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Evaluations of the CREAMS Model. III.* Simulation of the Hydrology of Vertisols

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Abstract

The CREAMS hydrology model was evaluated for two Vertisols, each with three fallow management strategies, by comparing predictions of runoff, soil moisture and drainage with 5–8 years of measured data. Model parameter values were derived by: (i) using a combination of measured site characteristics and published values, and (ii) optimizing selected parameters, particularly the runoff parameter (curve number).

With parameter values from published sources, runoff was overpredicted by 1 to 39%; good estimates of total soil moisture were obtained. Using optimized curve numbers, runoff was predicted well (daily, $r^2 = 0\cdot83$; monthly, $r^2 = 0\cdot92$; annual, $r^2 = 0\cdot94$). Total soil moisture values were predicted well, the main source of error being from overprediction of transpiration. Errors in predicted runoff caused little of the error in predicted total soil moisture. The distribution of soil moisture in the soil was poorly predicted. Drainage predictions were similar to estimates from steady-state solute mass balance.

Optimized curve numbers derived in this study provide parameter values for modelling the water balance of self-mulching Vertisols. Values of other model parameters, derived from field measurements and published sources were near optimal, and predictions were not improved by adjusting the more sensitive of these parameters. The model is considered adequate for many practical applications. Some enhancements to the model are suggested.

Keywords: Water balance, runoff, soil moisture, drainage, simulation, model validation.

Introduction

The CREAMS model (Knisel 1980) was developed in North America specifically to evaluate effects of agricultural management systems on non-point source pollution from field-sized areas. The model contains hydrology, erosion/deposition and chemical components in separate computer programs. The daily time-step water balance and runoff method (Williams and Nicks 1982; Williams *et al.* 1980) from the hydrology component is used as the hydrologic component in a number of models. These include the crop production oriented CERES models (e.g. Jones and Kiniry 1986), the erosion productivity EPIC model (Williams *et al.* 1984), a rural basin scale water resources model SWRRB (Williams and Nicks 1985), rangeland models SPUR and ERHYM (Bouraoui and Wolfe 1990), the chemical transport models CREAMS (Knisel 1980), GLEAMS (Leonard *et al.* 1987),

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and ADAPT (Ward *et al.* 1988) and the cropping systems model PERFECT (Littleboy *et al.* 1989, 1992). These models all simulate agricultural systems through time, with emphasis on different aspects of these systems. Predictions of all target outputs are dependent on predicted components of the water balance. Therefore, an understanding of the confidence that can be placed in the hydrologic predictions is a necessary first step in application of CREAMS or any of its derivatives.

Although the model contains a large number of functions describing aspects of the water balance, the rainfall/runoff equation used—the SCS curve number method (USDA 1972)—is of particular interest, as this method has been criticised in Australia (Australian Water Resources Council 1971; Boughton 1989, Hoesein *et al.* 1989). Comments such as those of Hoesein *et al.* (1989), that the method has been extensively tested with generally poor results, do little to engender confidence.

Previous experience with the USDA curve number method in Australia used antecedent rainfall as a surrogate for antecedent soil moisture. Australian Water Resources Council (1971) found that the antecedent rainfall method performed poorly with curve numbers estimated from soil and catchment information using USDA guidelines, and also when curve numbers were optimized. Boughton (1989) found runoff predictions using the antecedent rainfall method less accurate than those from a calibrated water balance model. As well, some evaluations of the method, for instance by Wood and Blackburn (1984), used by Hoesein *et al.* (1989) as evidence of 'generally poor results', involved testing tabulated values of curve numbers for various soil/cover conditions. An alternative explanation is that this was a test of the parameter database; it reveals little about the predictive accuracy of the model given good estimates of the parameters.

In CREAMS and its derivatives, the runoff curve number is varied as a continuous function of soil moisture. There is considerable experience with this method in the U.S.A., generally with good results (for example, Knisel 1980; Williams and Nicks 1982; Arnold and Williams 1987). However, this method has not been evaluated for Australian conditions or for Vertisols. We consider that the poor performance of the antecedent rainfall curve number method and of the use of tabulated parameter values is not a good guide to the potential of the CREAMS hydrology model.

In the first two papers in this series, the erosion/deposition component of CREAMS was evaluated (Silburn and Loch 1989, Loch *et al.* 1989). In this paper, we evaluate the daily rainfall option of the CREAMS hydrology component by comparing predicted runoff, soil moisture and drainage with measured data from two sets of catchments on Vertisols, using both estimated and optimized parameter values.

The CREAMS Hydrology Model

A brief description of the CREAMS hydrology model follows. A comprehensive description is provided in the CREAMS manual (Knisel 1980) and Williams and Nicks (1982). The CREAMS hydrology model (hereafter referred to as 'the model') runs a continuous one-dimensional simulation of the water balance of the soil profile to the depth of the root zone. It is a generic model which allows the water balance of any crop to be partitioned into its components (soil evaporation, transpiration, soil water redistribution, deep drainage, infiltration and runoff). A daily time step is used, except in the optional Green and Ampt infiltration method, which was not used in this study. The daily rainfall option was used because the model was being assessed for use with long-term records of daily rainfall.

