

MODELLING RUNOFF FROM SUGARCANE FIELDS

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Abstract

In order to produce recommendations for soil and water conservation practices, a research programme to measure runoff and erosion from sugarcane fields was initiated in 1977 by the SA Sugar Association Experiment Station. Part of the integrated project was to verify hydrological models with these measured data. These models could then be applied to ungauged catchments within the sugar industry to predict the quantity and quality of runoff water. Two physical conceptual models were chosen, viz. the Agriculture Catchments Research Unit (ACRU) model and the Chemicals, Runoff and Erosion from Agricultural Management Systems (CREAMS) model. The two physical-conceptual models were tested and compared for their abilities to predict runoff from the four research catchments at La Mercy on which different conservation and management practices have been implemented. The main concepts and structures of the models are outlined, the catchments described, and the results of the verifications presented.

Introduction

The agro-hydrological investigation of catchment areas is time-consuming, can be protracted and is site specific. Thus, the alternative of simulation modelling of hydrological processes has become an important research tool and a number

of hydrological models have been developed. Two such models are the ACRU and CREAMS models.

A model can only be used with a degree of confidence once it has been applied over a wide range of geographic and cultural conditions and its output has been verified against observed data. The CREAMS and ACRU models have been shown to perform well under various conditions by Knisel⁵ and Schulze^{9,10} and they have been used effectively as management decision tools in Natal sugarcane areas by Schulze⁹ and Platford;⁶ but they still needed to be verified by observed data from sugarcane catchments.

The SASA Experiment Station has monitored research catchments, situated 28 km north of Durban, since 1977. The results of a study to verify the performances of the ACRU and CREAMS models in simulating eleven years of monthly totals of daily runoff from four catchments with different cropping systems, are presented here.

Catchment Descriptions

The topographic and soil characteristics of the La Mercy catchments as described by Platford and Thomas⁷ are typical of those found in sugarcane growing areas of the Natal north coast. The four catchments have been numbered from 101 (southernmost) to 104 (northernmost). The catchments range in size from 2,7 ha to 6,6 ha, with slopes varying from 5%

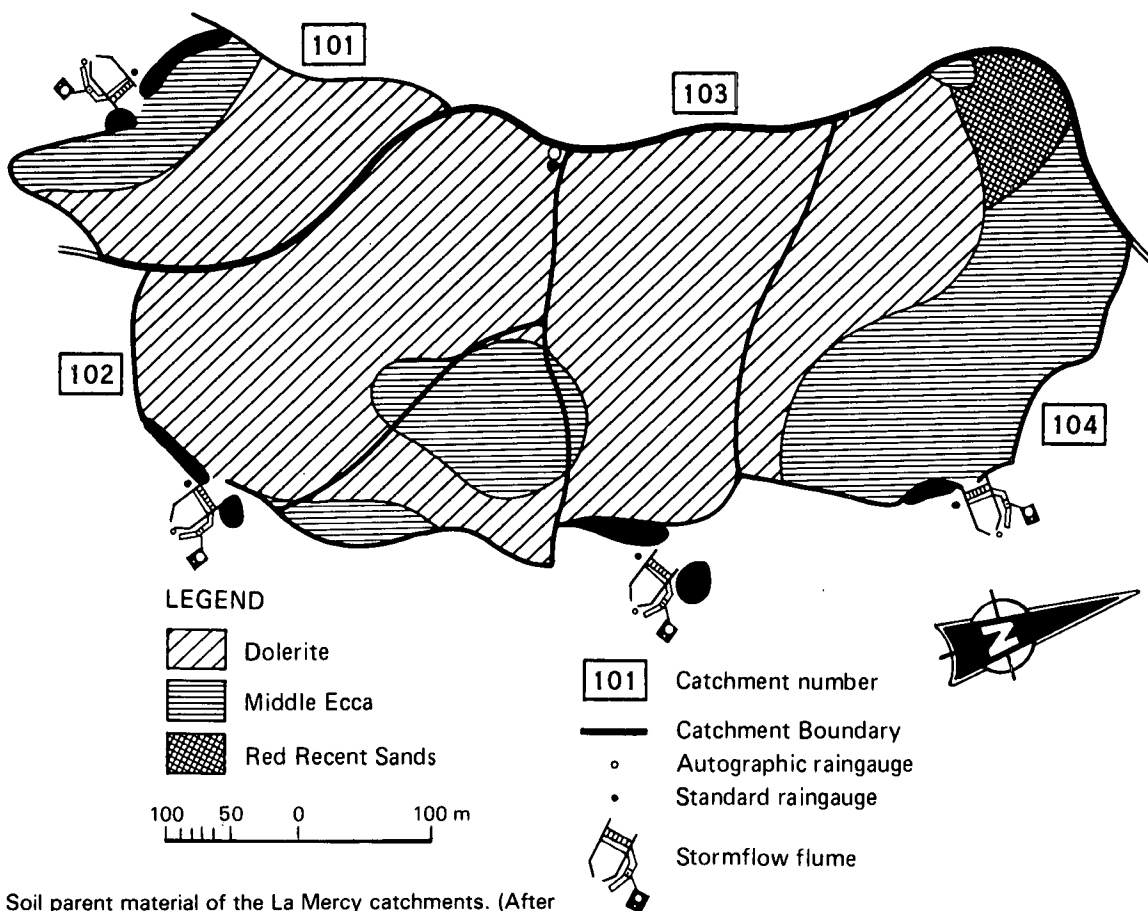


FIGURE 1 Soil parent material of the La Mercy catchments. (After Platford and Thomas, 1985.)

to 35%. The soils are derived from recent sands, dolerite and middle ecca sediment parent materials (Fig 1). Measuring devices were installed to estimate rainfall and runoff continuously, as well as accumulated sediment loss from each catchment.

