schulze, 1991; Summerton, 1995).

A model such as *ACRU* can only be used with confidence if its output has been verified against observed data sets. The version of the *ACRU* model used in this study can perform such statistical analyses of model performance at both daily and monthly levels of output for a number of variables, including streamflow, which is used in the verification of output from forested catchments. The equations and objective functions used in *ACRU* have been explained and discussed in detail by Smithers and Schulze (1995).

Verification of output from *ACRU* for forested catchments was undertaken with the aim of determining whether the *ACRU* model can be used with confidence to simulate streamflow from catchments afforested with different species and at different stages of growth using different site preparation techniques. In the light of South Africa's new National Water Act, it is the water yield of an area that is of utmost importance to the water resources planner acting for the local catchment management agency (CMA), thus statistics of monthly totals of daily simulated streamflows are presented in this paper.

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The *ACRU* agrohydrological modelling system

The *ACRU* agrohydrological modelling system has been developed in the Department of Agricultural Engineering (now the School of Bioresources Engineering and Environmental Hydrology) at the University of Natal. The *ACRU* model is described by the developers as a multi-purpose and multi-level integrated physical conceptual model that can simulate streamflow, total evaporation, and land cover/management and abstraction impacts on water resources at a daily time step.

Model documentation was first published in 1984 (Schulze, 1984) and updated in 1989 (Schulze, 1989). The latest public domain version of the model is *ACRU327* and updated documentation has been published (Schulze, 1995). Model input parameters are contained in a menu file. Input to the menu is controlled by a "menubuilder" program where the user enters parameter or catchment related values or uses defaults provided. In the case of simulations of forest hydrology, this function is performed by the ACRU forest decision support system.

The *ACRU* model revolves around multi-layer soil water budgeting. Runoff is generated as stormflow dependent upon the magnitude of daily rainfall in relation to dynamic soil water budgeting. Components of the soil water budget are integrated with modules in the *ACRU* system to simulate many other catchment components including irrigation requirements and sediment yield.

Spatial variation of rainfall, soils and land cover is facilitated

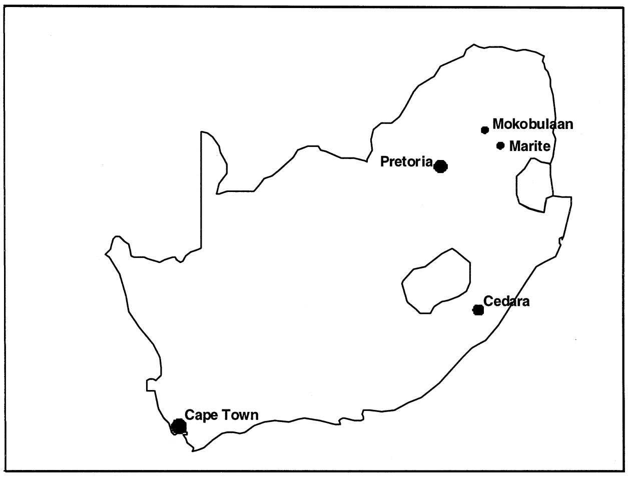

Figure 1
Location of the study sites

by operating the model in "distributed" mode in which case the catchment to be modelled is subdivided into cells, or subcatchments, each of which represents a relatively homogenous area of hydrological response.

Description and results of verification studies

The catchments where streamflows were simulated are:
- One of the University of Natal's School of Bioresources Engineering and Environmental Hydrology research catchments at Cedara in the KwaZulu-Natal Midlands, U2H018.
- A Department of Water Affairs and Forestry catchment on the Marite River, X1H003, a tributary of the Sabie River, in Mpumulanga.
- Three of the CSIR's Mokobulaan research catchments, in the Northern Province.

The location of these catchments is shown in Fig. 1. The Cedara and Mokobulaan catchments are considered to be "research" catchments as they are operated by research organisations as field sites. Consequently model input information is available at a far greater level of detail than for catchments such as that of the Marite River. The Marite catchment is considered to be an "operational" catchment, as input data to the model are obtained from the national bodies responsible for the collection of such data as part of the national network at a spatially less dense level than is available for the research catchments.

As *ACRU* is considered to be a physical-conceptual rather than a calibration model, the simulations performed are based on physically measurable or derivable catchment characteristics. In addition to these studies, the *ACRU* model has previously been used to simulate streamflow from a research catchment afforested to *Pinus patula* at Cathedral Peak in the Natal Drakensberg. This particular study is documented in detail in the international literature by Schulze and George (1987) who obtained a good match between simulated and observed streamflow for a time series during which the forest was actively growing.