Runoff is calculated using a modified USDA Curve Number (CN) method (Williams and LaSeur 1976), with the potential retention parameter varied as a continuous function of antecedent available soil water. The form of the rainfall/runoff relation is similar to the *tanh* function used by Boughton (1966). Potential evaporation, soil evaporation and transpiration are calculated using the method of Ritchie (1972), using daily solar radiation and mean temperature, which are calculated from mean monthly values. Transpiration is determined using annual leaf area index (LAI) temporal patterns specified by the user. Root growth and water uptake distribution are simulated using the method of Williams and Hann (1978).

The soil is represented using seven layers, each being a fixed proportion of the maximum rooting depth. The upper limit of plant available water capacity (UL), defined as total porosity minus wilting point, is specified for each layer. A parameter (FUL) is used to define the fraction of UL filled at field capacity, that is (1−FUL) is the proportion of UL that may drain. The same value of FUL is used for all soil layers. Soil water redistribution is calculated using a storage routing technique from Williams and Hann (1978). Drainage from a layer filled to above field capacity is a function of the volume in the store and an effective hydraulic conductivity parameter (RC).

Description of Catchments (Data Sources)

Rainfall, runoff and soil moisture data from contour bay catchments of about 1 ha (Freebairn and Wockner 1986, Freebairn *et al.* 1986) were used. The catchments are located at Greenmount and Greenwood on the eastern Darling Downs, Qld.

Soil and Climate

The soil at Greenmount is a black earth (Ug 5·15; Northcote 1979) derived from basalt, is a Udic Pellustert—fine montmorillonitic—and belongs to the Irving clay soil association (Thompson and Beckmann 1959). This soil is strongly self-mulching and exhibits gross cracking on drying. The soil at Greenwood is a 'brigalow' grey clay, Ug 5·16, derived from Walloon sandstone (fine grained), is a Udic Chromustert and belongs to the Moola clay soil association. This soil is of finer surface structure, is less strongly self-mulching than the black earth, and exhibits gross cracking on drying.

Average annual rainfall is 750 mm at Greenmount and 650 mm at Greenwood, with 60 to 80% of rainfall occurring in the period October to March. Average annual class A pan evaporation is about 1800 mm.

Treatments

After wheat harvest in November–December, several crop residue management practices were applied, resulting in a range of soil surface conditions during fallow periods (December to May). Three treatments were considered in this paper:

(1) bare fallow: Residue burnt soon after harvest; cultivation by tined implements; stubble cover declined from 12 to <5% over the summer fallow.
(2) stubble mulch: Weed control by cultivation with sweep implements; stubble cover declined from 70 to 20% over the summer fallow.
(3) zero tillage: Residue not disturbed; herbicide weed control; summer fallow stubble cover >50%.

Rainfall, Runoff and Soil Moisture Data

Rainfall and runoff from five contour bay catchments were measured during the period May 1976 to November 1984, at each site. Soil moisture was measured by gravimetric sampling to 1·5 m at nine locations in each bay; at planting, harvest and several times during each fallow. Per cent projected crop and residue cover were measured (Freebairn and Wockner 1986) on all bays whenever runoff occurred. Soil surface microrelief roughness was also estimated, by ranking in five classes from smooth to rough (classes 1 to 5).

Fallow treatments were rotated between bays each year as part of the experimental design. Runoff and soil moisture data for five to eight years of crop-fallow were compiled for each treatment by concatenating records from different contour bays. Records were split at harvest time when differences in soil moisture between treatments were small and differences in residue remaining from the previous fallow were small compared with residue available from the recently harvested crop. Data for each crop period were kept with the data from the preceding fallow, since fallow management may influence growth and water balance of the subsequent crop.

Soil Profile Drainage

Predictions of drainage below the root zone from the model were compared with long-term average drainage estimated using steady-state solute (chloride) mass balance (Thorburn *et al.* 1990) for the black earth. The geometric mean drainage for nine profiles analysed was 3·3 mm yr^{-1}. The range was 1·0–21·0 mm yr^{-1}. The chloride profiles, measured at the start of the experiments, reflect the equilibrium chloride balance and drainage of previous land use; predominantly winter cereal crops and bare summer fallows. Also drainage in this environment is sporadic (Freebairn *et al.* 1990) and drainage during the period of the experiment may not be indicative of long-term drainage. Therefore, drainage estimates from chloride profiles were compared with drainage predictions using CREAMS for the period 1952–1975, with Greenmount daily rainfall data.

Model Inputs and Parameter Values

Climatic Inputs

Mean daily temperature for each month was calculated from daily maximum and minimum temperatures from Pittsworth (Bureau of Meteorology station No. 041082), located 28 km west of Greenmount and 45 km south of Greenwood. Average monthly solar radiation recorded at Crows Nest (unpublished data), within 50 km of both sites, was used. Daily rainfall (9 a.m.–9 a.m.) records from the pluviograph at each site were used.

Leaf Area Index (water use) Patterns

A leaf area index (LAI) pattern for medium maturing wheat on the Eastern Darling Downs (Woodruff 1969) was used for all crops. The pattern was shifted within each year to reflect planting dates, but was not adjusted for differences in phenological development or crop growth between years.

Soil Parameters

Upper limit available moisture capacities (UL) were estimated for the two soils in the following manner. For the surface 0–100 mm, UL was the total porosity, calculated from bulk density for wet soil, less the air dry moisture content; for 100–300 mm, UL was the difference between total porosity for wet soil and wilting point (sunflower method); for soil below 300 mm, UL was the difference between the wettest and driest soil moisture contents measured in each layer. This schema provides moisture storage capacities that allow for drying below wilting point and wetting greater than field measurements in the surface layers.