It had originally been planned to keep the catchments in a continuously bare fallow state from the period 1977 to 1984. The desired fallow state was not maintained at all times because weed growth could sometimes not be controlled due to the soil being too wet for cultivation. In July 1984, various agronomic practices were planned, different field layouts were implemented, and sugarcane (variety NCo376) was established (Fig 2).

Model Concepts and Parameters

Detailed descriptions of the ACRU and CREAMS models have been given respectively by Schulze^{9,10} and Knisel,⁵ and only brief descriptions follow.

The CREAMS model

A team of USDA-ARS scientists developed the CREAMS model as a physically-based state-of-the-art model to simulate runoff, sediment yield, plant nutrient and pesticide

runoff from field-sized areas (Knisel⁵). The model consists of three major components, namely hydrology, erosion, and chemistry, and each operates as a continuous model on a daily basis. The general structure of the CREAMS model is presented in Fig 3.

The hydrology component operates from a rainfall data file and a parameter file that contain average monthly radiation and temperature data, and information to describe crop characteristics, the soil profile, and field shape. The output generated includes runoff volume and peak flow rate, infiltration, percolation, total evaporation and soil moisture content. This output information is used by the erosion, pesticide and nutrient models. The erosion component estimates erosion and sediment yield, and includes particle distribution at the outlet of the catchment. The chemistry component estimates associated and dissolved plant nutrients and pesticides in the runoff, in the sediment, and in the percolate fractions.

Two methods are available to produce the hydrology model outputs, the option used depending on the availability of rainfall data. Option 1 (CREAMS1) uses daily rainfall data and the SCS curve number method (Anon¹) to estimate runoff volume. Option 2 (CREAMS2) uses hourly or breakpoint rainfall data and applies the Green and Ampt³ infiltration

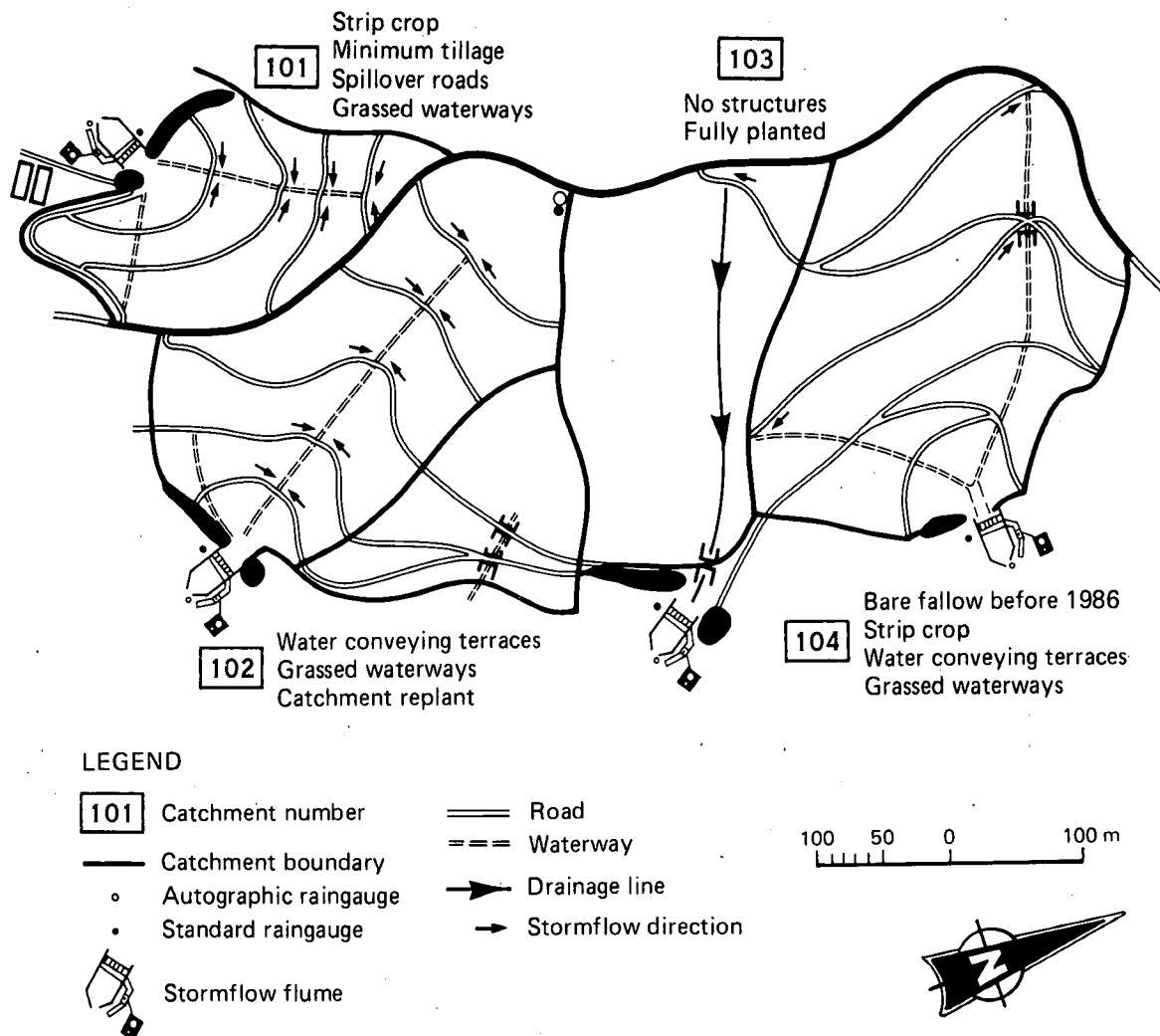


FIGURE 2 The different field layouts on the catchments. (After Platford and Thomas, 1985.)

