THE USE OF THE CREAMS COMPUTER MODEL TO PREDICT WATER, SOIL AND CHEMICAL LOSSES FROM SUGARCANE FIELDS AND TO IMPROVE RECOMMENDATIONS FOR SOIL PROTECTION

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Abstract

The structure of the Chemicals, Runoff and Erosion from Agricultural Management Systems (CREAMS) model is described. Each of the three sub-models, 'Hydrology', 'Sediment' and 'Chemical Production' is outlined to show the range of conditions to which they can be applied. The reasons for the choice of this particular model are discussed; its calibration using data from the rainfall simulator and five pairs of runoff plots is described. The model is used to predict which land management systems would give the best protection under various soil, topographic and regional conditions. Modifications to the existing recommendations are suggested.

Introduction

A report and a manual of operation of the CREAMS model was published by the United States Department of Agriculture (Anon[1]). This paper is based on that publication and the computer programmes which the USDA developed.

To control the loss of soil and water from agricultural lands, the mechanics of the processes involved must be understood. Mathematical models can then be fitted to these processes to predict what will happen under a given set of conditions. When the variations and permutations of conditions have been tested, the set of practices which provide most protection can be selected. The processes involved in the rainfall-erosion cycle are complex and in research work done prior to 1978 only single aspects or parts of the whole cycle, were considered. The Universal Soil Loss Equation (USLE) (Wishmeier and Smith[2]), which is the only model incorporating factors for the full cycle, was developed from data obtained from many sources. Predictions over the long term were good but because the model was based on average conditions, it was of little use on a storm by storm basis. The concept of the USLE was advanced, however, because it incorporated all the relevant factors and because the crop was regarded as a potential agent for conservation.

In 1978 the Science and Education Agency of the United States Department of Agriculture collected all of the available data on erosion control and set objectives for a computer model which would allow protective measures to be selected for any set of agricultural practices. The model had to be universally applicable; based on soil physical properties and water movement; a field scale model initially; suitable for estimating runoff (volume and rate), percolation, erosion and dissolved and adsorbed chemicals; suitable for measuring the differences between management systems. The (CREAMS) model was the outcome of this excercise.

Structure of Creams model

The infiltration of water into the soil, its movement through the soil profile, runoff of excess rainfall from the soil surface and the movement of sediment and chemicals, all vary from