Maximum rooting depth at each site was derived from soil depth, soil water extraction and salinity data: 1200 mm for the black earth (Greenmount) and 900 mm for the grey clay (Greenwood). The fraction of plant available moisture storage filled at field capacity (FUL) was calculated to be 0·90 for both soils, given that the air-filled void space of swelling soils is 0·05 v/v at their drained upper limit (Gardner 1985). A value of 3·5 was used for the soil evaporation parameter CONA, as suggested by Ritchie (1972) for clay soils. In preliminary tests for the environment under study, the effective saturated hydraulic conductivity of the soil (RC) was found to have little effect on predicted runoff, soil moisture or total drainage, in agreement with Lane and Ferreira (1980). Drainage was sensitive to the drainable porosity (1–FUL). RC of 2·54 mm h^{-1} were used for both sites (Freebairn *et al.* 1984).

Runoff Parameters

Initial estimates of curve number for average antecedent moisture condition (CNII) (Table 1) were taken from an update of the analysis given by Freebairn and Boughton (1981). Curve numbers calculated from rainfall and runoff for each storm were classified into low, medium and high classes according to 5-day antecedent rainfall (Boughton 1989). The mean for events in the medium class was taken as CNII. As these curve numbers were calculated from part of the data used in this study, albeit by a different method, they cannot be considered independent. However, use of these estimates provides a test of model performance using CNII derived from the antecedent rainfall, for which some data are available (Freebairn and Boughton 1981; Boughton 1989). Initial abstraction (SIA) was assumed to equal 0·2, the default value recommended by Williams *et al.* (1980).

Model Runs

Parameter Estimates

The model was run for the two sites and three treatments, for periods of record of five to eight years. Measured runoff, total available soil moisture and

Table 1. Curve numbers for average antecedent moisture conditions (CNII), defined according to 5 day antecedent rainfall, for black earth (Greenmount 1976–1983) and grey clay (Greenwood 1978–1983), and average per cent cover during the summer fallow periods

Fallow management treatment	Black earth		Grey clay	
	CNII	Mean cover (%)	CNII	Mean cover (%)
Bare fallow—wheat	79 (6)[A]	5	72 (6)	5
Stubble mulch—wheat	65 (5)	40	63 (4)	45
Zero-till—wheat	72 (6)	65	72 (6)	50

[A] Numbers in parenthesis are the number of storms in antecedent rainfall condition class II, used to calculate the average curve numbers presented.

distribution of soil moisture in the profile were compared with values predicted using two sets of parameters: the *initial parameter estimates* described above, derived from field measurements, the CREAMS manual and published sources; and *optimized parameters*. Optimization was performed in two stages:

(i) Optimization of the four most sensitive parameters (CONA, FUL, SIA and CNII) was studied using data **for black earth–bare fallow only**. Firstly, improvement in soil moisture predictions was investigated by adjusting CONA and FUL only. To remove errors due to runoff prediction, measured runoff data were input to the model and used in place of predicted runoff in the water balance. Using the resulting optimized values of CONA and FUL, improvement in runoff prediction was then examined by adjusting CNII and initial abstraction (SIA).

(ii) Optimized values of CNII **for all treatments** were determined by fitting the model to measured runoff and soil moisture data, using optimal values of CONA, FUL and SIA derived above.

Also the model was run **for all treatments** using measured runoff in place of predicted runoff, to test whether predictions of soil moisture were affected by the errors in predicted runoff.

Optimization Criteria

Criteria for optimizing prediction of soil moisture were to: (i) minimize the average error in predictions of total available soil moisture (ASM), and (ii) to minimize the root mean square error (RMSE) of total ASM, and then (iii) to predict mean ASM and minimize the RMSE for the surface layer (0–100 mm), and upper one-third and lower two-thirds of the subsoil. Use of multiple objective functions was achieved by overlaying plots (not presented) of the contours (response surfaces) of the various objective functions, and selecting the combination of parameters that best fit the optimisation criteria.

Criteria for optimization of runoff prediction were to predict total runoff for the 5–8 yr record to within $\pm$ 3% of total measured runoff (an arbitrary value), and minimize RMSE and average absolute error in predicted daily runoff. The three criteria gave the same optimal parameter values, therefore no weighting of criteria was needed. In statistical comparisons, daily runoff data were used for all days when either measured or predicted values exceeded 0·5 mm.

Results and Discussion

Initial Parameter Estimates

Total runoff was consistently overpredicted when the initial estimates of CNII were used. For the black earth, predicted total runoff was 139, 119 and 111% of total measured runoff for bare, mulch and zero-till, respectively. For the grey clay, predicted runoff totals were closer to measured values, being 101, 104 and 122% of total measured runoff for bare, mulch and zero-till, respectively. Initial estimates of curve numbers, from the antecedent rainfall analysis (Table 1), were in most cases greater than those needed to accurately predict runoff using CREAMS. This difference may be due to the small sample of events in the medium antecedent rainfall class (Table 1).