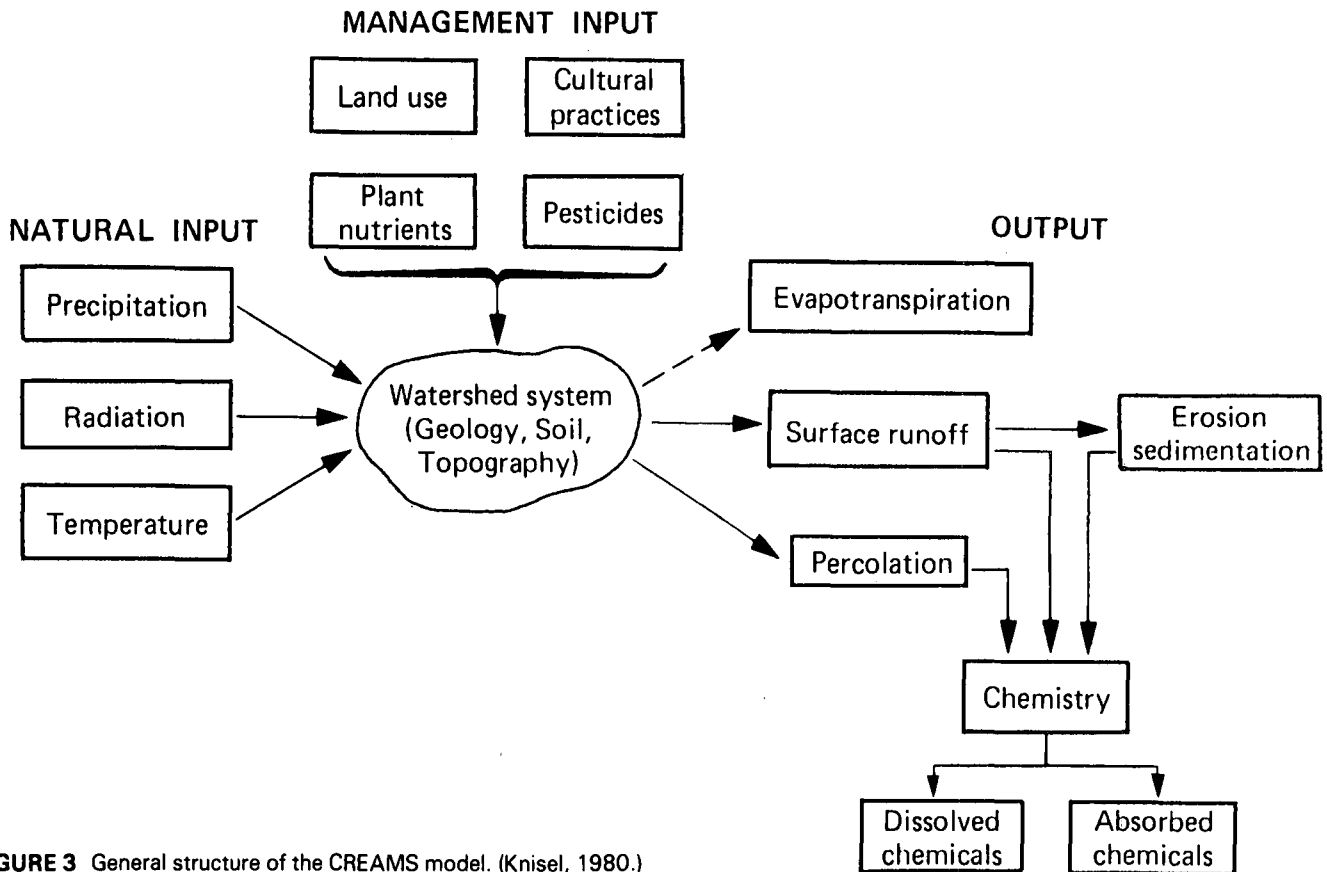


FIGURE 3 General structure of the CREAMS model. (Knisel, 1980.)

model to estimate runoff volume, which is computed from the summation of differences between rainfall and infiltrated water during each time interval. Both methods provide total evaporation and percolation through the root zone of the soil.

The CREAMS model uses a water budget model, where water that enters the soil becomes either storage, evaporation, or seepage below the root zone. The evaporation element is the same for both hydrology models. The soil water budget model considers both soil and plant evaporation losses, which are calculated separately, and treats the growth of the plant leaf area and depth of root extraction explicitly. The model uses the soil storage routing technique to predict flow through the root zone. When the daily rainfall hydrology option is used, the root zone is divided into seven storage layers for routing. When the breakpoint infiltration model is used for runoff calculations, the soil water movement involves only two storage elements, a surface soil zone, and a root soil zone. Percolation from a layer only occurs when soil moisture exceeds field capacity and is dependent on the saturated hydraulic conductivity of the soil. Apart from percolation losses, there are evaporation losses from each soil storage. A model for simulating root growth is used to predict evaporation distribution through the storages, and the rate of water use is expressed as a function of root depth.

