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A PARAMETRIC MODEL TO ESTIMATE RUNOFF FROM SMALL AGRICULTURAL WATERSHEDS IN THE SEMI-ARID TROPICS*

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ABSTRACT

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Hydrologic data collected from small agricultural watersheds on Vertisols at I.C.R.I.S.A.T. were used to develop a parametric water-balance simulation model. Satisfactory prediction of runoff was obtained; other components of the water budget such as evapotranspiration and soil moisture can also be estimated. The model is designed to operate with limited input and facilitates the evaluation of the hydrologic responses of traditional and improved techniques of land management in relation to their effect on rainfall utilization for crop production.

INTRODUCTION

~~In the greater part of India, the rainy season lasts on an average from 4~~ to 5 months a year. During this period, the several high-intensity storms that occur cause large amounts of runoff and erosion on many soils, particularly under conditions of limited vegetative cover. Although solar radiation levels and temperatures permit year-round crop production, inadequate water availability frequently results in only one crop per year in rainfed areas; the erratic rainfall distribution often causes drought stress even to rainy-season crops. Improved estimates of runoff are an important prerequisite for the design of more effective land- and water-management systems. Runoff, if collected, stored, and used later for supplemental irrigation may also contribute to greater stability of rainy-season crops and expansion of the double-cropped area.

Because of the limited understanding of the hydrology of agricultural watersheds in the semi-arid tropics (SAT), several small research watersheds were developed at the International Crops Research Institute for the Semi-Arid Tropics (I.C.R.I.S.A.T.) near Hyderabad, India, in 1973. The data

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collected provide initial estimates of the design of waterways and structures for excess water disposal or storage of runoff. However, rainfall in the SAT varies greatly from year to year. A simulation model was therefore developed to estimate the occurrence of runoff and also to extrapolate the information gained to other areas. The available information in developing countries is often limited. Thus, a physically based model with minimal input data that would result in estimates of storm-runoff volumes was considered appropriate.

LAND TREATMENTS AND HYDROLOGIC DATA COLLECTION

The watershed treatments ranged from traditional methods to improved systems of resource management applied to a deep Vertisol. The Vertisols are dark-coloured soils with a high content of montmorillonitic clay; they have a low hydraulic conductivity and are often imperfectly drained (Kampen and Krishna, 1978). In large areas, it is common to fallow the land in the rainy season and to grow a crop on residual soil moisture, and this practice was simulated on one watershed (BW*4*C). The improved land-management methods consist of land smoothing and graded (0.6% slope) ridges or beds and furrows in order to provide adequate surface drainage during wet periods and simultaneously allow sufficient time for infiltration. With this watershed treatment on BW*1*, it was feasible to grow a rainy-season crop as well as a second crop in the postrainy season. A modification of this treatment (represented by BW*2*) was laid out in small fields surrounded by low embankments (bunds). These three treatments represented by BW*1*, BW*2* and BW*4*C were used to develop a simulation model for runoff prediction and water-balance analysis (Krishna and Hill, 1979). Another watershed at ~~the U.S.D.A.~~ Research Center in Texas (TW*13*) was also used for testing (C.W. Richardson, pers. commun., 1978). The watershed areas and respective land-management treatments are shown in Table I.

The rainfall in 1975 was above normal and that in 1976 below normal.

TABLE I

Land treatments on research watersheds

Watershed	Area (ha)	Location	Land treatment
BW*1*	3.4	Hyderabad	ridges and furrows
BW*2*	4.0	Hyderabad	ridges and furrows within farmers' field bunds
BW*4*C	3.5	Hyderabad	flat, fallowed in the rainy season
TW*13*	4.5	Riesel, Texas	ridges and furrows

The hydrologic data of these two years were therefore used for calibration, and the model was tested with 1974 data when rainfall was about normal at the I.C.R.I.S.A.T. Center. There was no runoff in 1977 and modeling work commenced in 1978. The total rainfall on individual watersheds was determined using a Thiessen network. Runoff was monitored by means of Parshall flumes and continuous waterstage recorders located at the watershed outlets. Soil-moisture measurements were made by the gravimetric method and also with a neutron probe. Daily pan evaporation data were used to compute the crop evapotranspiration demands.

