Estimation of runoff at Glen in the Free State Province of South Africa

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Abstract

Reliable runoff estimation is important for simulating long-term crop yields in semi-arid areas. It requires reliable data including soil and rainfall characteristics. This paper aims to simulate runoff for each rainfall event on the Glen/Tukulu ecotope, in central South Africa, using annual runoff data measured over 18 years (1937 to 1955) on a conventional tilled soil, annually planted to maize, and a bare untilled soil. Runoff calculated for these two treatments provides information needed to simulate long-term crop yields using conventional tillage and in-field water harvesting. The PutuRun model was used to stochastically disaggregate daily rainfall data into shorter duration rainfall intensities and to simulate runoff for each rainfall event during a particular season. The simulated runoff data were summed for each season and compared with the observed annual runoff values during the respective years to evaluate the performance of the model. The model was calibrated using half of the data and validated using the rest. Calibration was carried out by running the model a number of times with a different set of input parameter values, until acceptable results were obtained. The following statistical results were obtained for the validation tests: for the maize plots index of agreement (d) = 0.85, root mean square error (RMSE) = 24 mm, mean absolute error (MAE) = 18 mm, systematic RMSE (RMSEs) = 16 mm, unsystematic RMSE (RMSEu) = 17 mm, and coefficient of determination (r^2) = 0.58; and for the bare plots d = 0.90, RMSE = 51 mm, MAE = 48 mm, RMSEs = 13 mm, RMSEu = 49 mm, and r^2 = 0.74. It is concluded that the PutuRun Model can be used with reasonable confidence after calibration to simulate long-term runoff on conventionally tilled, and bare untilled plots on the Glen/Tukulu ecotope using daily rainfall data. This procedure is expected to yield satisfactory results on other ecotopes with similar soil, slope, and rainfall characteristics.

Keywords: Glen, modelling, PutuRun, runoff

Introduction

In arid and semi-arid areas long-term modelling of agricultural productivity is a valuable tool in agricultural research, land evaluation and production planning. This requires reliable estimates of the components of the soil water balance: rainfall, runoff, deep drainage and evapotranspiration (Jury et al., 1991). Runoff is particularly important for comparing crop yields using conventional tillage and in-field rain-water harvesting (IRWH). Runoff is considered a loss in conventional tillage and can be made into a profit using IRWH (Hensley et al., 2000). It is, however, often difficult to estimate runoff reliably. Bennie et al. (1998), after many years of research on the soil water balance, admitted that much more research is needed to estimate runoff reliably. Runoff estimation is complex because it is affected by several factors including rainfall intensity, slope of the land, initial and final infiltration rates, roughness of the surface, initial soil water content, crust formation, land use, and land cover (Morin and Benyamini, 1977; Allen et al., 1998). Bennie et al. (1998) indicated that, if surface storage is ignored, runoff during a rainstorm normally starts to take place when the rainfall intensity exceeds the infiltration rate of the soil. Accurate estimation of runoff therefore requires rainfall intensity (Pi) data and reliable data for the factors mentioned. Where Pi is not available daily rainfall has to be used. Seeking a relationship between daily rainfall and runoff is therefore important, making the results of long-term runoff experiments particularly valuable. This is especially true in semi-arid areas where a considerable fraction of annual rainfall occurs as high-intensity thunderstorms, and where soils tend to crust. Both these conditions occur at Glen.

In a study on a red loamy fine sand surface soil with a 5% slope at Glen (Glen/Tukulu ecotope) with a mean annual rainfall (MAR) = 545 mm, Du Plessis and Mostert (1965) measured runoff and soil loss for 18 years (1937 to 1955) on runoff plots. They reported mean annual runoff of 8.5% and 31.9% of the mean annual rainfall from the plots under continuous maize cultivation, and from the untilled, crusted bare plots respectively. In a study under similar soil and slope conditions to those of Du Plessis and Mostert (1965), over a period of 27 years at Pretoria (MAR = 730 mm), Haylett (1960) reported runoff of 26.7% and 49.4% of the mean annual rainfall from continuous maize and from untilled, crusted, bare soil respectively.