The ACRU Model

The Agricultural Catchments Research Unit (ACRU) model, (described in Fig 4), was developed by the Department of Agricultural Engineering, University of Natal, Pietermaritzburg. It was developed as a physical-conceptual, multipurpose, multi-layer soil water budgeting model. It was structured to be highly sensitive to land use changes, using daily climatic data, and the model can be operated at a point

location or as a lumped or as a semi-distributed cell-type model, using various levels of technology and data (Schulze¹⁰).

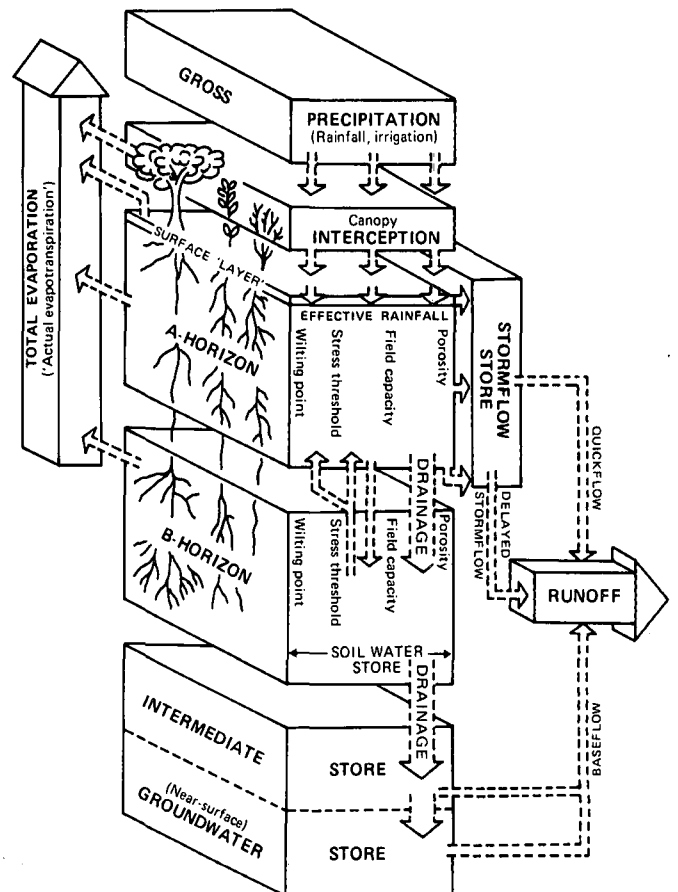


FIGURE 4 General structure of the ACRU model. (Schulze, 1989.)

The model outputs include, with risk analysis, runoff elements (i.e. stormflow, baseflow, peak discharge), sediment yield from a catchment, soil water status and total evaporation. Other outputs include reservoir yield analysis, irrigation water demand and supply, effects of land use changes, and seasonal crop yields models.

The ACRU model generates stormflow, assuming that after initial abstractions, the runoff produced from rainfall is a function of the soil water deficit, which is simulated by multi-layer soil water budgeting. Rainfall not abstracted as interception or as stormflow percolates into the subsoil horizon(s). Should the bottom subsoil storage horizon of the plant root zone attain saturation, recharge into the groundwater store occurs, from which baseflow is generated. Evaporation takes place simultaneously from previously intercepted water and from the various horizons as soil evaporation and plant transpiration. Plant transpiration is estimated according to stages of growth, and the roots absorb the water from the soil water in proportion to the root mass distributions of the respective horizons.

Input Parameters

The ACRU and CREAMS models have not been developed as parameter-optimising models and thus do not need calibration. It is assumed that model users with an understanding of agro-hydrological principles would obtain similar results to those presented here. The only changes compiled for any of the models was on CREAMS1. The curve number parameter, which is a runoff response index, was updated on a continuous basis to vary with stage of plant growth instead of having a single value for the whole simulation period. Vegetative changes could thus be simulated more accurately.

A summary of the input parameters for the ACRU, CREAMS1 and CREAMS2 models for the catchments are

Table 1

Hydrological input parameters for ACRU

Item	Catchment Number			
	101	102	103	104
Area (km ²)	0,0027	0,0047	0,0044	0,0066
Latitude (°)	31,11 S	31,11 S	31,11 S	31,11 S
Longitude (°)	29,63 E	29,63 E	29,63 E	29,62 E
Altitude (m)	75	75	90	80
Coefficient of Baseflow Response	0,020	0,020	0,020	0,020
Coefficient of Quickflow Response	0,900	0,900	0,900	0,900
Coefficient of "A to B" response	0,300	0,260	0,250	0,380
Coefficient of "A to GW" response	0,300	0,260	0,250	0,380
Effective Depth: Stormflow Response	0,300	0,300	0,300	0,360
Depth of A-horizon (m)	0,300	0,300	0,300	0,360
Depth of B-horizon (m)	0,430	0,490	0,490	0,470
Wilting point of A-horizon (m/m)	0,222	0,247	0,248	0,194
Wilting point of B-horizon (m/m)	0,238	0,244	0,244	0,249
Field capacity of A-horizon (m/m)	0,338	0,366	0,367	0,306
Field capacity of B-horizon (m/m)	0,368	0,375	0,375	0,347
Porosity of A-horizon (m/m)	0,461	0,479	0,480	0,447
Porosity of B-horizon (m/m)	0,461	0,479	0,480	0,447