Average error in prediction of total ASM in the profile was <4% for all treatments, except for the bare fallow treatments at both sites. For black earth-bare fallow, ASM was underpredicted by 15% on average, which is consistent with the overprediction of runoff obtained. For the grey clay-bare fallow, ASM was overpredicted by 9% on average, while predicted runoff was within 1% of measured runoff. This error in soil moisture prediction was probably due to a combination of errors in other components of the water balance and in the measured data. Soil moisture in the lower subsoil was consistently underpredicted, while soil moisture in the surface (0–100 mm) and upper subsoil was overpredicted, particularly for the grey clay. Further evaluation of model performance will be confined to the optimized curve numbers, where systematic bias due to errors in parameterization of the model is reduced.

Optimized Parameters

Optimization of soil moisture and runoff parameters

No improvement was gained in prediction of total ASM for black earth-bare fallow by altering the values of CONA (the evaporation parameter) and FUL (the drainable porosity parameter) from the initial estimates. Also, prediction of the distribution of water in the profile was not improved by altering CONA and/or FUL. The value used for CONA of 3·5, suggested for clays by Ritchie (1972), and the value of FUL of 0·9, calculated using the assumption of 0·05 v/v air-filled porosity at the drained upper limit suggested as being general for swelling clays by Gardner (1985), appear to have general application. Therefore no changes were made to these parameters as a result of the optimization of soil moisture parameters.

Simulations of black earth–bare fallow for various combinations of CNII and initial abstraction (SIA) indicated that there was little improvement in runoff prediction gained by adjusting SIA that could not have been obtained by adjusting CNII. Therefore the suggested default value for SIA of 0·2 was adopted, and optimization by adjusting CNII alone was carried out for all treatments/sites.

Daily Runoff Prediction

Optimized curve number values and statistics of fit for daily runoff are given in Table 2. Optimizing the curve number reduced systematic bias, though errors between predicted and measured daily runoff values (scatter about 1:1) still exist (Fig. 1). Even with a curve number that gives optimal prediction of average

Table 2. Statistics for prediction of daily runoff depths (mm) using the CREAMS hydrology model with optimized curve numbers

Site/ treatment	Curve number (CNII)	N[A]	P:O total runoff[B] (–)	RMSE[C] (mm)	Regression[D] Int[E]	Slope	r^2
Black earth (Greenmount)							
Bare fallow	71	51	1·02	8·0	−1·23	1·09	0·81
Stubble mulch	61	27	1·03	9·7	−1·28	1·03	0·75
Zero-till	69	34	1·00	7·4	−0·09	0·97	0·85
Grey clay (Greenwood)							
Bare fallow	72	48	1·01	7·3	1·56	0·84	0·75
Stuble mulch	62	31	1·03	8·6	2·43	0·76	0·73
Zero-till	66	30	1·02	7·7	2·42	0·76	0·79
All data combined							
Daily	—	221	1·01	7·9	0·92	0·91	0·83
Monthly	—	140	1·01	9·2	0·04	0·88	0·92
Annual	—	38	1·01	20·4	1·81	0·86	0·94

[A] Number of observations.
[B] Ratio of predicted to observered total runoff.
[C] Root mean square error (mm).
[D] Linear regression: Measured = Int + Slope (Predicted), for runoff values (mm).
[E] None of the intercepts are significantly different from zero.

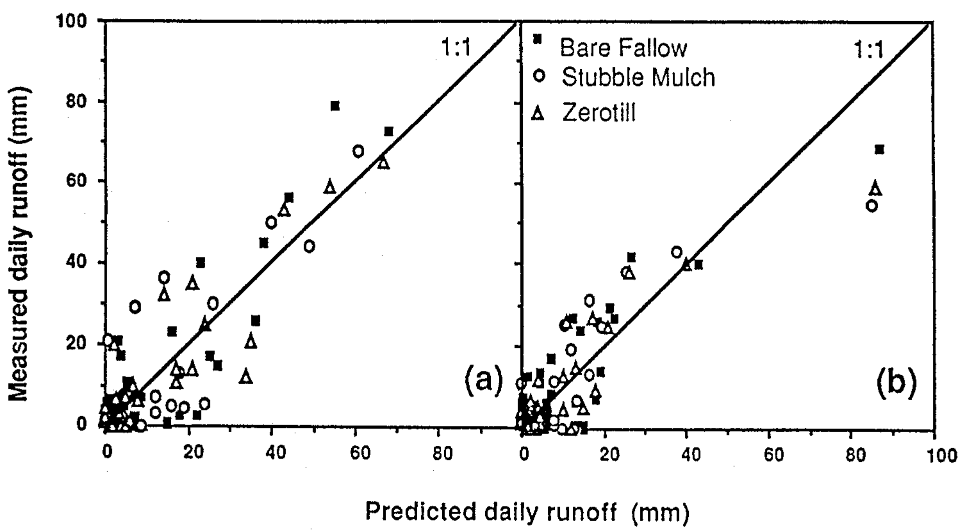

Fig. 1. Measured and predicted daily runoff (mm) for (*a*) black earth (Greenmount), and (*b*) grey clay (Greenwood), for three fallow management treatments.

runoff, there are variations in the real system (for example, varying rainfall intensity and temporal pattern, cover, roughness, etc.) that are not considered in the model. Together with data errors, these factors account for some 17% of the variance in daily runoff predictions (combined data, Table 2).

Prediction of runoff was poorest for stubble mulch, presumably due to greater variation in surface cover and roughness under this treatment. Crop residue cover during the fallow was consistently low (<12%) for bare fallow and consistently high (>50%) for zero-till, while for stubble mulch, cover varied from >50% at the beginning of the fallow to <20% at the end of the fallow. This dynamic behaviour of crop residues cover is not considered by the CREAMS model.