Gibbs et al. (1993) reported annual runoff measurements from bare plots at Cedara over 10 years. The soil was classified as an Inanda form with a clay texture. The correlation between annual runoff and annual rainfall was poor (r^2 = 0.44). Mean annual runoff was 15% of the mean annual rainfall. These values are considerably different from those obtained at Glen and Pretoria. The following are probable reasons: Firstly, rainfall at Cedara includes a considerable amount of soft rain, and secondly, because the Inanda soil is highly weathered, high in clay and high in organic matter, very little crusting is expected, and the final infiltration rate is expected to be relatively high. Both these factors will reduce runoff.

Hensley et al. (2000) found that the final infiltration rate (I_f) on two ecotopes at Glen (Glen/Bonheim and Glen/Swartland) was approximately 6 mm·h^{-1}, and that runoff occurred on a crusted flat

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TABLE 1
Runoff as a percentage of rainfall on the Glen/Bonheim and Glen/Swartland ecotopes, with 1% slope, for bare, untilled, crusted flat surfaces; and for annually tilled surfaces (Hensley et al., 2000)

	Season	Rain (mm)	Runoff (%)	
			Glen/ Bonheim	Glen/ Swartland
Bare, untilled, crusted flat surfaces	1996/97	452	19	31
	1997/98	589	14	18
	1998/99	462	13	13
Annually tilled surfaces	1997/98	589	6	7
	1998/99	462	2	1

surface (negligible surface storage) when *Pi* exceeded this value. It is therefore reasonable to expect that where *Pi* data are available, runoff on similar surfaces on similar ecotopes should be correlated with the amount of rainfall during any event that exceeds 6 mm·h^{-1}. Results of runoff measurements made by Hensley et al. (2000) on the Glen/Bonheim (GB) and Glen/Swartland (GS) ecotopes, with 1% slope, for three seasons from bare, untilled, crusted flat surfaces, and for two seasons from annually tilled surfaces, are given in Table 1.

On both ecotopes runoff was found to be negligible for rainfall events of less than 8 mm. These results demonstrate clearly the large influence of crusting combined with the absence of surface storage on runoff.

McPhee et al. (1983) measured runoff, to assess erodibility, on a wide range of South African soils used for crop production. They simulated rainfall with a large rotating-boom simulator which delivered a constant intensity of approximately 63 mm·h^{-1}. Two 1h storms separated by a 24 h period were applied to two adjacent plots with different surface conditions. Both were initially tilled up and down the slope to produce a suitable tilth for a seedbed. One of the plots was covered with mulch and the other left bare. Runoff, expressed as a percentage of the 'rainfall' applied (RP), was measured for each of the two 'storms'. For some soils with fairly coarse textured topsoils and gentle slopes (<5%), RP was frequently very low and sometimes zero. This indicates that I_f was greater than the constant application rate of around 63 mm·h^{-1}. On the same soils RP for the second storm was generally far higher, amounting in some cases to more than 70%. Average I_f values for the second storm on seven soils of the Hutton form ranged from 20 to 50 mm·h^{-1}. These results demonstrate the large influence of crusting and antecedent soil water content on I_f. On the non-crusted dry soil and during the first storm, I_f was much higher than on the partially crusted wet soil during the second storm due to the combined action of these two factors.

Snyman and Van Rensburg (1986) measured runoff from natural veld with different plant densities using a rainfall simulator which gave a *Pi* value of approximately 63 mm·h^{-1}. Two 'storms', separated by 24 h, were simulated; the duration of each presumably being one hour. The crust on the gently sloping sandy clay loam Valsrivier Arniston soil (MacVicar et al., 1977) would most likely have been developed to its maximum extent on the undisturbed veld. For the first storm RP values ranged from 30% for the well vegetated plots (climax vegetation) to 70% for the plots with a poor cover (pioneer vegetation). RP values for the second storm were considerably higher. Comparing these results with those of McPhee et al. (1983), for soils with similar topsoil texture and on similar slopes, demonstrates the importance of crusting on I_f and therefore runoff.