shown in Tables 1, 2 and 3, respectively. Continuous rainfall was measured at the catchments and other climatological parameters such as air temperatures, solar radiation, and Apan evaporation were obtained from the nearby Sugar Association meteorological sites at Mount Edgecombe and Tongaat. Hydrological and soil parameters used in this study were obtained from topographical and soil maps, the CREAMS (Knisel⁵) and ACRU (Schulze, *et al*¹¹) user manuals or were taken from average values of soil properties reported by Rawls *et al*.⁸ Parameter values to describe the crop characteristics were obtained from various sources: leaf area index (LAI) values from Inmam-Bamber,⁴ vegetation cropping factors from Thompson,¹² and curve number values from Cooley and Lane.²

Table 2

Hydrological input parameters for CREAMS1

Item	Catchment Number			
	101	102	103	104
Field area (hectares)	2,7	4,7	4,4	6,6
Rooting depth (m)	0,730	0,790	0,790	0,830
Saturated conductivity (mm/hr)	1,270	1,270	1,270	1,778
Fraction of pore space filled at field capacity	0,830	0,830	0,830	0,800
Field capacity (m/m)	0,444	0,444	0,444	0,410
Initial abstraction	0,200	0,200	0,200	0,200
Evaporation coefficient	3,500	3,500	3,500	3,500
Porosity (m/m)	0,480	0,480	0,480	0,440
Channel slope	0,210	0,160	0,080	0,130
Watershed length/width ratio	2,500	2,990	2,470	1,600
Peak flow rate coefficient	21,053	28,740	25,475	39,652
Peak flow rate exponent	0,850	0,858	0,857	0,863
Upper limit of storage (m)	0,171	0,171	0,171	0,113
Immobile soil water content (m/m)	0,270	0,270	0,270	0,290

Table 3

Hydrological input parameters for CREAMS2

Item	Catchment Number			
	101	102	103	104
Effective hydrologic length (m)	272	409	358	329
Effective hydrologic slope	0,200	0,160	0,080	0,130
Effective Manning's n	0,050	0,050	0,050	0,050
Depth of surface layer (m)	0,051	0,051	0,051	0,051
Depth of remaining root zone (m)	0,679	0,739	0,739	0,779
Effective capillary tension (m)	0,650	0,650	0,650	0,605
Evaporation coefficient	3,500	3,500	3,500	3,500
Sat. conductivity cultivated (mm/hr)	1,270	1,270	1,270	1,778
Sat. conductivity fallow (mm/hr)	1,016	1,016	1,016	1,422
Soil porosity	0,480	0,480	0,480	0,440
Immobile soil water content (m/m)	0,270	0,270	0,270	0,290
Upper limit of storage (m)	0,171	0,171	0,171	0,113

Results and Discussion

The period of simulation for all four catchments was from January, 1977 until the end of April, 1989, but the verification period started after April, 1978. This was done so that there would be a period during which the soil water

distribution of the models could equilibrate. The simulation period was divided into the periods before and after sugarcane was planted.

For each of the hydrological models plots of simulated versus observed monthly totals of daily runoff have been

compared for each catchment for the two periods (Haywood, unpublished data). For illustrative purposes, only graphs for catchment 102 are presented in this paper (Figs 5, 6 and 7). The statistical results are presented in Tables 4, 5 and 6, for the ACRU, CREAMS1 and CREAMS2 models respectively.

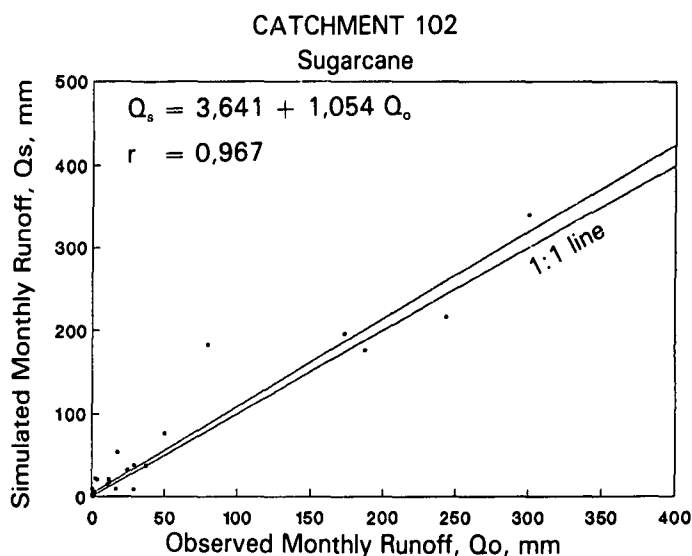
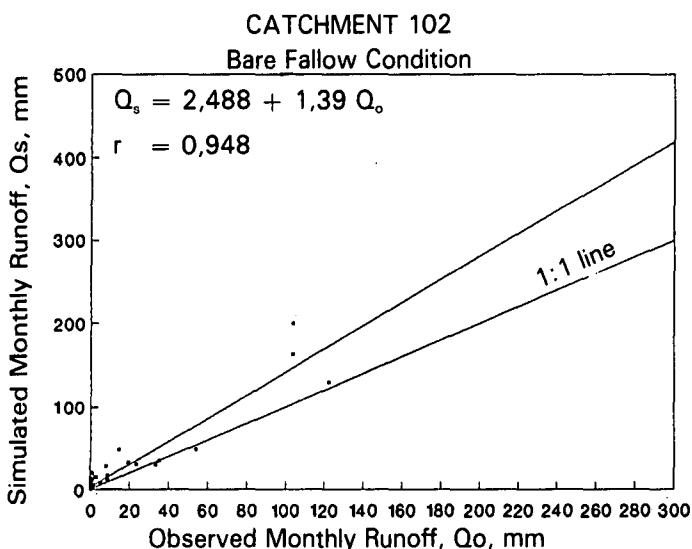