MODEL DESCRIPTION

A parametric simulation model (RUNMOD) was developed to predict storm-runoff volumes and to compute other components of the water balance on a daily basis (Krishna, 1979). The daily input data required are rainfall amount, storm duration or rainfall intensity, and evaporation. If pan data are not available, empirical or other methods of determining crop evapotranspiration may be used. Information on the soil-moisture status at the beginning of the growing season and knowledge of the waterholding capacity of the soil are also required.

The model utilizes the concept of two soil-moisture zones, an upper zone of 20 cm and a lower zone of 160 cm. The daily evapotranspiration loss is assumed to exclusively occur from the upper zone initially; only after the moisture there is depleted, will evaporation loss occur from the lower zone. The soil-water budget is maintained on a daily basis and when rainfall is received, the upper zone is fully recharged before any moisture is added to the lower zone.

The evapotranspiration computation is similar to that used by Ligon et al. (1965) and Haan (1972):

$$\mathrm{AE_{cr}} = \mathrm{PE_{cr}}*(\mathrm{AW}/\mathrm{AWX}), \qquad P = 0; \quad M_\mathrm{u} = \mathrm{MUI} \tag{1}$$

$$\mathrm{AE_{cr}} = \mathrm{PE_{cr}}, \qquad P = 0; \quad \mathrm{MUI} < M_\mathrm{u} \leqslant \mathrm{MUX} \tag{2}$$

$$\mathrm{AE_{cr}} = 0.5*\mathrm{PE_{cr}}*(\mathrm{AW}/\mathrm{AWX}), \qquad P > 0; \quad M_\mathrm{u} = \mathrm{MUI} \tag{3}$$

$$\mathrm{AE_{cr}} = 0.5*\mathrm{PE_{cr}}, \qquad P > 0; \quad \mathrm{MUI} < M_\mathrm{u} \leqslant \mathrm{MUX} \tag{4}$$

where

$\mathrm{AE_{cr}}$ = actual crop evapotranspiration (mm)
$\mathrm{PE_{cr}}$ = potential crop evapotranspiration (mm)
AW = available moisture in lower zone on any given day (mm)
AWX = maximum available moisture in lower zone at field capacity (mm)
P = daily precipitation (mm)
M_u = moisture in upper zone on any given day (mm)

MUI = initial moisture content in upper zone (mm)
MUX = maximum moisture content in upper zone (mm)

An "infiltration index" (F) is computed on the basis of two parameters RIH and RIL, which refer to the "high" and "low" rates of infiltration. The higher value is assumed when the soil surface is totally dry, which corresponds to an MUI of 60 mm in the montmorillonitic-clay soils at I.C.R.I.S.A.T. The parameter RIL is used when the upper-zone moisture equals 90 mm (MUX). Finally, AWX is ~220 mm in these soils. Depending upon the value of M_u on any given day, the infiltration index F (mm/hr.) for a given storm is computed according to one of the following relationships:

$$F = \text{RIH}, \qquad M_u = \text{MUI} \tag{5}$$

$$F = \text{RIL}, \qquad M_u = \text{MUX} \tag{6}$$

$$F = \text{RIH} - [(\text{RIH} - \text{RIL}) * \{(M_u - \text{MUI})/(\text{MUX} - \text{MUI})\}], \quad \text{MUX} > M_u > \text{MUI} \tag{7}$$

During heavy rainfall, the infiltration index F obtained from the above equation is used with the storm duration (in hours) to obtain the infiltrated amount INF:

$$\text{INF} = \text{F} * \text{SD} \tag{8}$$

where

INF = infiltration depth (mm)
F = infiltration index (mm/hr.)
SD = storm duration (hr.)

The computed storm runoff CRO (mm) is then computed as:

$$\text{CRO} = P - \text{INF} \tag{9}$$

where the terms are as defined earlier, and $P > \text{INF}$.

The computed runoff and the measured runoff data are compared through a simple univariate optimization procedure to select the values of RIH and RIL. The values of RIH and RIL were identified from 2-yr. data (1975, 1976) and the model was tested with data of the third year (1974). Even though the model uses a lumped approach, it nevertheless predicts surface runoff with a fair degree of accuracy. Further refinement of the model is possible with additional hydrologic data.