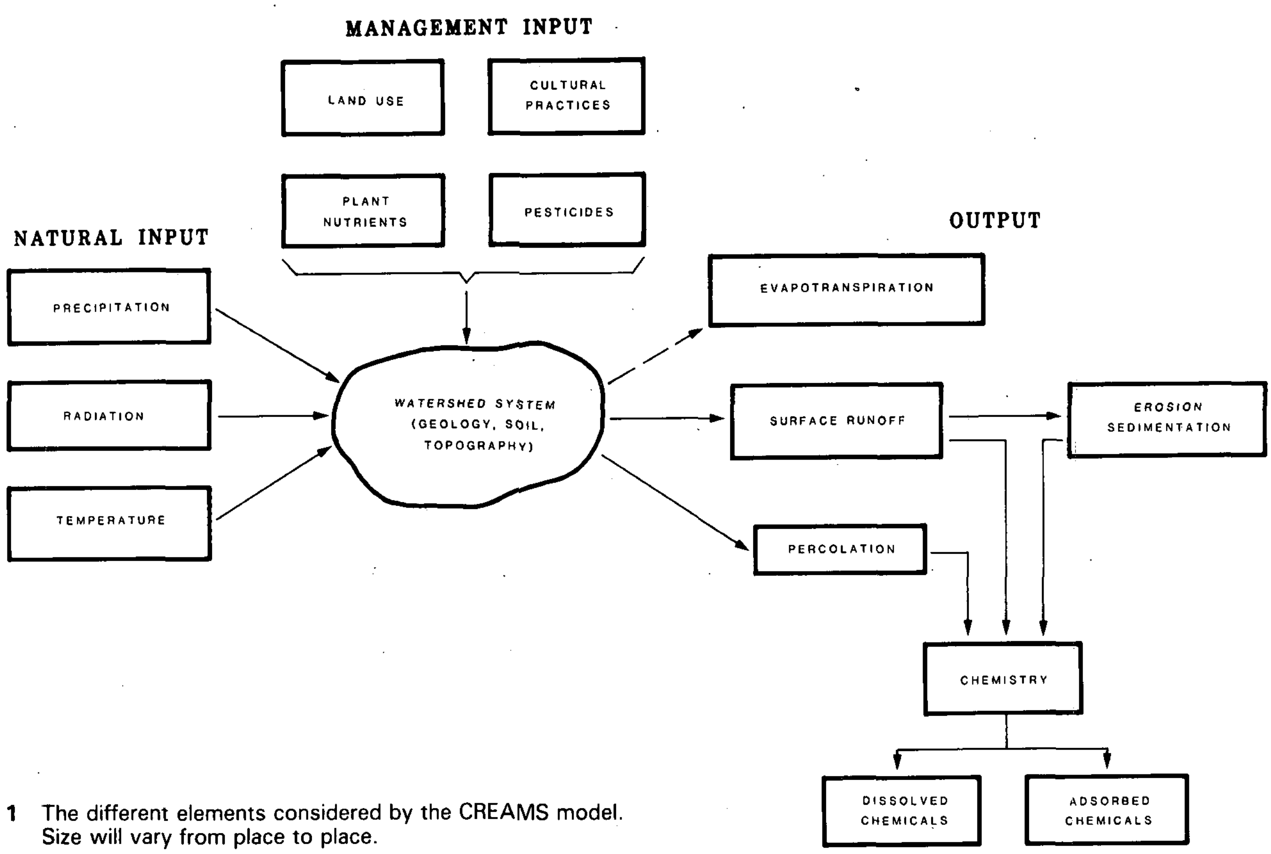

FIGURE 1 The different elements considered by the CREAMS model. Size will vary from place to place.

one locality to another. These parameters and others have been used, as shown in Figure 1, to develop a model which consists of three sub-models. Each of these depends on additional sets of parameters. The construction and routing used for the sub-models is shown in Figure 2.

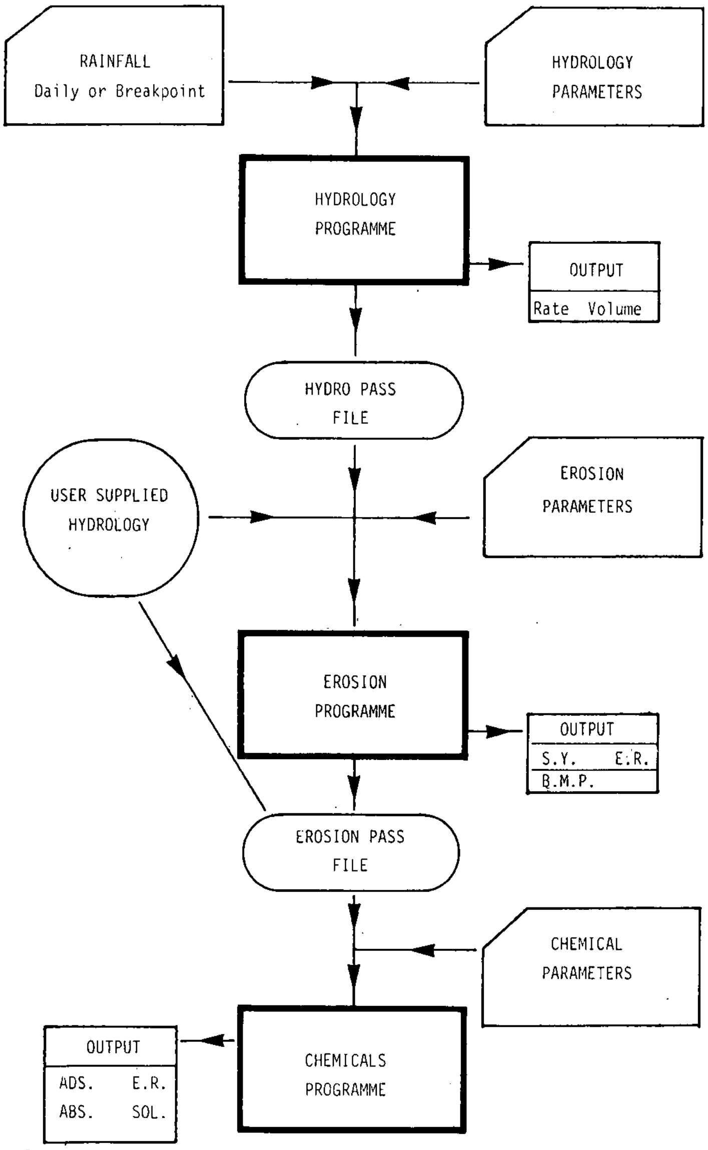

FIGURE 2 The general structure and files required to run the CREAMS programme. Each programme may be run separately if required.

1. *Hydrology sub-model*

The hydrologic processes such as infiltration, surface runoff and percolation which occur during and after a rain storm, can be simulated in a model. The sub-model is continuous and operates in conjunction with other models and routines concerned with the hydrologic processes. Evaporation and movement of soil water between storms are estimated on a daily basis. Shorter time intervals can be used during the storm if rainfall intensity has been measured continuously. By estimating the amount of percolation that takes place between storms, the model allows seepage below the root zone to be predicted and antecedent moisture contents at the beginning of each storm to be calculated. Accurate predictions of surface runoff depend heavily on antecedent soil moisture content.