This paper discusses the calibration and validation of the PutuRun model (Walker and Tsubo, 2003b) using annual Glen/Tukulu ecotope runoff data for 18 years (Du Plessis and Mostert, 1965) and daily rainfall for that period.

Materials and methods

Site description and data collection

The runoff experiment site is located at Glen, a semi-arid area in the Free State Province of South Africa. The mean annual rainfall of the area is 545 mm and the aridity index (rainfall/ potential evaporation) is 0.24. The site is located on a mid-slope terrain unit with a straight, 5% slope in a south-easterly direction. The soil was described (Zere, 2003) and classified as Tukulu Dikeni (Soil Classification Working Group, 1991). The topsoil, which is of major importance for runoff characteristics, consists of reddish brown loamy fine sand with 11.2% clay. Du Plessis and Mostert (1965) conducted long-term runoff measurements with different plant covers and cultivation practices on this ecotope, using 2.7 m x 30.5 m runoff plots. Only annual runoff values, and not those for each rainfall event, were reported. Among the various treatments were one with conventional tillage annually planted to maize, and one with a bare, untilled soil. This paper focuses on these two treatments because they provide the information needed to simulate long-term crop yields using two different production techniques, viz. conventional tillage, and the in-field rainwater harvesting technique, which would enable effective comparison between the two techniques. Results obtained by Du Plessis and Mostert (1965) for the two treatments are presented in Fig. 1. The y-axis units (inches) used by Du Plessis and Mostert (1965) have been converted to mm for this study.

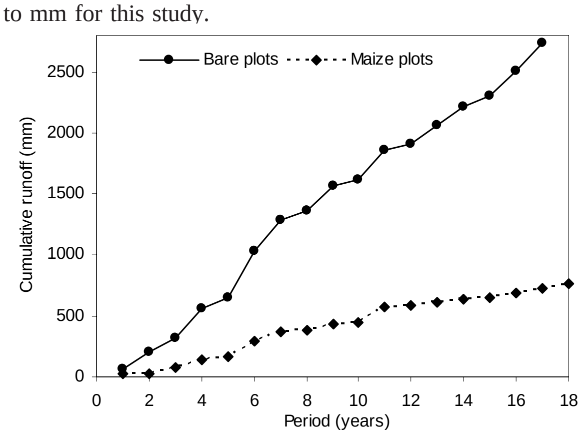

Figure 1
Long-term (1937/38-1954/55) cumulative runoff graphs for bare, and conventionally tilled annual maize plots (after Du Plessis and Mostert, 1965; y-axis units given in mm, instead of inches as used by the authors)

Runoff estimation procedure

Annual runoff from conventionally tilled maize plots and from bare plots was interpolated from the graphs presented in Fig. 1. Results

TABLE 2
Measured annual runoff for the Glen/Tukulu ecotope (Du Plessis and Mostert, 1965)

Season	Rainfall[1]	Maize plots runoff		Bare plots runoff	
	(mm)	(mm)	% of rain	(mm)	% of rain
1937/38	325	21	6	64	20
38/39	464	7	2	139	30
39/40	579	43	7	121	21
40/41	642	71	11	235	37
41/42	421	22	5	96	23
42/43	915	135	15	380	42
43/44	730	64	9	249	34
44/45	409	14	3	82	20
45/46	539	55	10	199	37
46/47	349	16	5	57	16
47/48	706	128	18	235	33
48/49	213	7	3	57	27
49/50	531	29	5	142	27
50/51	550	21	4	164	30
51/52	336	14	4	85	25
52/53	496	43	9	207	42
53/54	582	34	6	220	38
54/55	510	44	9	-	-
Mean	**516**	**43**	**7**	**161**	**29**

[1] Measured rainfall from the ARC-ISCW climate database.

are presented in Table 2. Ten and nine seasons were randomly selected from the maize and bare plots respectively, and were used to calibrate the PutuRun Model. The remaining seasons were used for validation. Daily rainfall was used as input for the model. The model first generated rainfall intensity for each rainfall event using the Huff curve procedure.