FIGURE 5 Scatter diagrams of simulated and observed daily totals of monthly runoff by ACRU.

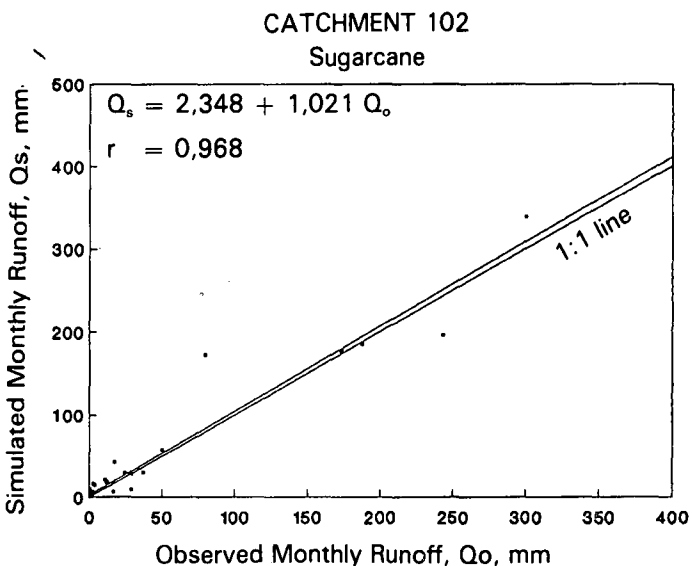
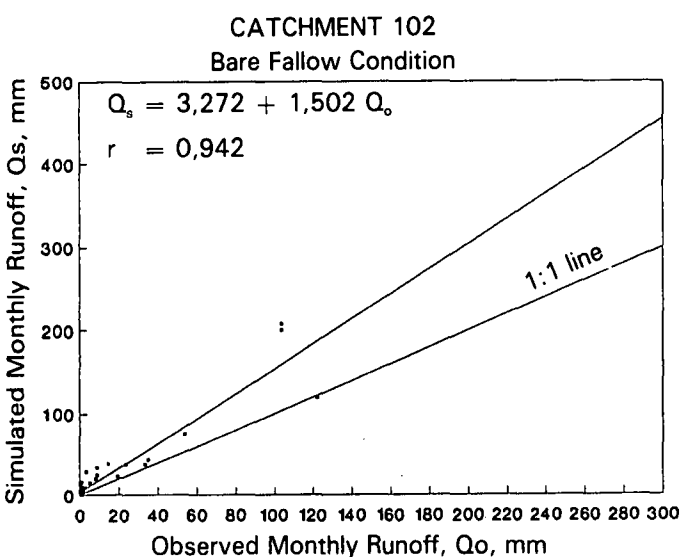


FIGURE 6 Scatter diagrams of simulated and observed daily totals of monthly runoff by CREAMS1.

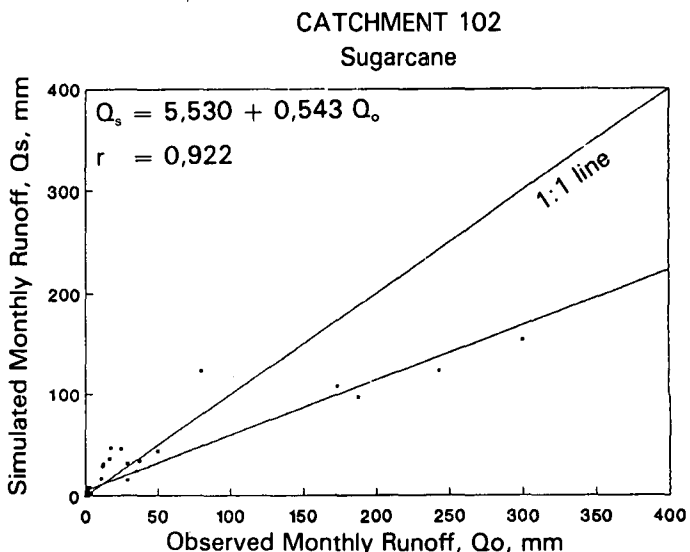
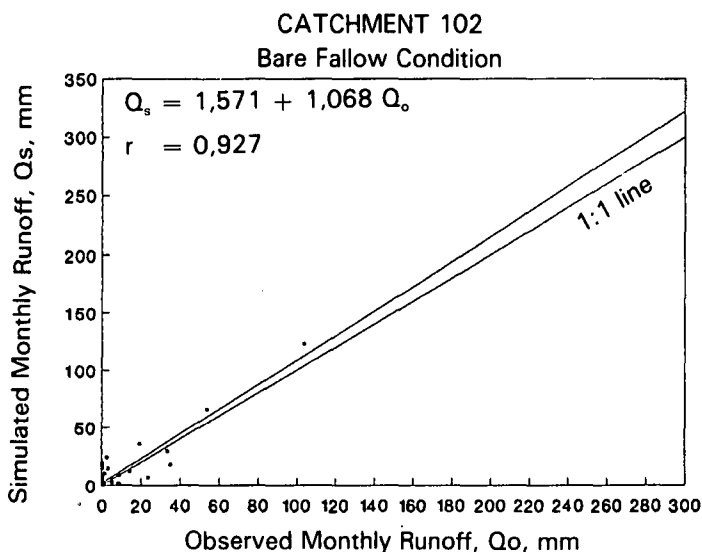