Cedara catchment, U2H018

The Cedara catchment U2H018 is a small forested catchment typical of many in the Midlands of KwaZulu-Natal. Situated 20 km north of Pietermaritzburg, the catchment forms part of a network of catchments formerly monitored by the School of Bioresources Engineering and Environmental Hydrology at the University of Natal through funding from the Water Research Commission (WRC) before persistent vandalism and theft of equipment lead to all instrumentation being removed. Schmidt and Schulze (1989) have published a comprehensive report on these catchments. The catchment characteristics used in this modelling exercise have been obtained from that report and are summarised in Table 1.

Owing to its small size and relatively homogenous land use, the catchment's streamflow was simulated using *ACRU* operated in

TABLE 1
SELECTED FEATURES OF CEDARA CATCHMENT U2H018

Subcatchments	1
Latitude	29° 43'S
Longitude	30° 15'E
Altitude (m)	1 250
MAP (mm)	991
Area (km^2)	1.31
Aspect	North facing
Mean slope (%)	29.2
% afforested	92
Species	Mixed – *Pinus patula, Pinus radiata* and *Eucalyptus grandis*
Age (yrs)	Mixed – ranging from young to mature
Site preparation	Pitting

TABLE 2
GOODNESS OF FIT STATISTICS FOR SIMULATION OF MONTHLY TOTALS OF DAILY STREAMFLOWS IN CATCHMENT U2H018

Statistics of performance of *ACRU* model, U2H018 Cedara: A comparison of simulated and observed streamflows for monthly totals of daily values 1977-1988

Total observed flows (mm)	=	1 664.834
Total simulated flows (mm)	=	1 687.621
Mean observed flows (mm)	=	12.152
Mean simulated flows (mm)	=	12.313
Correlation coefficient	=	.861
Students "t" value	=	19.661
Linear regression coefficient	=	.807
Base constant for regression equation	=	1.783
Standard error of simulated flow	=	49.644
Variance of observed flow	=	724.266
Variance of simulated flow	=	636.132
Standard deviation of observed flow	=	26.912
Standard deviation of simulated flow	=	25.220
% difference in standard deviation	=	6.282
Coefficient of determination	=	.741
Coefficient of efficiency	=	.750
No systematic errors detected		

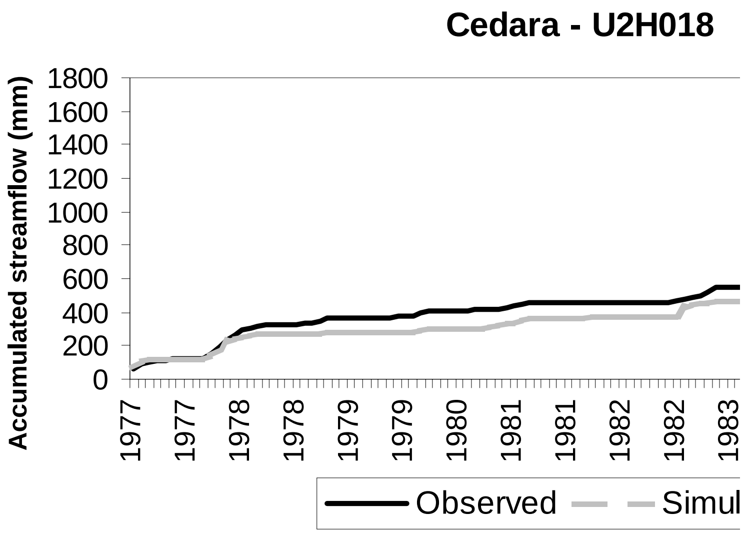

Figure 2
Accumulation totals of monthly streamflows at U2H018

lumped mode. The soils consist mainly of clays of shallow depth. Depth of the topsoil horizon is typically 150 mm with subsoil depth usually less than 500 mm. The catchment is steep with an average slope of 29.2%. Daily rainfall data were obtained from a rain-gauge which is located within the catchment. The monthly averages of daily maximum and minimum temperatures used were determined by Schmidt and Schulze (1989) and from these, potential evaporation was estimated using the temperature-based Linacre (1984) equation.

Daily streamflow values for weir U2H018 are available for the period 1977 to 1988 inclusive, and these are used in the verification study. Quality of data is generally good with only a few days of missing data. However, one critical period where data are missing covers the heavy rainfall and flood period of September 1987, when instrument failure resulted in data being lost.