Based on the work of Bonta (1997), Walker and Tsubo (2003a) used the Huff curve procedure to generate long-term rainfall intensity probabilities from long-term daily rainfall data. The procedure is based on dimensionless hyetographs, which are curves of dimensionless rainfall amount vs. dimensionless rainfall duration. Huff curves are frequency curves obtained from dimensionless hyetographs, which can be developed for a particular site using relatively short-term rainfall intensity data. Once the rainfall pattern for a particular site has been characterised using this procedure, it can be applied to long-term daily rainfall data to provide long-term intensity data. The procedure generates rainfall intensity in a stochastic manner; each time the model is run, a slightly different set of data is generated. As the temporal variation of rainfall within a rainfall event is highly variable and therefore not predictable, a stochastic model is appropriate for generating the data (Bonta, 1997). Walker and Tsubo (2003a) used rainfall intensity data for 30 years for Bloemfontein to develop and successfully validate the model. It was also found to predict rainfall intensity in a satisfactory manner for Pretoria. Because Glen is situated close to Bloemfontein (20 km) it is reasonable to assume that the model will also predict rainfall intensity in a satisfactory way for Glen.

The model was then run again, using the generated rainfall intensity and some soil parameters as input, to estimate runoff for each rainfall event using the Morin and Cluff (1980) runoff equation.

Morin and Cluff (1980) proposed Eq.(1) to calculate the total infiltration for bare, crusting soils during any one time segment of a storm with specified rainfall intensity, based on the infiltration equation of Morin and Benyamini (1977):

$$I_k = I_f \Delta t_k + \frac{(I_i - I_f)}{-\gamma P_k}\left[\exp(-\gamma D_k) - \exp(-\gamma D_{k-1})\right] \quad (1)$$

where:

I_k = total infiltration during any period k (mm)
P_k = rainfall intensity during period k ($mm \cdot h^{-1}$)
D_k = $\Sigma P_k \Delta t_k$, the total amount of rainfall during period k (mm)
I_i = initial infiltration rate of the soil ($mm \cdot h^{-1}$)
I_f = final infiltration rate of the soil ($mm \cdot h^{-1}$)
Δt_k = $t_k - t_{k-1}$ (a given period, h)
γ = soil coefficient related to aggregate stability during crust formation (mm^{-1})

Equation 1 enables computation of runoff (R_k) for any storm for which rainfall intensity is available, time step by time step, using Eq. (2) (Morin and Cluff, 1980).

$$R_k = D_k - I_k - (SD_{max} - SD_{k-1}) \quad (2)$$

where:

R_k = surface runoff during period k of the storm (mm)
D_k = total amount of rainfall during period t_k (mm)
I_k = total infiltration during period t_k (mm)
SD_{max} = maximum surface storage and detention for the soil (mm)
SD_{k-1} = surface storage and detention in the previous period Δt_{k-1} (mm)

The total runoff per rainfall event is therefore given by the sum of all R_k values for all periods during the rainfall event. Equation 2 assumes that total evaporation is negligible during the storm event.

Aided by a programmer, Walker and Tsubo (2003b) developed a composite model called PutuRun by combining the Huff curve rainfall intensity generator, Eqs. (1) and (2), and the Putu Crop Model (De Jager et al., 2001). PutuRun enables the estimation of runoff from daily rainfall data for a site where the Huff curve procedure has been validated, and where values are available for the parameters needed for the Morin and Cluff (1980) model.

Maize plots

Calibration was carried out repeatedly by changing the model parameters required by Eq. (2). The following initial values were chosen: $I_i = 25\ mm \cdot h^{-1}$; $I_f = 10\ mm \cdot h^{-1}$; $\gamma = 0.2\ mm^{-1}$; $SD_{max} = 10$ mm. The selection was guided by previous experience of runoff measurements made at Glen (Hensley et al., 2000). The model was then run a number of times, each time changing one of the above parameters while keeping the rest constant. The output runoff values per rainfall event were added for each season and compared with the measured value for the same season. This procedure was repeated for each calibration season until all the possible combinations of 'reasonable' parameter values had been tested. The parameter combination that statistically (Willmott, 1982) produced the best runoff estimates for the ten calibration seasons was selected to validate the model. The initial input for the validation process was the daily rainfall for the eight remaining seasons. The PutuRun Model calculated rainfall intensity from these and then proceeded to estimate runoff using the 'best fit' parameters for the Morin and Cluff (1980) runoff sub-routine selected during the calibration process. Estimated and observed annual runoff values were com-