FIGURE 7 Scatter diagrams of simulated and observed daily totals of monthly runoff by CREAMS2.

Table 4

Statistic outputs of monthly totals of daily runoff for ACRU

Item	Catchment Number			
	101	102	103	104
Bare fallow condition				
Total observed flow (mm)	534,132	544,130	582,750	725,999
Total simulated flow (mm)	724,936	940,219	864,052	709,416
Correlation coefficient	0,917	0,948	0,923	0,770
Regression coefficient	0,936	1,390	1,090	0,886
Base constant for regn. eqn.	3,213	2,488	3,096	0,763
Std deviation of observed flow (mm)	31,461	23,037	24,775	22,922
Std deviation of simulated flow (mm)	32,104	33,770	29,232	26,376
Sugarcane				
Total observed flow (mm)	809,943	1 227,583	1 136,363	964,783
Total simulated flow (mm)	1 341,544	1 498,069	1 528,475	807,507
Correlation coefficient	0,974	0,967	0,969	0,969
Regression coefficient	1,413	1,054	1,084	0,878
Base constant for regn. eqn.	3,585	3,641	5,404	-1,038
Std deviation of observed flow (mm)	42,525	60,339	60,300	64,199
Std deviation of simulated flow (mm)	61,664	65,752	67,447	58,140

Table 5

Statistic outputs of monthly totals of daily runoff for CREAMS1

Item	Catchment Number			
	101	102	103	104
Bare fallow condition				
Total observed flow (mm)	534,132	544,130	582,750	725,999
Total simulated flow (mm)	813,867	1 059,002	1 064,209	986,587
Correlation coefficient	0,906	0,942	0,933	0,793
Regression coefficient	1,023	1,502	1,384	1,054
Base constant for regn. eqn.	3,820	3,272	3,481	2,540
Std deviation of observed flow (mm)	31,461	23,037	24,775	22,922
Std deviation of simulated flow (mm)	35,463	36,729	36,767	30,360
Sugarcane				
Total observed flow (mm)	809,943	1 227,583	1 136,363	964,783
Total simulated flow (mm)	1 307,439	1 384,833	1 421,231	919,505
Correlation coefficient	0,976	0,968	0,979	0,982
Regression coefficient	1,452	1,021	1,062	0,968
Base constant for regn. eqn.	2,197	2,348	3,894	-0,323
Std deviation of observed flow (mm)	42,525	60,339	60,300	64,199
Std deviation of simulated flow (mm)	63,713	63,618	65,406	62,926

Months for which recorded runoff or breakpoint rainfall were missing were excluded from the analyses. Conclusions were drawn from examining the scatter of the plotted points and from comparisons of the statistical output.

Before sugarcane was planted

The ACRU and CREAMS1 models, on average, over-predicted runoff, with CREAMS1 overpredicting more than ACRU. The correlation coefficient for CREAMS1 varied from 0,793 to 0,942 between catchments, and the correlation coefficients for ACRU varied from 0,770 to 0,948 (Tables 4 and 5). The slopes of the regression lines were close to unity except for catchment 102, and were better for the ACRU

Table 6

Statistical outputs of monthly totals of daily runoff for CREAMS2

Item	Catchment Number			
	101	102	103	104
Bare fallow condition				
Total observed flow (mm)	375,300	319,000	354,100	488,800
Total simulated flow (mm)	348,691	453,796	488,361	410,947
Correlation coefficient	0,933	0,927	0,938	0,660
Regression coefficient	0,506	1,068	0,925	0,676
Base constant for regn. eqn.	2,336	1,571	1,679	0,946
Std deviation of observed flow (mm)	29,075	14,829	17,146	13,949
Std deviation of simulated flow (mm)	15,885	17,204	17,031	14,620
Sugarcane				
Total observed flow (mm)	809,943	1 227,583	1 136,363	964,783
Total simulated flow (mm)	980,389	967,054	935,531	539,217
Correlation coefficient	0,923	0,922	0,920	0,953
Regression coefficient	0,782	0,543	0,547	0,404
Base constant for regn. eqn.	5,857	5,530	5,700	3,750
Std deviation of observed flow (mm)	42,877	60,339	60,300	64,944
Std deviation of simulated flow (mm)	36,291	35,532	35,894	26,933

model. The standard deviations of simulated flow for ACRU were closer to the standard deviations of the measured flow than were those for CREAMS1.

For the same period, the results of CREAMS2 indicated that total runoff was simulated well and that the correlation coefficients were reasonably good (ranging from 0,927 to 0,938). An exception was catchment 104, for which it was 0,660 (Table 6). The regression coefficients varied from 0,506 to 1,068, with the model generally tending to underpredict the large runoff events. On average, the standard deviations were good, but the large rainstorms that occurred during January and February, 1984 were excluded because of missing data.