Infiltration

- Daily rainfall records

If rainfall is recorded on a daily basis, the Soil Conservation Service (SCS) Curve Number (Anon[3]) method, which includes an antecedent rainfall index (I = dry, II = normal, III = wet), is used to calculate infiltration and runoff. A curve number which depends on the nature of the catchment and on the types of soil and vegetation, is then allocated to the simulated storm. The SCS Curve Number method has been linked to other models concerned with evapotranspiration and percolation so as to maintain a continuous water balance. The output is expressed as the daily volume of runoff and peak runoff rates.

- Breakpoint records (amount of rainfall with time)

Changes in rainfall intensity, or breakpoints, can be used to increase the accuracy with which volumes and rates of runoff are predicted. Infiltration rates and rainfall intensities vary during storms, and the changes affect the amount of runoff that takes place.

Evapotranspiration and soil water routing

Water that enters the root zone is lost due to evaporation and transpiration, stored in the soil profile, or seeps below the root zone. The water balance is calculated daily.

- Transpiration

The loss of water due to transpiration and evaporation is accounted for in the model and the leaf area of the crop and the depth from which roots extract water are also considered. The estimation of potential evapotranspiration, is based on air temperature, the vapour pressure curve and the amount of radiation.

- Soil evaporation

Evaporation from the soil is calculated in two stages. When the surface of the soil is wet, evaporation is limited only by the amount of energy available at the soil surface, and this is 'potential' evaporation. When water is no longer freely available at the soil surface due to the amount of evaporation that has taken place, the second stage begins. Evaporation during this stage is limited by the rate at which water moves upward towards the soil surface due to capillarity, and by the heat transfer characteristics of the soil. The total amount of evaporation during these two stages cannot exceed the potential amount of evaporation that could occur.

- Drought conditions

These conditions are simulated by allowing water to be removed from the profile only until soil moisture tension reaches 1500 kPa (15 bars). At this stage plant growth is inhibited and the leaf area index is held constant until water from rainfall again becomes available.

Percolation

If only daily rainfall records are available, percolation is determined by dividing the root zone into seven layers and calculating the amount of rain water entering each layer. The available moisture holding capacity of the soil is taken into account, and allowance is made for the surface layer being shallower than the others. Percolation does not take place until field capacity has been exceeded in each layer. Besides percolation losses, each layer loses water due to transpiration by the crop and these losses have to be distributed throughout the rooting zone. There is therefore also a minor sub-model for root growth, which allows for the rate of water uptake as a function of root depth.

If breakpoint data are available, the profile is divided into only two soil layers; the surface layer which is sensitive to infiltration, and the rest of the root zone. Water is lost from the surface layer of soil due to evaporation and to extraction by the plant's roots for transpiration. The moisture status of this layer determines the initial conditions for the infiltration model. Water in the deeper soil zone can be extracted by roots and the root growth model is used to relate root depth to the leaf area index.

2. *Erosion/sediment sub-model*

Data from the hydrology sub-model can be used in this sub-model. Proven relationships from the USLE and new modelling concepts are used to provide a very flexible yet comprehensive model which requires only a small amount of input data. The yield, composition and sediment enrichment ratios of soil loss are computed on a storm by storm basis. It is a continuous model and is limited only by available records. The model is based on the fundamental concept that if the sediment load exceeds the carrying capacity of the runoff water, then carrying capacity limits erosion. Conversely, if sediment load is less than carrying capacity, the amount of sediment available for transport limits erosion.

There are three components of the sub-model and they are: overland flow; concentrated (channel) flow; and impoundments (ponds). Although various combinations of these components can be used, the correct sequence must always be followed (Figure 3).

- Overland flow

A modified version of the USLE allows the detachment of soil particles due to overland flow and raindrop impact to be computed. Input from the hydrology model includes volume of runoff and storm energy values, and they reach the erosion programme via an hydrology pass file. Other inputs include physical properties of soil some of which are readily available and others which have to be calculated. The topography of the route of overland flow and channel specifications are also necessary inputs, while soil erodibility, crop cover management and contouring practices are modified from the USLE. These factors are merged into co-ordinates for the specific slope profile which is being assessed. The shape of slopes which can be analysed are shown in Figure 4.

To compute the soil losses from rills and interrills, the slope profile is divided into segments from the top downwards. The number of segments depends on the overall shape of the slope.