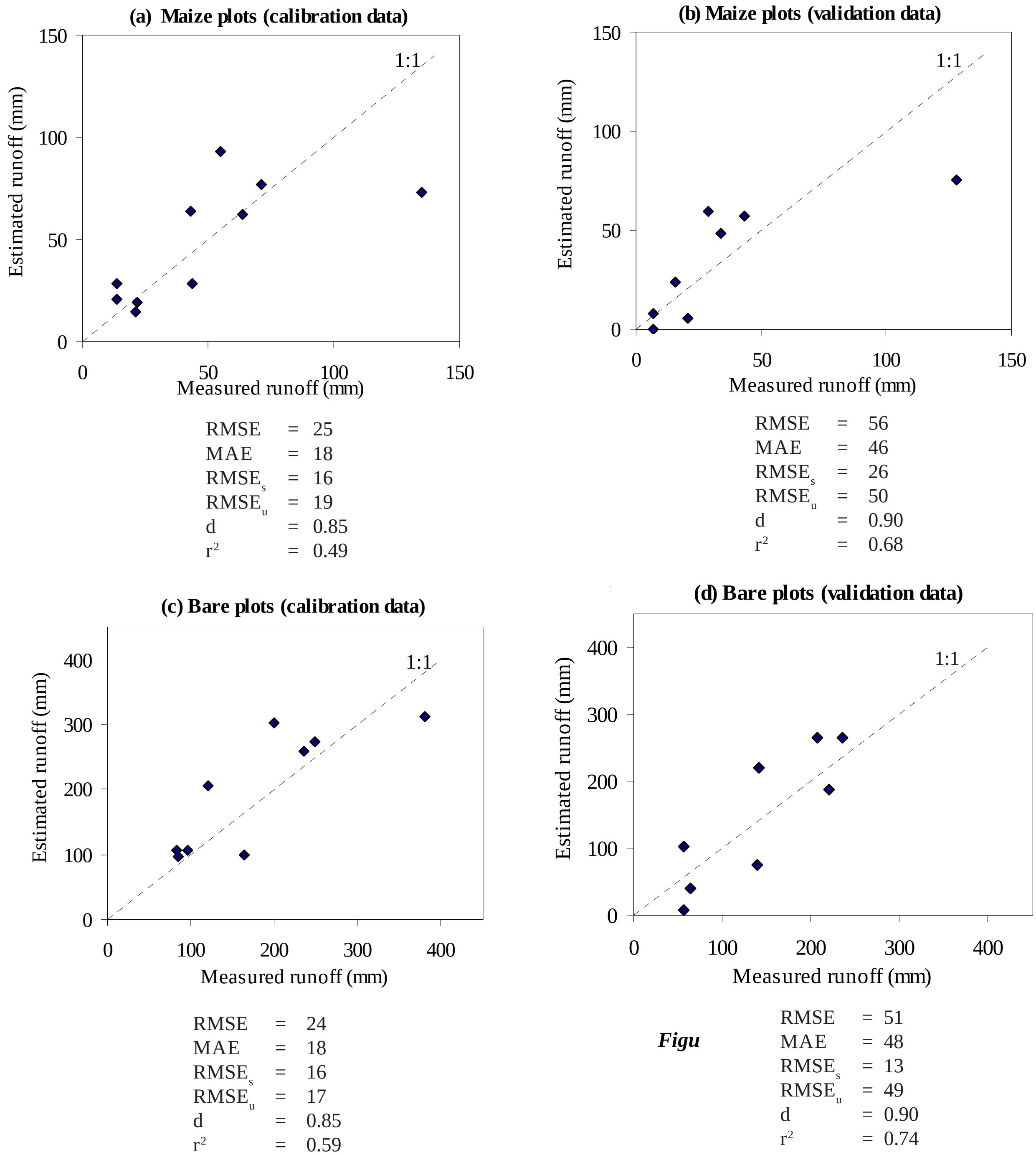

Figure 2
PutuRun estimated vs. measured annual runoff for maize plots (a & b), and for bare plots (c & d) on the Glen/Tukulu ecotope

pared using the statistical measures for evaluating model performance suggested by Willmott (1982), namely, index of agreement (*d*), mean absolute error (MAE), root mean square error (RMSE) together with its systematic (RMSEs) and unsystematic (RMSEu) components, and the coefficient of determination (r^2). Results are presented in Fig. 2.