The steep slopes and shallow soils, as well as the mixed land cover of short grassland (8%) and three tree species of various ages (92%), render this a difficult catchment to model. However, most goodness of fit statistics are highly acceptable as shown in Table 2 below. Accumulated totals of simulated and observed streamflows follow very similar patterns with only an as yet unexplained shift in 1978-79 and a reversal of trends in 1985-1987 as shown in Fig. 2.

Total values of streamflow are simulated accurately. Streamflow is highly variable as a result of altitude differences and the consequent well documented rainfall variation within the catchment (Schulze and Schmidt, 1989). Despite this, streamflow variances are well-simulated by the model as shown in Table 2. The positive base constant for the regression equation implies that low flows were oversimulated and high flows undersimulated to some extent.

ACRU has performed well on this catchment. Statistics produced are good enough to allow the use of the model to simulate streamflows on similar catchments with a reasonable degree of confidence.

TABLE 3
SELECTED PHYSICAL FEATURES OF THE MARITE SUBCATCHMENTS

Subcatchment	1 (Upper)	2 (Middle)	3 (Lower)
Latitude	24° 49'S	24° 52'S	24° 50'S
Longitude	31° 00'E	31° 02'E	31° 05'E
Altitude (m)	950	900	880
MAP (mm)	1 413	1 287	908
Area (km^2)	67.01	88.95	56.45
% afforested	85	84	45
Main species	*Eucalyptus grandis*	*Pinus patula*	Mixed eucalypt and pine
Age (years)	12	20	15
Site preparation	Pitting	Pitting	Pitting

The Marite catchment, X1H003

The Marite River study, in the Sabie River catchment in Mpumulanga was initiated as part of a WRC funded project undertaken by the University of Pretoria's Department of Landscape and Architecture, to assess streamflows into the Kruger National Park. The catchment is large (212 km^2) and is considered to be an "operational" catchment for the purposes of this simulation exercise. As such, it forms an important study of a typical catchment within the South African national streamflow gauge station network, on which model users frequently have to make hydrological impact decisions.

Because of its size and afforestation characteristics, the catchment was delineated into three relatively homogenous subcatchments for purposes of applying the distributed version of the *ACRU* hydrological model. A summary of subcatchment information is contained in Table 3.

Soils information was obtained from the former Soil and Irrigation Research Institute (SIRI) land type maps and associated memoirs for the area. Soils are generally deep, but variable, as can be expected in such a large catchment. The catchments were afforested initially between 1950 and 1989 and only minimal site preparation was used.

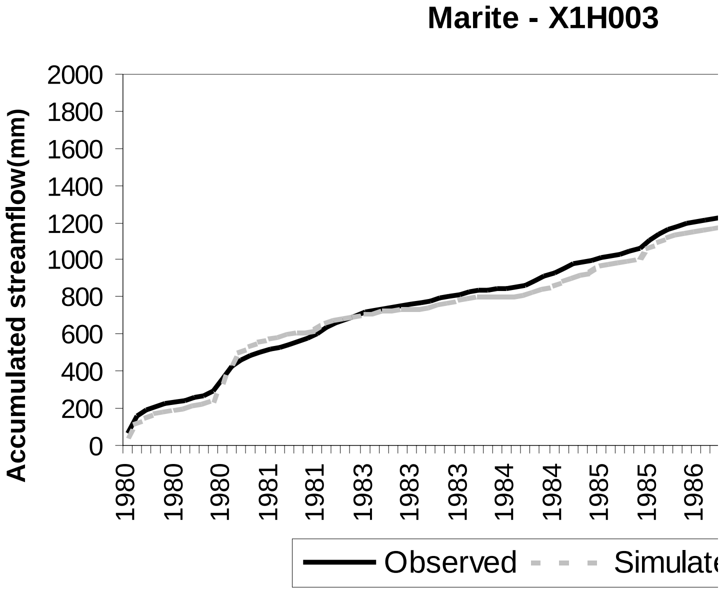

Figure 3
Accumulation totals of monthly streamflows at X1H003

TABLE 4
GOODNESS OF FIT STATISTICS FOR SIMULATION OF MONTHLY TOTALS OF DAILY STREAMFLOWS FROM THE MARITE RIVER

Statistics of performance of *ACRU* model, X1H003 Marite River: A comparison of simulated and observed streamflows for monthly totals of daily values 1980-1989