For each segment of the slope, starting at the top, interrill erosion is calculated and the amount of sediment is accumulated to give the potential sediment load. The carrying capacity of runoff water is calculated to see if it is sufficient to remove the potential sediment load. If carrying capacity is lower than the potential sediment load, selected deposition can take place; the heavier, larger particles and aggregates are withdrawn from the flow until the carrying capacity is equal to the sediment load. Any particles which settle are assumed to be re-attached to the surface. This process caters for the enrichment of the runoff water with finer particles that is seen in practice. The calculation is repeated for each segment down the slope, the output from the preceding segment being used as the input for the succeeding segment. If only overland flow is being considered, output from the final segment is the predicted value for the slope. In other circumstances this may be the input required for the estimation of other downstream elements.

- Concentrated flow (channel)

The effects of various structures such as the earth channels of terrace banks, grassed waterways, intermittent streams and natural depressions in fields which have been culti-

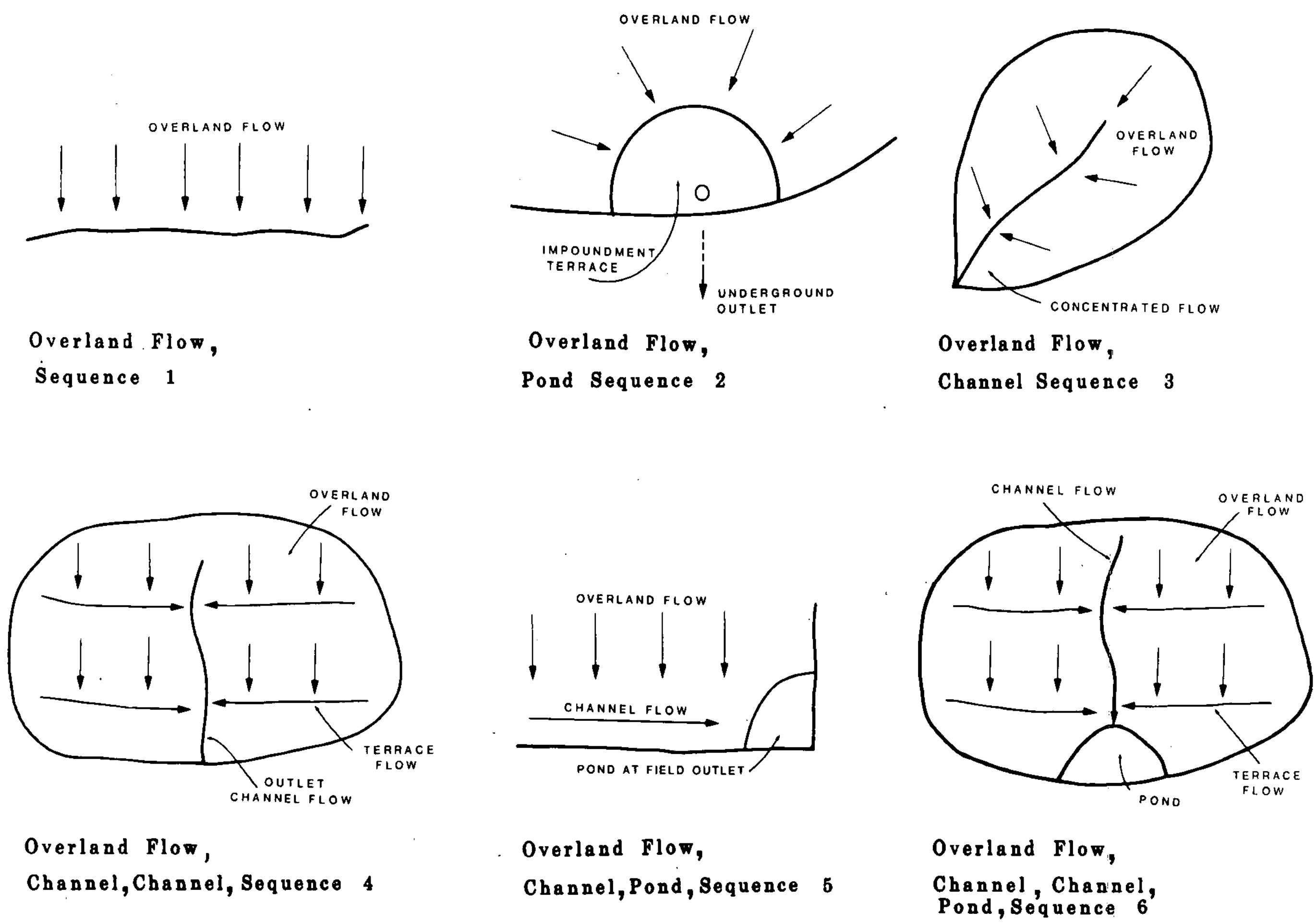

FIGURE 3 The different components which make up any flow route. Each component is used in its logical downhill sequence when combined with other components.