Daily runoff depths were predicted well for the black earth, with errors distributed evenly between over- and under-predictions throughout the range of measured runoff values (Fig. 1*a*). The three largest daily runoff values, which resulted in significant soil erosion (Wockner and Freebairn 1991), were well predicted for all treatments. However, for some small to medium sized runoff events (0–40 mm), errors in predicted runoff were large (10–20 mm). For instance, six events (out of 51) for bare fallow were overpredicted by more than 10 mm, and five events were underpredicted by more than 10 mm, with the largest errors being about 20 mm. These few large errors make a large contribution to the total error, with five events contributing 80% of the sum of squares of errors and 50% of the RMSE for zero-till on black earth. Such large errors may be of concern when predictions of daily runoff are used directly to model other processes such as erosion and pollutant transport.

For the grey clay, one event with daily runoff >50 mm was recorded (Fig. 1*b*); runoff was overpredicted by 27–55%, depending on treatment. This event occurred during a 4-day period when there was 246 mm of rain. Runoff predictions were better for the 4-day period than for the daily values. For instance, measured runoff from bare fallow was 145 mm and predicted runoff was 155 mm, for the 4 days.

Improved predictions of cumulative runoff for periods greater than one day are related to: (*a*) compensating errors (overprediction on some days is offset by underprediction on others); and (*b*) fewer problems caused by discretisation of data into daily values. Occasionally rainfall and runoff continue through 9 a.m., with some rain just prior to 9 a.m. being measured as runoff after 9 a.m. Different arbitrary breakups of the measured rainfall and runoff into 24 h values results in different predictions. Discretisation into daily values contributes to the variance in daily runoff not explained by the model, a problem inherent to validation of daily time step models.

Monthly runoff prediction

Monthly runoff was well predicted for both sites (Fig. 2 and combined statistics in Table 2). For individual treatments all regression intercepts were $< \pm 3$ mm and slopes were $0\cdot9$ to $1\cdot1$. Except for the stubble mulch treatment on the black earth ($r^2 = 0\cdot72$) all r^2 values were in the range $0\cdot87$–$0\cdot96$. Monthly runoff was very well predicted for all treatments on grey clay with all statistics indicating a better fit (e.g. $r^2 > 0\cdot92$) than for any treatment on black earth. RMSE values for monthly runoff were similar in magnitude to RMSE values for daily predictions. Thus monthly runoff was considerably better predicted, in both absolute and relative terms, than daily runoff. This improvement is due to compensating errors in daily values within months, including a reduction in discretisation problems described above.

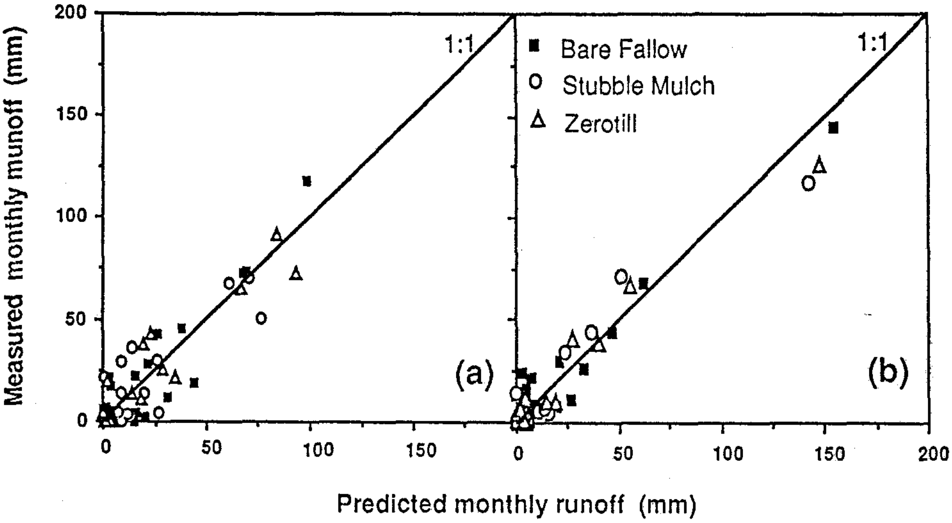

Fig. 2. Measured and predicted monthly runoff (mm) for (*a*) black earth (Greenmount), and (*b*) grey clay (Greenwood), for three fallow management treatments.