RESULTS AND DISCUSSION

Parameter calibration with data from BW*1* collected in 1975 and 1976 resulted in values of 34 and 27 mm/hr. for RIH and RIL, respectively. When these values were used with 1974 data for testing, an accurate estimate of 112 mm of runoff was obtained (the measured amount was 114 mm). Comparison (Fig. 1A) shows a reasonable similarity between computed and observed individual storm-runoff events. In the case of BW2, there were some measurement errors during 1974, and therefore 1976 data were used for calibration and the model was tested with data from 1975. The calibrated values for RIH and RIL were 38 and 33 mm/hr., respectively. Upon testing

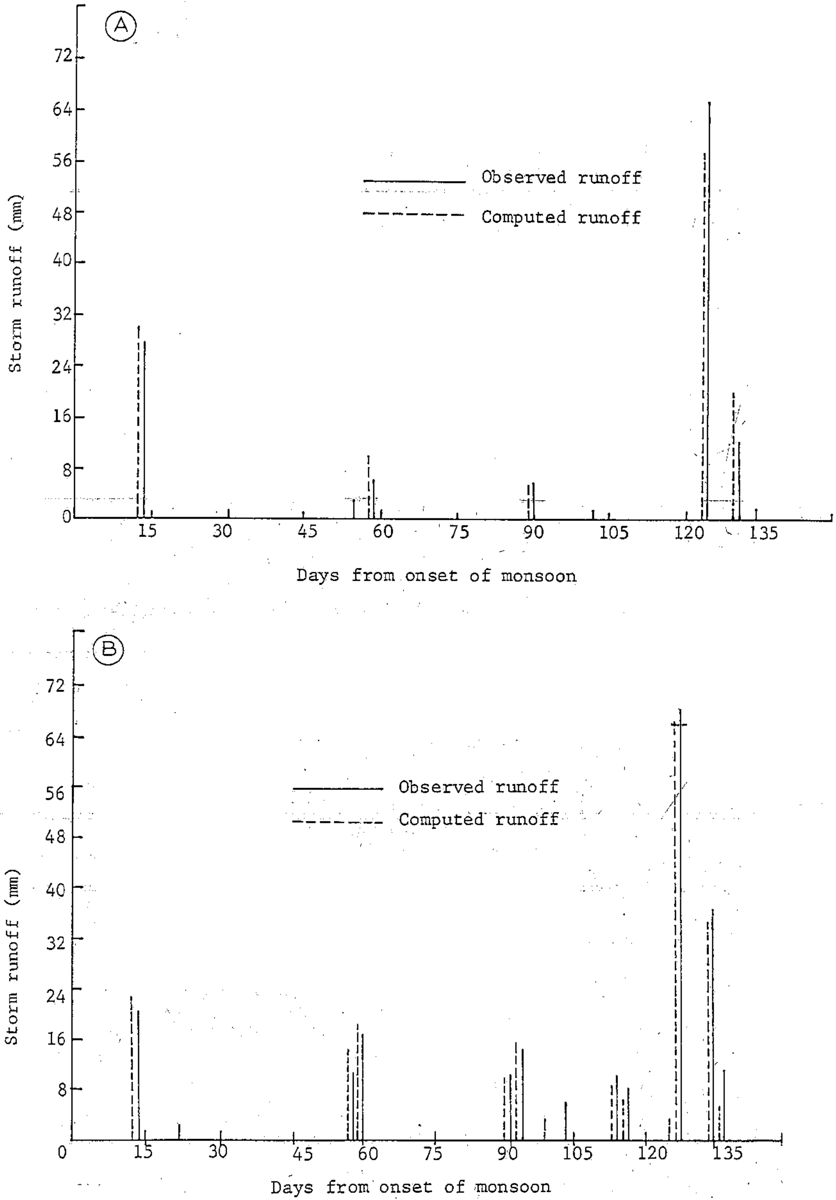

Fig. 1. Comparison of observed and computed runoff events in: (A) watershed BW*1*; and (B) watershed BW*4C*.

with these values, a runoff of 134 mm was predicted, while the measured runoff was 124 mm. The computed and measured runoff values in BW2 were not as close as in BW*1*. The fact that BW2 has several field bunds that intercept varying amounts of runoff may explain the difference. For BW*4*C, the