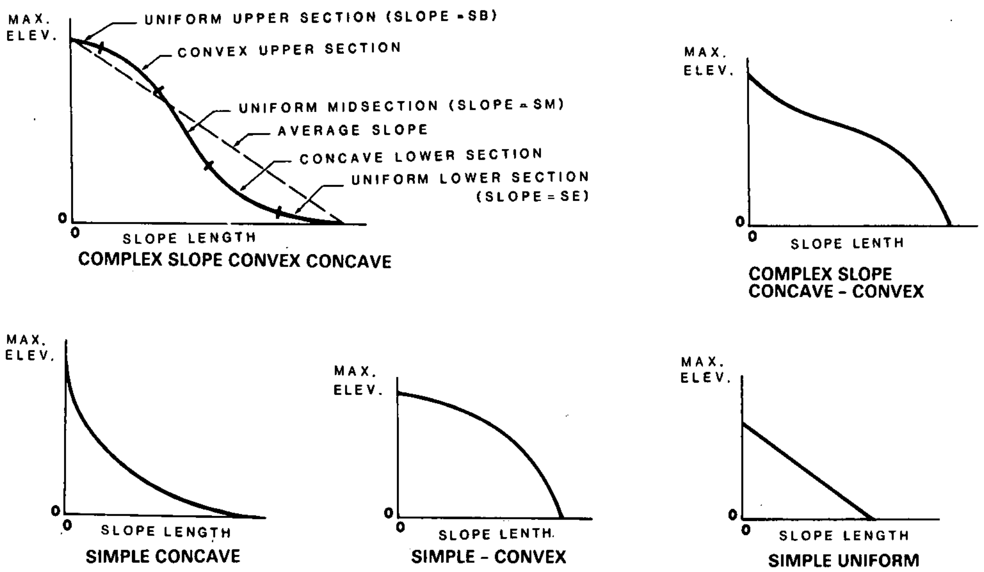

FIGURE 4 Different shaped slopes can be analysed with the computer programme.

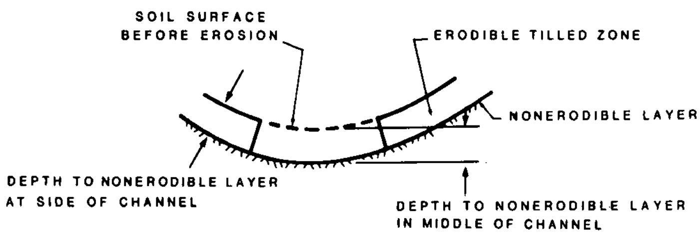

FIGURE 5 The model assumes no erosion takes place below the ploughed layer when concentrated channel flow takes place in a ploughed field.

vated (Figure 5), can be analysed by means of this section of the model.

For natural depressions, a non-erodible layer is assumed to be present and erosion can occur only to that depth before being forced to continue sideways. Soil, topography and crop cover management information that is required in order to estimate concentrated flow, are available from the parameters file which feeds into the erosion programme (see Figure 2). The sequence is the same as that for overland flow, starting at the top of the slope and moving downwards. Output comprises sediment load, particle distribution of the sediment, and the enrichment ratio.

- Ponds (impoundments)

This is a small sub-programme which is used to estimate the amount of sediment deposited in an impoundment terrace which has a controlled pipe outlet. Where shallow dams or field drains are the final element in the path of flow, analysis is normally based on flow in a channel with a backwater condition, but this situation is unlikely to be of any significance in local predictions.

3. *Chemistry sub-model*

Chemicals such as fertilizers, herbicides and pesticides, are usually applied to the surface of the soil or sprayed onto crops, so they are liable to be washed away during heavy rain storms. For fertilizers to be effective, they must be in solution, which means that they are most likely to be carried away in runoff water or lost through deep percolation. The last phase of the CREAMS model was designed to account for the loss of chemicals.

Operating the model

Each of the three main sub-models, ie hydrology, erosion and chemicals, can be used separately but in this instance the hydrology and erosion programmes have been used in sequence. Information is entered into the programme by means of card formats.

Hydrology

The rainfall data are filed separately on cards. With daily rainfall data there are 10 values per card so 37 cards can accommodate the rainfall records for a year.

Rainfall intensity records are prepared as follows: on Card 1 the year of, and day on which the storm started, the number of breakpoints, the duration of the storm and the amount of rain which fell during the storm, are recorded. A separate card is used for each breakpoint to show the cumulative rainfall and the duration (in minutes) of the rain.

The second step in operating the programme is to construct the hydrology parameters file. The list of parameters required for daily and breakpoint rainfall options are shown in Appendix I. Most of the values are readily obtainable but where values have not been established, estimates have to be used. Certain parameters such as air temperature, solar radiation and the leaf area index may or may not be used. Output can be on a storm by storm basis or an annual basis, or a combination of the two. If information is to be used for later sections of the model, an hydrology pass file is created. A sample of this file and of outputs from the hydrology programme are shown in Table 1.