Bare plots

The calibration procedure was basically the same as that used for the maize plots. The following initial values for Eq. (2) were selected: $I_i = 25$ mm·h^{-1}; $I_f = 10$ mm·h^{-1}; $\gamma = 0.2$ mm^{-1}; $SD_{max} = 1$ mm. The surface storage was reduced from the 10 mm used for the annually tilled maize plots to 1 mm for the bare, probably flat, crusted surface of these plots. This was assumed to be the major difference between the two sets of plots. The procedure described for the maize plots was then followed until the 'best fit' set of parameters was identified. The validation procedure was as for the maize plots. Results are presented in Fig. 2.

Results and discussion

The 'best fit' parameters for Eq. (2) for the maize and bare plots were found to be the following: Maize plots: $I_i = 25$ mm·h^{-1}; $I_f = 10$

mm·h^{-1}; γ = 0.2 mm^{-1}; and SD_{max} = 6 mm; bare plots: I_i = 25 mm·h^{-1}, I_f = 5 mm·h^{-1}, γ = 0.2 mm^{-1}, and SD_{max} = 0.1 mm. Calibration and validation results are presented in Fig. 2 as well as the statistical tests of reliability.

The scatter plots and statistical values indicate that the model can estimate annual runoff fairly well for both kinds of plots on the Glen/Tukulu ecotope. The model estimates runoff more accurately from the bare soil than from the conventionally tilled soil. This is to be expected since the value for I_f and SD would probably be different every season due to differing rates of crust formation caused by different early season rainfall patterns, and the different degrees of surface roughness caused by inevitable differences in cultivation at the start of each season. In the bare, untilled, crusted soil these two factors would be absent, and therefore one can expect I_f and SD to be reasonably constant.

In the case of the maize plots, PutuRun appears to underestimate runoff during excessively wet years. For instance, during the wet seasons of 1942/43 (total rainfall = 915 mm) and 1947/1948 (total rainfall = 706 mm) the estimated annual runoff values were considerably lower than the observed values, i.e. 73 mm vs.135 mm in 1942/43, and 75 mm vs. 128 mm in 1947/48. The rainfall in both these seasons is far above the long-term average of 545 mm for Glen. The failure of the Morin and Cluff (1980) model for these very wet seasons may be due to unsatisfactory soil parameters for large storms, especially if they should occur close together. It needs to be kept in mind that the runoff model was designed for semi-arid areas where rainfall events are generally reasonably far apart. However, in spite of these shortcomings the statistical evaluation for the maize plots gives reasonably satisfactory results with d = 0.85, r^2 = 0.59, MAE = 18 mm and RMSEu as a percentage of RMSE slightly low at 71%. The model gave reliable estimates of runoff from the bare plots. This is shown by the statistical results of the validation procedure: d = 0.90, r^2 = 0.74, MAE = 48 mm and RMSEu a satisfactory 96% of RMSE.

Conclusion

It is shown that the PutuRun Model can be used with reasonable confidence to predict event runoff using daily rainfall data on the Glen/Tukulu ecotope on conventionally tilled and bare, untilled plots. This is very helpful in modelling the long-term soil water balance and, therefore, making long-term yield predictions for this ecotope and others with similar rainfall characteristics, and with similar slopes and soils. For example long-term comparisons between the in-field water harvesting, no-till, basin tillage production technique proposed by Hensley et al. (2000) can be compared with conventional tillage using this procedure.

References

ALLEN RG, PEREIRA LS, RAES D and SMITH M (1998) Crop evapotranspiration: Guidelines for computing crop water requirements. *FAO Irrig. Drain. Paper* **56** FAO, Rome.