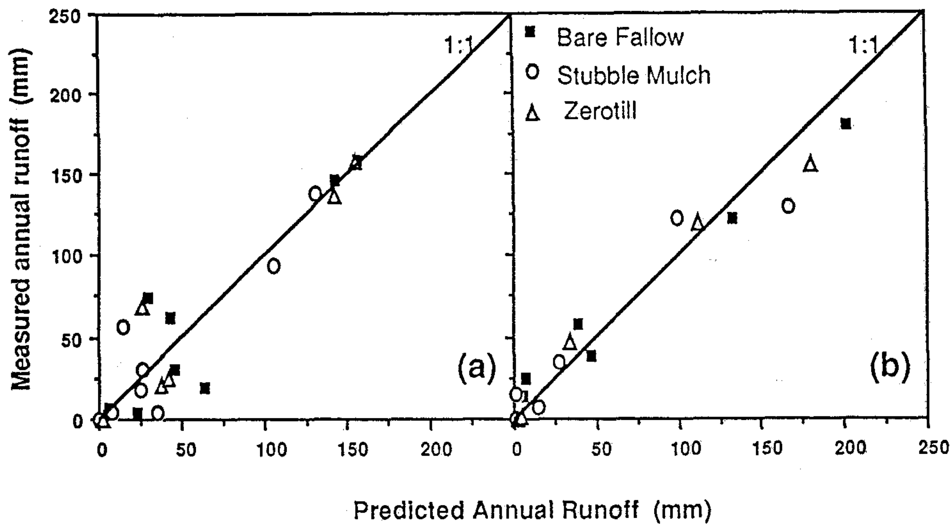

Fig. 3. Measured and predicted annual runoff (mm) for (*a*) black earth (Greenmount), and (*b*) grey clay (Greenwood), for three fallow management treatments.

Annual runoff prediction

Prediction of annual runoff is often used to summarize runoff results from long-term simulations (e.g. 100 years), for instance in the form of probability distributions of annual runoff (Littleboy *et al.* 1989; Freebairn *et al.* 1990). Annual runoff was predicted well (Table 2 and Fig. 3), particularly for the grey clay. Runoff in wet (higher runoff) years and very dry (lower runoff) years

Table 3. Statistics for prediction of available soil moisture (mm) for the total soil profile, using the CREAMS hydrology model with optimized curve numbers

Site/ treatment	No. of observations	RMSE[A] (mm)	Mean error (%)	Mean error (mm)	Regression[B] Int (mm)	Regression[B] Slope (mm)	r^2
Black Earth (Greenmount)							
Bare fallow	31	34·1	−5	−7·0	38·4	0·74	0·76
Stubble mulch	30	35·0	−1	−1·7	42·0	0·74	0·83
Zero-till	16	44·0	+2	3·0	54·4	0·62	0·63
Grey Clay (Greenwood)							
Bare fallow	17	29·6	+7	5·0	27·7	0·61	0·75
Stubble mulch	17	25·8	−4	−3·8	28·5	0·71	0·82
Zero-till	12	22·7	−5	−5·4	24·5	0·80	0·85

[A] Root mean square error (mm).
[B] Linear regression, Measured = Int + Slope (Predicted), for total available soil moisture values (mm).

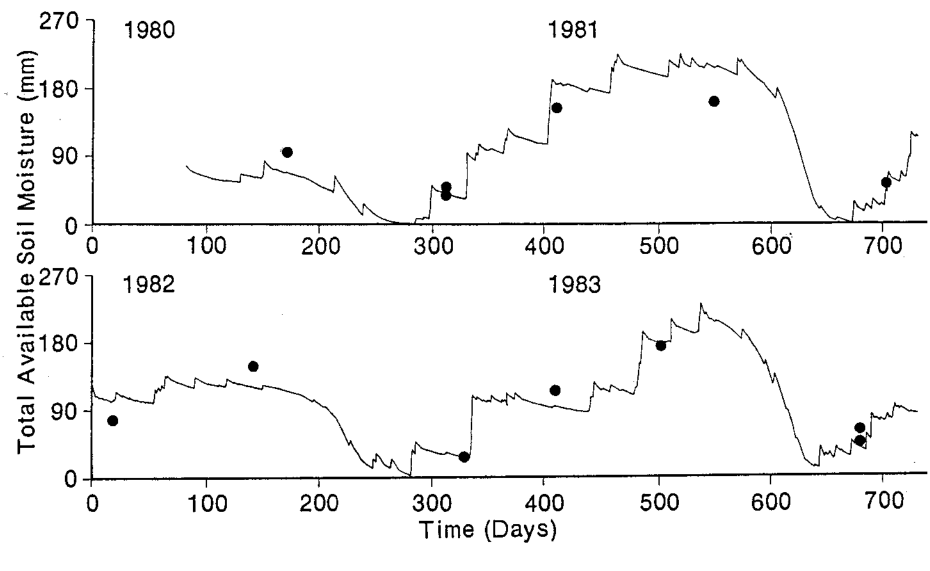

Fig. 4. Measured (●) and predicted (—) total available soil moisture (mm) through time for four years on the grey clay with zero-till fallow treatment.

was also consistently well predicted. However, for the black earth, runoff was underpredicted by approximately 50 mm for all three treatments in one year and overpredicted by approximately 50 mm in another year (Fig. 3*a*).

Total available soil moisture

Mean error in predicted total ASM was within ± 7 mm for all treatments (Table 3). RMSE values were 25–35 mm (Table 3), a similar range to those of Greacen and Hignett (1984) for cracking clays. Available moisture capacities of the black earth and grey clay are in excess of 200 mm, compared with 60–100 mm for the clays studied by Greacen and Hignett (1984), indicating that CREAMS gave better predictions in relative terms. An example of model performance is shown in Fig. 4. Fig. 4 also illustrates the dynamic nature of soil water.