Total observed flows (mm)	=	1857.944
Total simulated flows (mm)	=	1869.984
Mean observed flows (mm)	=	18.767
Mean simulated flows (mm)	=	18.889
Correlation coefficient	=	.889
Students “t” value	=	19.124
Linear regression coefficient	=	1.173
Base constant for regression equation	=	-3.131
Standard error of simulated flow	=	93.878
Variance of observed flow	=	246.331
Variance of simulated flow	=	429.113
Standard deviation of observed flow	=	15.694
Standard deviation of simulated flow	=	20.713
% difference in standard deviation	=	-31.796
Coefficient of determination	=	.790
Coefficient of efficiency	=	.605
Systematic errors detected		

Monthly means of daily maximum and minimum temperatures obtained from three local South African Weather Bureau (SAWB) temperature stations were used to estimate month by month potential evaporation values by the Linacre (1984) technique. Daily rainfall values were obtained through the Computing Centre for Water Research (CCWR) for three SAWB rainfall stations in the area. Each station was used to generate streamflow for a different subcatchment.

Daily observed streamflow records were available from the Department of Water Affairs and Forestry’s gauging station X1H003 for the period 1980 to 1989 and this period was therefore used for the verification study. Streamflow data records were generally complete from this gauging station with only occasional missing days’ data. As a practical application of the model to an operational catchment, this simulation, using *ACRU* as a distributed model, produced very good results, as shown in Table 4 and Fig. 3.

Totals of simulated and observed values are simulated well, the correlation coefficient and the coefficient of determination are high, showing good association between simulated and observed values. Variances are not particularly well preserved in the simulated values, and the systematic error and the negative base constant with regression coefficient higher than unity, suggest that low flows are undersimulated and higher flows oversimulated at times. This is possibly a result of the timing of low and high flows being incorrect in the simulation of these large catchments. This problem may be rectified with the use of more recent versions of *ACRU*, which now incorporate a flow routing module. In addition, it can be expected that by using only three rain-gauges to model such a large area, that some rainfall events are not measured and consequently no streamflow is simulated for them, although streamflow response to such events may be measured at the weir. It must be stressed that these results were produced for an “operational” catchment which was not visited and thus was simulated completely “remotely” using national network derived data and catchment soils and land cover information which was provided by the University of Pretoria.

The Mokobulaan catchments

The Mokobulaan small catchments forest hydrological experiment on the Drakensberg escarpment SE of Lydenburg was planned in 1956 and implemented as a supplement to investigations performed at Jonkershoek in the Western Cape and at Cathedral Peak in KwaZulu-Natal (Wicht, 1967). The study has been described in detail by Nänni (1971) and by Van Lill et al. (1980) and catchment characteristics described in this paper have been obtained from these reports.

A summary of pertinent catchment characteristics of the three Mokobulaan catchments studied, viz. catchments A, B and C is presented in Table 5. *ACRU* was used in a lumped catchment mode for each of these three small catchments.

Soils are generally very shallow, but underlying rocks are permeable to roots and water (Van Lill et al., 1980). The original vegetation on all three catchments was predominantly an annual grassland classified by Acocks (1988) as NE Mountain Sourveld. Catchment A was planted to *Eucalyptus grandis* in February 1969. Trees were planted in pits at intervals of 2.7 m (i.e. 1 370 stems per hectare). The stand was thinned to 750 stems per hectare in 1974. Catchment B was planted to *Pinus patula* in January 1971 also in pits established at 2.7 m intervals. Catchment C was retained as a control under natural grassland (Van Lill et al., 1980).

Monthly means of daily maximum and minimum temperatures obtained from SAWB files stored at the CCWR were used to estimate potential evaporation by the Linacre (1984) technique. Daily streamflow records were provided by the CSIR.

Unfortunately, detailed rainfall and evaporation data for each catchment were not available. Consequently, daily rainfall records for a nearby SAWB rainfall station were obtained through the CCWR and applied to all three catchments. Although these are research catchments, the lack of detailed rainfall and evaporation measurements from them results in the simulation being regarded and performed as an "operational" type simulation as was the case with the Marite catchment described previously. The small size of these catchments suggests that they will be particularly sensitive to accurate input data, and some error may be expected by applying coarse scale rainfall and evaporation data to a small catchment. Furthermore, the simulation was a "blind" one in the sense that the catchments were not visited.

The streamflow in Catchment C was simulated first as a test of the performance of the *ACRU* model for a catchment under natural grassland. The model was found to simulate accumulated streamflows well as shown in Fig. 4. Having shown that the model was effective in simulating responses of a grassed "control" catchment, streamflow in the forested catchments A and B was simulated.