BENNIE ATP, STRYDOM MG and VREY HS (1998) The Application of Computer Models for Agricultural Water Management at Ecotope Level [Afrikaans, with English abstract]. WRC Report No. 625/1/98. Water Research Commission, Pretoria.

BONTA JV (1997) Proposed use of Huff curves for hyetograph characterization. In: Richardson CW et al. (eds.) *Proc. Workshop on Climate and Weather Research*. Denver, Colorado. 17-19 July 1995. United States Department of Agriculture - Agricultural Research Service, 1996-03.

DE JAGER JM, MOTTRAM R and KENNEDY JA (2001) Research on a Computerised Weather-Based Irrigation Water Management System. WRC Report No. 581/1/01. Water Research Commission, Pretoria.

DU PLESSIS MC and MOSTERT JWC (1965) Runoff and soil losses at the Agricultural Research Centre, Glen. [Afrikaans, with English summary]. *S. Afr. J. Agric. Sci.* **8** 1051-1061.

GIBBS MD, RUSSEL WB and KLOPPERS PP (1993) Erosion Studies Using Natural Runoff Plots. Annual report on Research Facet No. N5711/38/1/1 to the Department of Agriculture, Republic of South Africa.

HAYLETT DG (1960) Runoff and soil erosion studies at Pretoria. *S. Afr. J. Agric. Sci.* **3** 379-394.

HENSLEY M, BOTHA JJ, ANDERSON JJ, VAN STADEN PP and DU TOIT A (2000) Optimizing Rainfall Use Efficiency for Developing Farmers with Limited Access to Irrigation Water. WRC Report No. 878/1/00. Water Research Commission, Pretoria.

JURY WA, GARDNER WR and GARDNER WH (1991) *Soil Physics*. John Wiley & Sons, New York.

McPHEE PJ, SMITHEN AA, VENTER CJ, HARTMANN MO and CROSBY CT (1983) The South African rainfall simulator programme for assessing soil loss and runoff. In: Maaren H (ed.) *Proc. S. Afr. Natl. Hydrol. Symp.* Department of Environment Affairs, Pretoria. Technical Report No. TR119.

MACVICAR CN, DE VILLIERS JM, LOXTON RF, LAMBRECHTS JJN, LE ROUX J, MERRYWEATHER FR, VAN ROOYEN TH, VON M HARMSE HJ and VERSTER E (1977) Soil Classification: A Binomial System for South Africa. Department of Agricultural Technical Services, Pretoria.

MORIN J and BENYAMINY Y (1977) Rainfall infiltration into bare soils. *Water Resour. Res.* **13** 813-817.

MORIN J and CLUFF CB (1980) Runoff calculation on semi-arid watersheds using a rotadisk rainulator. *Water Resour. Res.* **16** 1085-1093.

SNYMAN HA and VAN RENSBURG WLJ (1986) Effect of slope and plant cover on runoff, soil loss and water use efficiency of natural veld. *J. Grassl. Soc. South. Afr.* **3** (4) 153-158.

SOIL CLASSIFICATION WORKING GROUP (1991) Soil classification – A taxonomic system for South Africa. *Mem. Agric. Natl. Resour. S. Afr*. No. 15. Department of Agricultural Development, Pretoria.

WALKER S and TSUBO M (2003a) Estimation of Rainfall Intensity for Potential Crop Production on Clay Soil With In-Field Water Harvesting Practices in a Semi-Arid Area. WRC Report No. 1049/1/02. Water Research Commission, Pretoria.

WALKER S and TSUBO M (2003b) PutuRun: A Simulator for Rainfall-Runoff-Yield Processes with In-Field Water Harvesting. WRC Report No. K8/486. Water Research Commission, Pretoria.

WILLMOTT CJ (1982) Some comments on the evaluation of model performance. *Bull. Am. Meteorol. Soc.* **63** 1309-1313.

ZERE TB (2003) Evaluating Maize Production Potential of Selected Semi-Arid Ecotopes using a Water Balance Model. M.Sc. Agric. Dissertation, University of the Free State, Bloemfontein.