After sugarcane was planted

For the period after sugarcane was planted the performance of ACRU and CREAMS1 was similar, with runoff volumes generally predicted closely, except for catchment 101 (Tables 4 and 5). The correlation coefficients were all greater than 0,960. Excluding results from catchment 101, the regression lines were close to unity and the standard deviations of simulated flows compared favourably with those of observed flows.

The reason for the poorer results from catchment 101 was that strip cropping was practiced on this catchment with no water conveying terraces. Thus, the runoff flowed through alternating strips of vegetation that exhibited various densities of cover. Runoff generated from one strip could infiltrate into another and this would impede overland flow. The model parameters to describe this cover were average catchment values and thus were not representative of what actually existed in the field. Hence the models predicted more runoff than actually occurred.

For the same period, when the results of CREAMS2 are examined, it should be noted that total runoff was generally underpredicted, and also less than the ACRU and CREAMS1 model predictions. The correlation coefficients, while lower than for CREAMS1 and ACRU, were reasonable and varied from 0,920 to 0,953 (Table 6). The regression equation indicated that the larger runoff events were underpredicted

while the smaller runoff events were overpredicted. The reason for this is that the hydraulic conductivity of the soil is a very sensitive parameter in the CREAMS2. The hydraulic conductivity of the cracking clay soils that occur in the catchments varies greatly, being high when the soils are dry and low when the soils are moist. This cannot be simulated by the models.

The model simulations were better for the period after sugarcane had been planted than before, because the recorded dates of tillage operations in each catchment were more accurate. Before sugarcane was planted, the four catchments had been described as a single unit, and if a tillage operation occurred in one catchment, it was assumed to have occurred simultaneously over all four catchments.

Summary and Conclusions

The performances of the ACRU and the CREAMS hydrology models were verified on four catchments, ranging in area from 2,7 ha to 6,6 ha, on which different conservation practices had been implemented. The ACRU and CREAMS1 performed well and in a similar manner on catchments 102, 103, and 104. They performed better with a sugarcane cover, when the agronomic practice records were more accurate, than when the areas were fallow. The ACRU and CREAMS1 models did not simulate runoff as well on a strip-cropped catchment on which there were no water conveying-terraces. The performance of CREAMS2 was not as good as the two daily rainfall models, tending to overpredict smaller runoff events and underpredict larger runoff events. This was due to the very sensitive hydraulic conductivity parameter of CREAMS2 and the soil types in the catchments.

Further research is required to enhance the applicability of these models. In particular, a study is required to determine runoff curve numbers for fields in South Africa planted with sugarcane. The values must account for soil variations, different crop growth stages, and different conservation practices. Further model development should also be undertaken before the models are applied to areas where strip cropping is practised with no water-conveying terraces.

This study was performed to determine how well existing hydrological models could predict results obtained on gauged catchments in sugarcane growing areas. Bearing in mind the

conceptions on which the models were based, it appears that the daily rainfall models can be applied to ungauged catchments with confidence, so that alternative management practices for control or minimisation of runoff and sediment yield from small agricultural catchments can be evaluated.

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REFERENCES

1. Anon (1972) Soil Conservation Service. *National Engineering Handbook. Section 4, Hydrology*. USDA Soil Conservation Service, Washington DC
2. Cooley, KR and Lane, LJ (1982). Modified runoff curve numbers for sugarcane and pineapple fields in Hawaii. *J Soil and Water Cons* 37: 295-298
3. Green, WA and Ampt, GA (1911). Studies on soil physics, I. The flow of air and water through soils. *J of Agr Sci*, 4: 1-24
4. Inman-Bamber, NG (1986). *The reaction of sugarcane to water stress*. Univ of the Orange Free State, Bloemfontein. Dept of Agric Meteorology. Unpublished Ph D Dissertation: 88, 89
5. Knisel, WG (Ed) (1980). *CREAMS - a field scale model for Chemicals, Runoff, and Erosion from Agricultural Management Systems*. Cons Res Rpt No 26, USDA - Agric Res Service, Washington DC
6. Platford, GG (1983). The use of the CREAMS computer model to predict water, soil and chemical losses from sugarcane fields and to improve recommendations for soil protection. *Proc S Afr Sug Technol Ass*, 57: 144-150
7. Platford, GG and Thomas, CS (1985). The small catchment project at La Mercy. *Proc S Afr Sug Technol Ass*, 59: 152-159
8. Rawls, WJ, Brakensiek, DL and Saxton, KE, (1982). Estimation of soil water properties. *Trans ASAE* 25: 1316-1320
9. Schulze, RE (1984). *Hydrological models for application to small rural catchments in Southern Africa: Refinements and development*. Univ of Natal, Pietermaritzburg. Dept of Agric Eng. ACRU Report 19
10. Schulze, RE (Ed) (1989). *ACRU: Background, concepts and theory*. Univ of Natal, Pietermaritzburg. Dept of Agric Eng. ACRU Report 35
11. Schulze, RE, George, WJ, Angus, GR and Lynch, SD (1989). *ACRU-2.0: User Manual*. Univ of Natal, Pietermaritzburg. Dept of Agric Eng. ACRU Report 36
12. Thompson, GD (1976). Water use by sugarcane. *S Afr Sug J*, 60: 593-600