Streamflow from Catchments A and B was simulated utilising the dynamic land-use facility (Schulze, 1995) in *ACRU*. This allows the modeller to change catchment land cover variables in the time series covering the simulation to account for vegetative changes resulting from growth of the trees, or management changes such as thinning

TABLE 5
SELECTED FEATURES OF THE MOKOBULAAN RESEARCH CATCHMENTS

Catchment	A	B	C
Latitude	25° 17'S	25° 17'S	25° 17'S
Longitude	30° 34'E	30° 34'E	30° 34'E
Altitude (m)	1 354	1 396	1 427
MAP (mm)	959	959	959
Area (km^2)	2.62	3.46	3.69
Aspect	East facing	East facing	East facing
% slope	0.23	0.22	0.26
% afforested	100	100	0
Species	*Eucalyptus grandis*	*Pinus patula*	Grassland
Age (yrs)	0 - 12	0 - 10	N/A
Site preparation	Pitting	Pitting	N/A

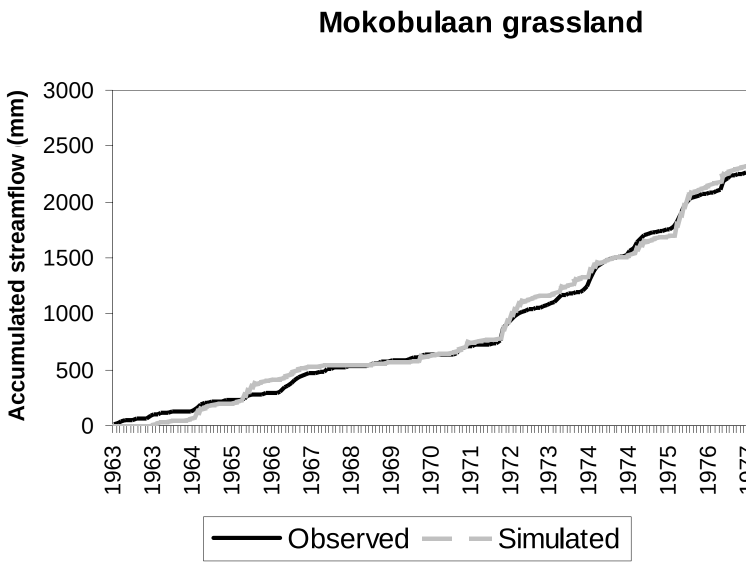

Figure 4
Accumulation totals of monthly streamflows at Mokobulaan Catchment C - grassveld catchment

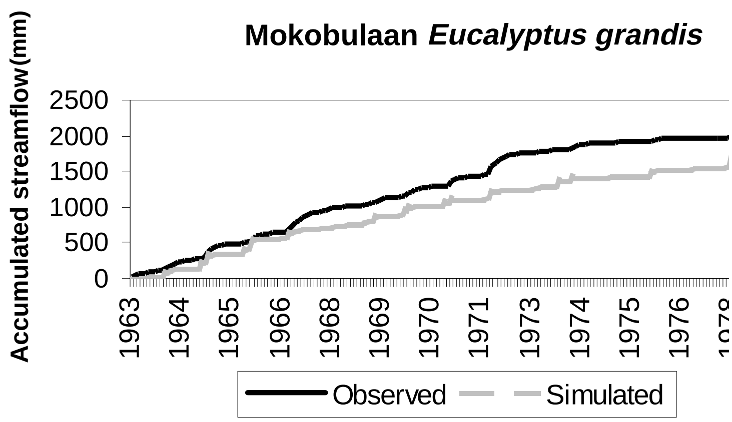

Figure 5
Accumulation totals of monthly streamflows at Mokobulaan Catchment A - Eucalyptus grandis

TABLE 6
GOODNESS OF FIT STATISTICS FOR SIMULATION OF MONTHLY TOTALS OF DAILY STREAMFLOW FROM MOKOBULAAN CATCHMENT A

Statistics of performance of *ACRU* model, Mokobulaan Catchment A: A comparison of simulated and observed streamflows for monthly totals of daily values 1963-1979