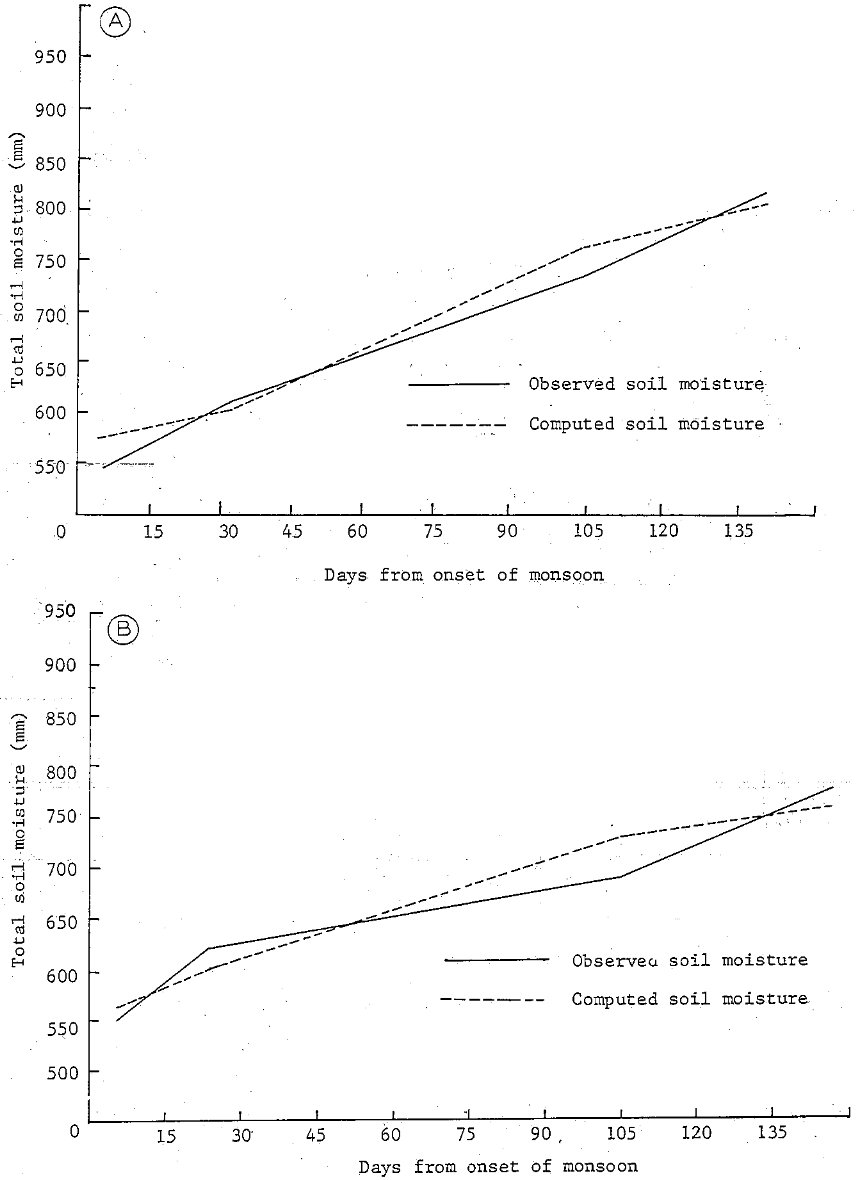

Fig. 2. Observed and computed soil-moisture variation in: (A) watershed BW*1*; and (B) watershed BW*4*C.

calibrated parameter values were respectively 21 and 16 mm/hr. When tested with these values, the runoff of 204 mm estimated for 1974 compared quite well with the measured amount of 210 mm. The comparison of individual storm events for BW*4*C is illustrated in Fig. 1B; estimated and measured values are closely correlated. To test the model's capability to simulate the soil-moisture variation, the measured soil-moisture data were compared with those computed by the model. The estimated and measured soil-moisture variations in BW*1* and BW*4* during the 1974 rainy season are shown in Fig. 2A and B, respectively; they also match well.

To further verify the model, it was applied to hydrologic data collected in 1971 and 1972 from similar soils in Texas. Satisfactory results were obtained in predicting runoff and the calibrated parameters were approximately of the same magnitude as those of I.C.R.I.S.A.T. watersheds with land-management treatments similar to the Texas watershed. These results demonstrate that parameter values determined at a given location may be used at similar sites elsewhere to predict runoff. Thus, transferability of research findings from one location to another is facilitated.