Erosion/sediment

The data required for this programme are taken from the hydrology pass file and from the list of parameters given in Appendix 1. Specific instructions are issued to determine which elements of the flow sequence will be called. The parameters are entered in a fixed order; general parameters and commands first, followed by fixed overland flow values, fixed channel and pond figures. Parameters which are updated during the simulation period are entered last.

Testing the model

Although the model is based on observed phenomena and has been tested extensively in the United States of America, it would be more acceptable here if the predicted losses could be compared with those which are actually measured. To give some indication of the reliability of the model, it was tested against the losses measured from runoff and simulator plots (Platford[4]). Considering only the simple slopes and soils of the plots, soil and water losses were accurately predicted from the model and the results are shown in Table 2.

TABLE 1

Some output values from the CREAMS model*

CREAMS HYDROLOGY OPTION TWO

(BREAKPOINT OR HOURLY PRECIPITATION VALUES)

Version 1.6 Dec 10 1981 Tifton GA

Daily Hydrology Working Parameters

Waldene Soil	Shakaskraal	Simulator 1981
0,005 Acres	9% slope	Length slope 10.7 m

Monthly mean temperatures, degrees Fahrenheit

74.95	74.26	72.23	69.40	66.54	64.41
63.58	64.28	66.31	69.13	71.99	74.12

Monthly mean radiation, Langleys per day

438.72	451.31	439.17	405.54	359.45	313.23
279.28	266.69	278.83	312.46	358.55	404.77

Effective Hydrologic length	= 35.000 ft
Effective Hydrologic slope	= 0.090
Effective mannings n	= 0.030
Depth of surface layer	= 2.000 in
Depth of remaining root zone	= 7.000 in
Effective capillary tension	= 13.000 in
Evaporation coefficient	= 3.750
Sat. conductivity cultivated	= 0.050 in/hr
Sat. conductivity fallow	= 0.040 in/hr
Soil porosity	= 0.470
Immobile soil water content	= 0.170 in/in
Upper limit of storage	= 2.196 in
Initial surface storage	= 0.540 in
Initial remaining storage	= 1.436 in
Total initial storage	= 1.976 in

Leaf Area Index Table

Date	Lai
1	0.0
366	0.00

Winter C Factor = 1.00
Lai-days = 0.00

Date Julian	Rainfall inches	Runoff inches	Percol. inches	Average temp. deg. F.	Average soil w. in./in.	Actual ep inches	Potent. ep inches
81001	2.5000	2.0161	0.0728	74.7334	0.4126	0.0000	0.0000
81002	2.5000	1.9835	0.3050	74.7593	0.4133	0.0000	0.0000
81007	2.5000	1.8040	0.1225	74.8257	0.3881	0.0000	0.0000
81014	5.0000	4.2682	0.0801	74.9156	0.3813	0.0000	0.0000

AVERAGE ANNUAL VALUES

Precipitation	= 12.500
Predicted runoff	= 10.072
Deep percolation	= 0.580
Total et	= 2.228

Minimum Total Storage was 1.596 on 81365
Maximum Total Storage was 2.190 on 81002

* This example is of outputs from a programme run in Tifton, Georgia, USA and is therefore in imperial units

TABLE 2

Predicted and measured soil and water losses using recorded data from simulator plots

Soil Series	Slope %	Measured		Predicted	
		Runoff %	Soil loss t/ha	Runoff %	Soil loss* t/ha
Cartref	9,0	87	30,0	78,4	25,0
Waldene	7,0	82	24,0	80,6	22,2
Clansthal	12,0	47	3,5	23,7	1,2
Clansthal	3,5	31	1,5	19,1	0,0

* converted from t/acre

Since both types of plots had uniform slopes and soils, the flexibility of the computer model, with regard to variable slopes, different soil types, flow routing and various cover practices, could not be tested.

Reasons for choosing the Creams model

The model was designed so that different agricultural management practices could be compared. The best way of controlling runoff and erosion can be determined by identifying those methods which cause the least amounts of water and soil to be lost. Accurate representations of the real condition in a field can be made in a model but parameters must be selected carefully and their sensitivity ratings must be known. Because the model works on a storm by storm basis and a continuous water balance is calculated, it is well suited to sugarcane where crop cycles are seldom annual. The structure of the model is such that it allows many different management practices to be evaluated. If slope, soil, temperature, rain and radiation are held constant, different surface water routing and crop cover sequences can be analysed (Figure 6).