Regression analysis (Table 3) indicates a tendency to underpredict ASM when profiles were dry and overpredicted slightly for wet profiles. Total ASM was generally predicted well, but on some occasions (e.g. 6 out of 31 values for black earth bare fallow) large errors (>50 mm) in total ASM occurred. As the causes of errors in soil moisture prediction are of interest, data for black earth-bare fallow (Fig. 5) were examined in greater detail. Total ASM just prior to planting was predicted with an average error of only −8·0 mm. However, total ASM following harvest was predicted with an average error of -34 mm and was underpredicted by 40–80 mm in five years. Predicted evapotranspiration during the crop was too large (by 32–73 mm) in seven out of eight years.

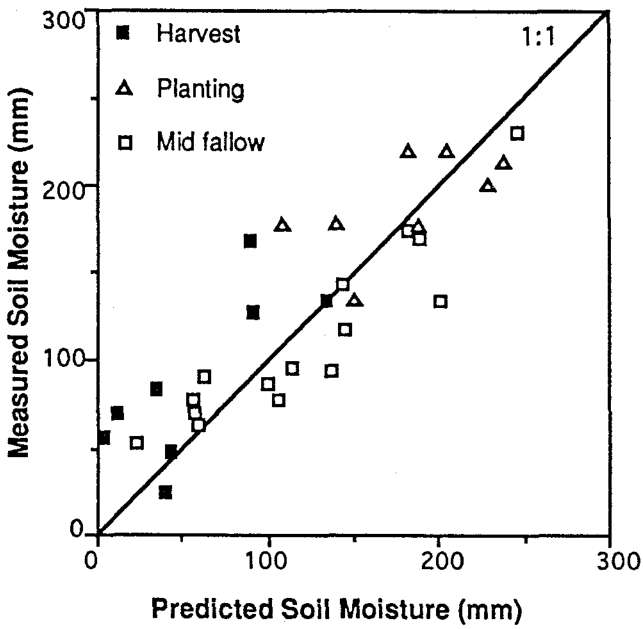

Fig. 5. Measured and predicted total available soil moisture (mm) for black earth–bare fallow, at harvest, planting and during the fallow period.

Poor prediction of evapotranspiration during crop growth was also responsible for poor prediction of ASM during some fallow periods. In two years, underprediction of soil moisture at harvest persisted throughout the fallow and resulted in the two worst predictions of pre-planting soil moisture. The otherwise good predictions obtained for ASM at the end of the fallow (when soil evaporation is dominant) indicates that cumulative soil evaporation was well predicted.

To determine the extent to which errors in prediction of soil moisture are related to errors in prediction of runoff, predictions of ASM obtained using optimized curve numbers were compared with predictions of ASM when **measured** runoff data were input and used in place of predicted runoff. Prediction of soil moisture was not improved, for all sites and treatments, indicating that errors in predicted runoff were not a major cause of errors in soil moisture prediction.

Distribution of soil moisture

The distribution of ASM within the soil profile was not as well predicted as the total ASM (Table 4). Distribution of ASM for the black earth was moderately well predicted, but with a tendency to overpredict for the upper subsoil (100–500 mm) and underpredict for the lower subsoil (500–1200 mm). For the grey clay this result was more extreme, and ASM in the surface 0–100 mm layer was also generally overpredicted. The model uses the same values of the drainage parameters FUL and RC for all soil layers, thus does not adequately reflect features of the soil that control moisture redistribution. In particular, the model structure does not allow the greater drainable porosity of the tilled layer to be represented. Also, overprediction of evapotranspiration during the crop noted above contributes to over-drying of the lower subsoil.

Table 4. Statistics for prediction of the distribution of available soil moisture (mm) for three layers, using the CREAMS hydrology model with optimized parameter values

Site/treatment	Mean error (%) Tilled layer 0–100 mm	Subsoil (upper 1/3)	Subsoil (lower 2/3)
Black Earth (Greenmount)			
Bare fallow	+3	+17	−27
Stubble mulch	+2	+14	−16
Zero-till	−5	+30	−17
Grey Clay (Greenwood)			
Bare fallow	+40	+45	−33
Stubble mulch	+42	+21	−37
Zero-till	+37	+20	−34

Deep drainage prediction

Mean drainage predicted for black earth–bare fallow using CREAMS was $2\cdot9$ mm yr^{-1} for 1952–1975. Drainage estimated from chloride profiles for similar land use was $3\cdot3$ mm yr^{-1}. While a rigorous comparison is not possible, the model prediction of deep drainage appears reasonable.

For the period used in testing runoff and ASM predictions (1976–1984), predicted drainage was a small component of the water balance (<3% of rainfall). Drainage occurred only sporadically, with all predicted drainage occurring in just two of the eight years. In these years, rainfall was >30% above average, and runoff and drainage were up to 15% and 8% of rainfall, respectively.

General Discussion—Model Applicability

For a model to be usefully applied it must give predictions that are sufficiently accurate for the intended application; validation relates to the potential applications of the model, not the model itself (McCarl 1984). Also the model may be valid for a range of applications, but if parameter values are difficult to obtain its use will be limited. The models under discussion are largely generic representations of a system; selection of parameter values results in representation of a specific system, for example, a particular soil type. Errors in prediction can be due to deficiencies in the model structure or due to the parameter values used. In this discussion, we focus on the validity of the model for particular applications and identify possible structural shortcomings of the model, and secondly, on how well the model can be parameterized in practice.