The objective function (r^2) is computed as:

$$\mathrm{RSQ} = [\Sigma(\mathrm{MRO}^2) - \Sigma(\mathrm{DIF}^2)]/\Sigma(\mathrm{MRO}^2)$$

and the mass balance (MB) is computed as:

$$\mathrm{MB} = [\{(\Sigma\mathrm{CRO} - \Sigma\mathrm{MRO})^2\}^{1/2}/\Sigma\mathrm{MRO}]$$

where

MRO = measured runoff (mm)
CRO = computed runoff (mm)
DIF = difference between each computed and measured runoff event (mm)

TABLE II

Results of the storm-runoff simulation model RUNMOD

Watershed	Calib./test.	Rainfall (mm)	RIH (mm/hr.)	RIL (mm/hr.)	Computed runoff (mm)	Measured runoff (mm)	RSQ	MB
BW*1*	calib.	1,613.0	34	27	225.6	228.3	0.994	0.012
BW*1*	test.	775.9	34	27	112.3	114.1	0.972	0.015
BW*2*	calib.	648.1	38	33	37.7	42.9	0.978	0.122
BW*2*	test.	964.9	38	33	134.3	124.2	0.989	0.082
BW*4*C	calib.	1,632.7	21	16	471.2	459.0	0.975	0.027
BW4C	test.	774.2	21	16	204.1	210.3	0.974	0.029
TW*13*	calib.	489.0	35	29	7.9	11.3	0.764	0.289
TW*13*	test.	549.4	35	29	20.8	28.3	0.970	0.264

RIH = infiltration parameter — high value; RIL = infiltration parameter — low value; RSQ = *R* square; MB = mass balance.

The results of the storm-runoff model RUNMOD are summarized in Table II. It is apparent from the results presented that the model's estimates of runoff are much more accurate when the storm data collected at I.C.R.I.S.A.T. are considered. This is probably due to the fact that most runoff-producing storms recorded at I.C.R.I.S.A.T. were of a high intensity and generally of short duration. For rainfall events of this nature, storm duration, which is an important input in the model, can be computed from the hyetographs with relative ease.

WATER-BALANCE ESTIMATES

Besides providing a reliable method of estimating runoff from small watersheds, the model was used to compute the water balance under traditional and improved systems of land and water management.

A summary of the water-balance results is shown in Table III. For watershed BW*4*C with traditional cropping in the postrainy season, 42% of the seasonal precipitation was lost as evaporation from bare soil during the wet season; the computed runoff was 28%, the profile moisture accretion amounted to 23% and the deep percolation was 7%. In the ridged treatment, executed within field bunds (BW2), 42% of the precipitation was used for evapotranspiration, 11% was computed as runoff, 19% contributed to profile accretion, and 28% was lost as deep percolation. In the graded ridge-and-furrow system without field bunds and with a well-defined grassed waterway (BW*1*), the corresponding figures for evapotranspiration, computed runoff, profile moisture accretion, and deep percolation were 45%, 14%, 22% and 19%, respectively. Figures of this order have also been reported in other studies at I.C.R.I.S.A.T. Center (I.C.R.I.S.A.T., 1975—1976, 1976—1977, 1977—1978).

TABLE III

Water-balance summary of three I.C.R.I.S.A.T. watersheds

Watershed	Units	Rainfall*, RF	ET	Computed runoff	Measured runoff	Deep percolation	Soil moisture accretion
BW*1*	(mm)	2,388	1,072	338	342	445	533
BW*1*	(% of RF)	100	45	14	14	19	22
BW2	(mm)	1,613	678	172	167	450	313
BW2	(% of RF)	100	42	11	10	28	19
BW*4*C	(mm)	2,406	1,007	675	669	179	545
BW*4*C	(% of RF)	100	42	28	28	7	23

*Three monsoon seasons for BW*1* and BW*4*C, two seasons for BW2.

No crop was grown in the rainy season on the traditionally managed watershed (BW*4C*), yet the moisture loss from bare soil was quite high due to frequent wetting of the soil surface. The deep percolation losses on BW*4C* were less than those in BW*1*. This reflects the fact that a substantial part of the rainfall on BW*4C* was lost as surface runoff (twice as much as BW*1*). The capacity of the model to compute all components of the water balance facilitates an evaluation of hydrologic response and rainfall utilization potential of traditional and improved land- and water-management systems.

CONCLUSIONS

A parametric model has been developed to estimate storm-runoff volumes for small agricultural watersheds. The model is physically based and appears promising under tropical situations. The model parameters appear to be transferable between similar sites, which will be helpful in runoff predictions for new locations. It is now intended to further test the model with more data, initially from deep Vertisols and later from other soils. This process will assist in the refinement of the model enabling its use for wider application.

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