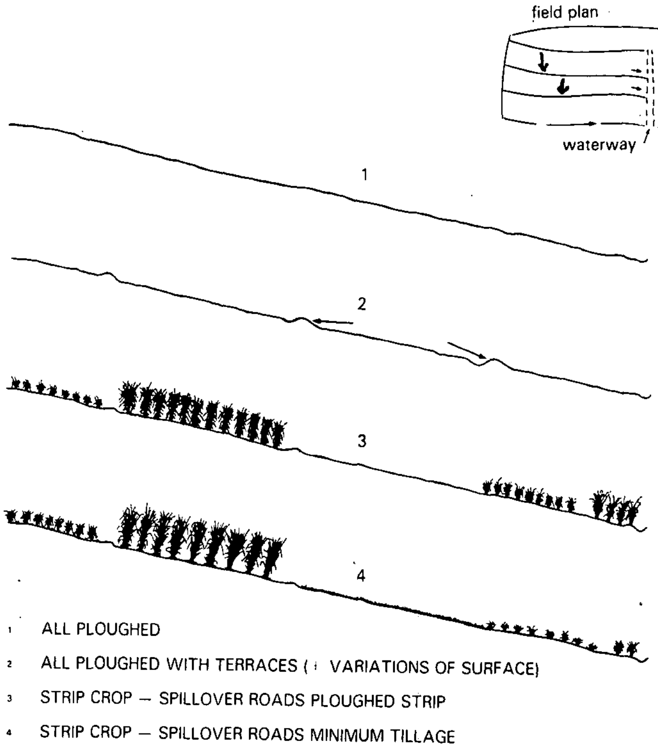

FIGURE 6 Different practices and protective systems can be compared to find the best management practice.

Models generally are a simplification of complex phenomena but they must nevertheless be reasonable representations of what actually occurs. This model was chosen because the effects of using different crop growing methods can be evaluated while predictions of soil and water loss remain accurate.

Field study

CG Smith Sugar Company at Sezela requested help in planning the layout of an area on the Nkwifa section and also to evaluate their strip cropping.

Local daily rainfall and other necessary data were recorded, aerial survey maps of the area were prepared, quota maps were used to establish the position of extraction roads, and areas were measured. The proposed plan was developed using graded water-carrying terrace roads and grassed waterways in the natural depressions (Figure 7). Five overland flow profiles which were typical of the area were used. The slope shapes which were analysed are shown in Figure 8.

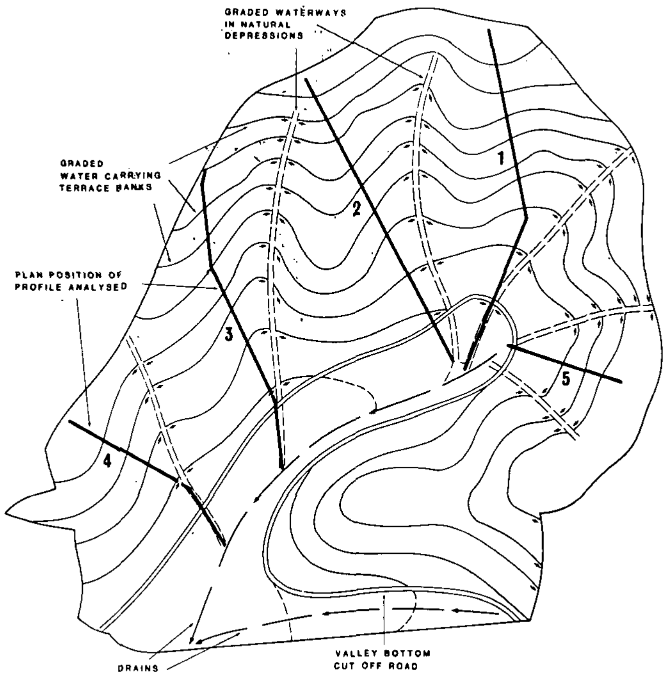

FIGURE 7 The field layout proposed for field 4460, Nkwifa section, CG Smith Sugar, Sezela, showing terrace banks, grassed waterways and profiles to be analysed.