Total observed flows (mm)	=	1992.271
Total simulated flows (mm)	=	1724.262
Mean observed flows (mm)	=	9.766
Mean simulated flows (mm)	=	8.542
Correlation coefficient	=	.419
Students "t" value	=	6.652
Linear regression coefficient	=	.532
Base constant for regression equation	=	3.258
Standard error of simulated flow	=	233.117
Variance of observed flow	=	201.879
Variance of simulated flow	=	324.818
Standard deviation of observed flow	=	14.208
Standard deviation of simulated flow	=	18.023
% difference in standard deviation	=	-26.845
Coefficient of determination	=	.176
Coefficient of efficiency	=	.554
Systematic errors detected		

TABLE 7
GOODNESS OF FIT STATISTICS FOR SIMULATION OF MONTHLY TOTALS OF DAILY STREAMFLOW FROM MOKOBULAAN CATCHMENT B

Statistics of performance of *ACRU* model, Mokobulaan Catchment B: A comparison of simulated and observed streamflows for monthly totals of daily values 1969-1980

Total observed flows (mm)	=	1913.084
Total simulated flows (mm)	=	1942.463
Mean observed flows (mm)	=	17.714
Mean simulated flows (mm)	=	17.986
Correlation coefficient	=	.731
Students "t" value	=	11.018
Linear regression coefficient	=	.902
Base constant for regression equation	=	2.011
Standard error of simulated flow	=	178.944
Variance of observed flow	=	421.405
Variance of simulated flow	=	641.990
Standard deviation of observed flow	=	20.528
Standard deviation of simulated flow	=	25.338
% difference in standard deviation	=	-23.428
Coefficient of determination	=	.534
Coefficient of efficiency	=	.282
Sytematic error detected		

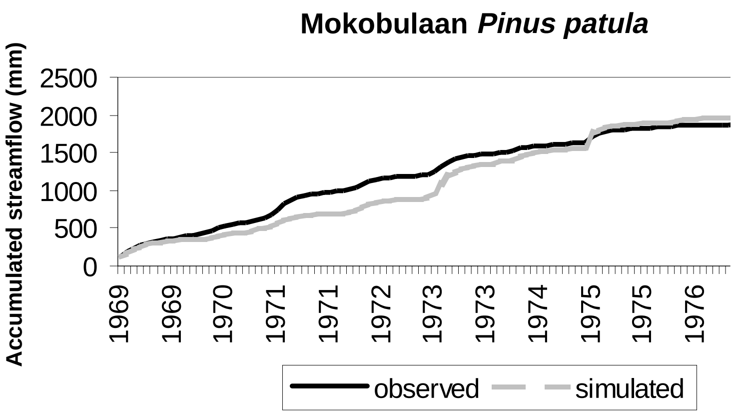

Figure 6
Accumulation totals of monthly streamflows at Mokobulaan Catchment B - Pinus patula

of the stand.

Streamflow was simulated poorly in Catchment A which was planted to *E. grandis*. The plot of accumulated values of simulated and observed streamflow (Fig. 5) indicate total streamflow was undersimulated. Statistics produced were consequently poor, as seen in Table 6. These results indicate that the difficulties entailed in modelling a very small catchment with shallow soils and with a changing land cover were not satisfactorily managed by the model. It is possible that runoff events in this catchment do not correspond adequately to the rainfall record used and that better results would be expected should rainfall measured within Catchment A become available and if the catchment were visited in order to note more detail, *inter alia*, on soils or adjunct impervious areas.

Overall streamflow volume in Catchment B, which was planted to *Pinus patula* in 1971, is simulated fairly well by *ACRU*. Statistics of goodness of fit, shown in Table 7, indicate that fair correlation between simulated and observed streamflow values exists. Higher variations and deviations of simulated values indicate that individual runoff events were poorly simulated. However, the total water budget and periods of low flow, which are critical to the water resources planner, are simulated accurately.

Discussion and conclusions

Based on the simulation results presented above, it is suggested that the application of the *ACRU* model in conjunction with the forest decision support system to simulate streamflow from forested catchments is viable. *ACRU* performed successfully on the forested catchments modelled, except for Catchment A and, to a lesser extent, Catchment B at Mokobulaan where poor input data, problems of scale and lack of actual catchment knowledge were experienced. In these small Mokobulaan catchments, *ACRU* did not accurately reproduce catchment runoff. In the large Marite catchment timing of streamflow events was problematic.

Despite these problems, results produced are generally acceptable and it is believed that the model used in conjunction with forest decision support system will provide a useful tool in the light of the National Water Act and the emphasis on SFRAs. *ACRU* used in conjunction with its forest decision support system should become a useful tool to catchment manager and water resources planner alike.

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