Range of Applicability of CREAMS

Runoff predictions are adequate for applications where predicted annual and monthly runoff are needed. However, errors in daily runoff predicted with CREAMS may be of concern when daily values are critical inputs to another model. Some 17% of variation in daily runoff was not explained by the model. These errors are partly explained by changes in the real system that are not considered in the model; for instance, changes in cover from day to day (due to breakdown and burial of crop residue and growth of plants) and effects of cover on runoff and evaporation. More complete models of crop-soil systems, such as PERFECT (Littleboy *et al.* 1989), simulate these processes, giving some improvement in prediction of runoff (Littleboy *et al.* 1992). Similarly, variation in soil surface roughness through time, due to tillage and subsidence under rain, is not described in CREAMS. Consequently, some errors in runoff prediction are related to roughness (Silburn, unpublished data).

Errors in runoff prediction were shown to contribute little to errors in prediction of total ASM. Drainage is also considered a minor source of error in ASM prediction. In the wetter years, runoff and drainage combined were a larger proportion of the water balance, totalling 20–25% of annual rainfall. However, as these periods of drainage and higher runoff occur when the soil profile is full, errors in ASM will not be caused by errors in estimates of runoff and drainage *per se*, but rather by poor estimation of the soil water holding capacity. For the environment studied, the runoff and drainage models in CREAMS (given reliable estimates of runoff parameters) are considered adequate for modelling total soil moisture in applications such as crop modelling.

Transpiration and soil evaporation combined account for 80–100% of annual rainfall. Errors in the soil water balance are more likely to be related to errors in prediction of these components. Good predictions obtained for soil moisture at the end of the fallow indicated that soil evaporation was predicted well. The model consistently overpredicted water use during the crop. The transpiration model and LAI data used did not reflect dynamic variations due to management (planting date, variety etc.) and seasonal conditions. Use of a dynamic crop model, which responds to management, and moisture and climate conditions, would improve prediction of transpiration and soil moisture. Better predictions of the same soil moisture data were obtained using the PERFECT model (Littleboy *et al.* 1989), which includes such a dynamic crop model.

For assessment of salinity, groundwater recharge and movement of pollutants in the soil, prediction of drainage and soil moisture redistribution is important. It was not possible to test prediction of drainage in this study other than to show that model predictions were within the appropriate order of magnitude.

Rather poor predictions of the distribution of soil moisture in the profile were obtained, and these predictions were insensitive to model parameters. Although this is partly related to the problems noted for crop water use, performance and flexibility of the model could be improved by allowing different values of drainable porosity to be used for each layer in the soil.

Model Parameterization

Estimation of values for model parameters is a major issue when models such as CREAMS are applied in practice. While we have shown that reasonable predictions can be obtained using measured values of soil water capacities and handbook values of other parameters, runoff prediction is sensitive to the value of CNII. To date, there has been no conclusive study showing that the optimal curve number for use in a water balance model can be obtained other than by calibration of the model to hydrologic data. This is not unique to curve number-based runoff models, being true for all daily time step runoff models. Thus, while the model can give adequate runoff predictions for many applications, its confident use will be limited by the availability of hydrologic data.

The optimized curve numbers (Table 2) are a source of parameter values for modelling the water balance of self-mulching Vertisols using CREAMS and derivative models. Optimized CNII values were similar for the two soils, and were consistent for bare and stubble mulch treatments. For these cultivated treatments, CNII decreased 10 units for a increase of average fallow cover from 5 to 42%. These data were used to build a submodel in PERFECT that reduces CNII with increasing cover (Littleboy *et al.* 1989); good runoff and soil water predictions were obtained for a range of tillage systems using this model (Littleboy *et al.* 1992).

Confidence in estimates of parameters will improve with calibration of the model for more hydrologic data sets. Generalizations may then be made in selecting parameters, by interpolating between values and through the use of surrogate soil properties and rainfall simulator studies. There are indications that curve number values are consistent for similar soils. For example, optimized CNII values for the black earth and grey clay for wheat-bare fallow were 71 and 72, respectively. A CNII of 73 gave optimal predictions of runoff for bare fallows, for wheat, sorghum and sunflower, on a black earth in central Queensland (Littleboy, Sallaway and Silburn, unpublished data). Boughton (1989) gave values of CNII, optimized for the antecedent rainfall model, for 27 catchments of varying size, soil and land use in Queensland and New South Wales. The mean curve number was 75 with a standard deviation of 7. Thus, values of CNII are within a limited range for a large range of catchment conditions. However, this range in CNII (approximately $\pm$ 10% around the mean) still represents a considerable range in runoff response. Boughton (1989) found that, for one catchment, a 10% change in curve number gave a change in estimated average annual runoff of approximately 50%.

Conclusion

The curve number rainfall/runoff method was developed before use of soil physics–based models was practical. Subsequently, the curve number method has been enhanced by including it in a water balance and linking curve numbers to antecedent soil moisture (the CREAMS method), and more recently, by adjusting curve numbers for soil cover. With these enhancements, the CREAMS method is capable of explaining >80% of the variation in daily runoff and >90% of the variation in monthly and annual runoff. Given that soil physical models are rapidly developing and becoming practical to use, is there still a place for this 'mature' technology? This study indicates that this approach can make efficient use of existing data and is adequate for many applications. It is compatible with the daily time step and daily rainfall data used in many agricultural systems models. However, its use will be limited by availability of key parameters, which must presently be derived from hydrologic data. It remains to be seen whether soil physics–based models will be more cost effective and more easily parameterized, and offer greater predictive accuracy when used with daily rainfall data.

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