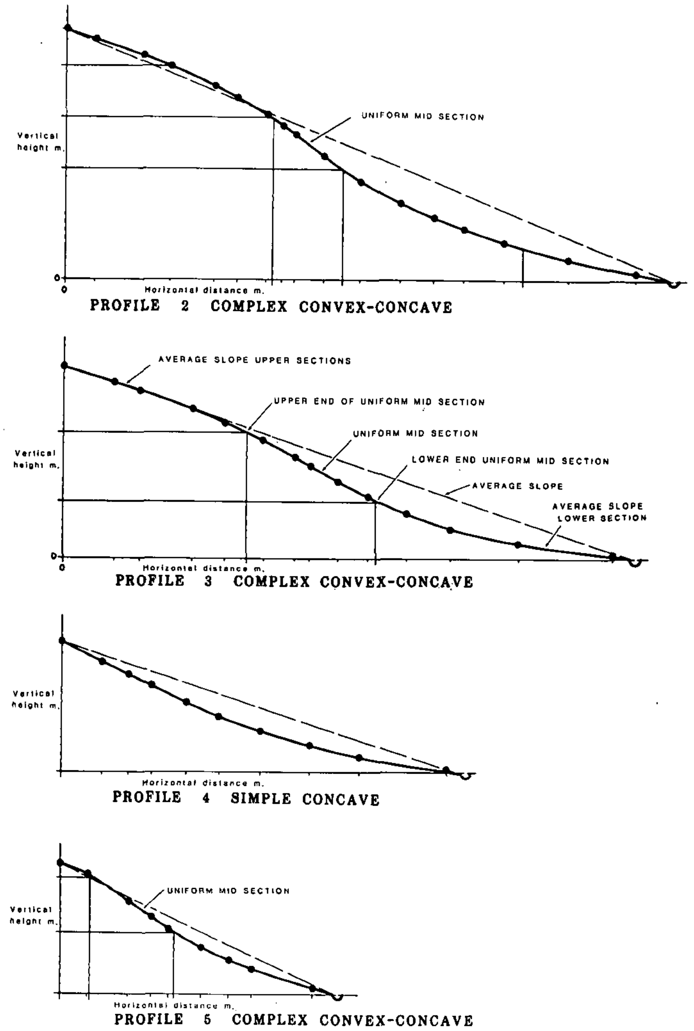

FIGURE 8 Profiles from field 4460 which were used to predict soil and water losses.

Soil depth and form were determined and samples were also taken to measure particle size.

Seven possible replanting practices were processed by the computer and the results are as shown in Table 3. The greatest soil losses occurred when the whole area was ploughed. Even though conventional protection measures such as terrace banks were used in one computer run excess losses were predicted. In this case some form of strip cropping would have provided additional protection. Not all the runoff during very heavy storms can be eliminated, and the column showing 'cane' in Table 3 is therefore an estimate of sugarcane losses which could probably be avoided if more rainfall was held on the land.

TABLE 3

Results of replant practices compared on field 4460 (per annum)

Practice	Soil t/ha	Water mm	'Cane'* tc/ha
All ploughed	150 - 250	90 - 100	7
All minimum tillage	80 - 92		
Strip ploughed	15	34	2
Strip minimum tillage	9	10 - 12	1 - 1,5
Terraces all ploughed	21 - 33	30	2
Terraces strip ploughed	10	12	1 - 1,5
Terraces strip minimum tillage	0,7	3	0,3

* Calculation assumes 80% of runoff water could have been avoided by a change in practice and 100 mm effective water = 9 tc/ha

The problems associated with implementing some of the replant systems may be unacceptable, but the consequences of using each type of field layout, are obvious.

Conclusions

The model can be run through a computer in a very short time and with few problems. Many of the input parameters are readily available. The topographic details are being produced as standard items for existing planning methods. In many cases, information on soils has to be extracted from different sources but if a central data bank could be established, there would be no need to search for parameters. Rainfall data are available as daily records but the number of stations recording rainfall intensity needs to be increased. Changes will undoubtedly be made to the model as experience increases but even in its present form, it is a significant step forward in predicting soil and water losses. The crop is an integral part of the system, so future recommendations for the control of soil, water and chemical losses must include replanting and other management practices. The present system of soil and water conservation, is based on terrace banks which are built at intervals determined by taking into account only the slope and soil type. A better and more comprehensive appraisal could be provided by the CREAMS model.

Acknowledgements

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APPENDIX I

Hydrology Parameters		**Erosion Parameters**	
Field area	SCS curve number AMC II	Kinematic viscosity	Manning n covered soil
Saturated hydraulic conductivity	Watershed L:W ratio	Mannings n soil Mannings n channel	Channel shape length outlet slope cover
Portion of plant available water storage filled at FC	Storage space 7 layers	Weight density soil	
Portion of plant available water storage filled start SIM	Depth surface layer	Soil erodibility channel	Critical shear stress (channel)
Soil evaporation	Depth root zone	Particle size distribution	Critical shear stress (cover)
Soil porosity	Effective capillary tension	Particle size class, density	Depth of non-erodible layer
Immobile water	Mannings roughness field surface	Overland flow, slope length average slope top slope mid slope bottom slope Co-ordinates mid slope	Channel width side slope
Average monthly temperature	Average field slope		Pond area/depth intake rate (co-efficient)
Average monthly radiation	Length of flow	Overland flow area	Intake rate
Winter cover		Soil erodibility (rill-interrill)	Pipe orifice diameter
SCS initial abstraction co-eff.		Cover management	Drainage area above pond
Channel slope		Contour factor	