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Simulation of direct runoff volumes and peak rates for rural catchments in Kenya, East Africa

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Abstract Estimation of direct runoff volume and peak runoff rates for small rural catchments in Kenya, East Africa, poses a problem in view of the limited gauged data available. The problem can be circumvented by adopting a modelling approach. This, however, does require some base data for model calibration and validation. A highly reliable data base for two small catchments, Sambret (7.02 km^2) and Lagan (5.44 km^2), for nearly 22 years (1958-1980) is used in the present study. These catchments lie in the headwaters of the Lake Victoria drainage basin in Kenya and were intensively instrumented by the former East African Agricultural and Forestry Research Organisation (EAAFRO). In the Sambret catchment, 41 rainfall-runoff events were available, out of which 25 were used for model calibration while the other 16 were used for validation. To further verify the applicability of the models to different catchments, 18 events from the neighbouring Lagan catchment were also used. The SCS curve number procedure proposed by the United States Soil Conservation Service was used to estimate the direct runoff volumes. The curve numbers were derived from storm rainfall-runoff relationships and the results obtained were satisfactory. Peak runoff rates were derived by both Nash and kinematic wave models for the estimated runoff volumes. The Nash model gave acceptable results in both Sambret and Lagan. The kinematic wave model performed well in Sambret only; in Lagan, it under-predicted the peak runoff rates.

La simulation des volumes ruisselés et des débits de pointe de bassins versants ruraux du Kenya en Afrique de l'Est

Résumé L'évaluation des volumes ruisselés et des débits de pointe de petits bassins hydrographiques ruraux du Kenya en Afrique de l'Est est délicate en raison de la quantité limitée de données de jaugeage disponibles. Cette difficulté peut être surmontée en adoptant une démarche de modélisation. Celle ci exige toutefois des bases de données pour calibrer et valider les modèles. Une base de donnée très fiable concernant deux petits bassins hydrographiques, Sambret (7.02 km^2) et Lagan (5.44 km^2) et couvrant une durée de presque 22 ans (1958-1980) a été utilisée dans la présente étude. Ces deux bassins hydrographiques se situent à l'amont du bassin versant du lac Victoria au Kenya et ont été bien équipés par l'ancienne Organisation de recherches agricoles et forestières de l'Afrique de l'Est (East Africa Agricultural and Forestry

Open for discussion until 1 December 1995

Research Organisation, EAAFRO). Dans le bassin du Sambret, 41 évènements pluie-débit étaient disponibles, dont 25 ont été utilisés pour le calibrage du modèle, les 16 restant étant utilisés pour sa validation. De plus, pour vérifier l'applicabilité des modèles à différents bassins, 18 évènements pluie-débit du bassin de Lagan, géographiquement très proche du bassin du Sambret, ont également été utilisés. Une méthode proposée par le Service de protection des sols des Etats Unis (The United States Soil Conservation Service, SCS) a été utilisée pour l'évaluation des volumes de ruissellement direct. Les hydrographes ont été déduits des relations pluie-débit observées et ont fourni des résultats satisfaisants. Les débits de pointe ont été calculés grâce aux modèles de Nash et de l'onde cinématique. Les résultats du modèle de Nash sont acceptables tant pour le bassin du Sambret que pour celui de Lagan. Le modèle de l'onde cinématique donne de bons résultats seulement pour le bassin du Sambret; à Lagan, ce modèle sous-évalue les débits de pointe.

INTRODUCTION

The determinations of runoff volumes and peak runoff rates are important elements of direct runoff simulation and are also prerequisites for the design of soil and water conservation and other hydraulic structures. They also form significant components of catchment studies aimed at determining the hydrological response and water resource availability as influenced by changes in land use. The water yield and peak runoff rates from a catchment can be computed by recorded data derived from automatic recorders. However, in developing countries, including Kenya, such instruments are lacking in the majority of catchments due to the high costs associated with their procurement and maintenance. Thus alternative techniques through the use of versatile models need to be sought in order to derive estimates of storm runoff volumes and peak runoff rates.

The concept of runoff volume prediction based on the curve number procedure advanced by the US Soil Conservation Service (SCS curve number) has been applied widely in developed countries (Williams & LaSuer, 1976; Aron, *et al.*, 1977; Hawkins, 1979; Hjelmeflt, 1991) and to a few cases in developing countries (TAMS, 1979; Schmidt & Shulze, 1987; Pathak *et al.*, 1989). Peak runoff rates are determined by generating direct runoff hydrographs. These have been modelled by a number of methods including the Nash linear reservoir method and kinematic wave theory. The form and mode of application of these models are widely documented in hydrological texts (Shaw, 1983; Chow *et al.*, 1988; Hogan, 1989; Bedient & Huber, 1992). In the case of the kinematic wave model, both analytical and nonlinear numerical solutions have been applied (Brakensiek & Comer, 1965; Rastogi & Jones, 1969; Singh, 1976; Van Liew & Saxton, 1984; Stephenson, 1986; Borah, 1989). In Kenya and Uganda, Fiddes (1976, 1979) developed a model based on linear reservoir theory and finite difference approximations for predicting floods for the design of small hydraulic structures.

DESCRIPTION OF STUDY CATCHMENTS AND DATA ACQUISITION

The study catchments of Sambret and Lagan lie in the Kericho district of the Rift valley province of Kenya, East Africa. The catchments form the headwaters of the Sondu River which drains into Lake Victoria (Fig. 1). The area lies within an altitude range of 2100-2500 m a.m.s.l. The mean annual rainfall is about 2000 mm. The seasonal distribution of rainfall is characterized by one long rainy season with peaks occurring in the months of April-May and

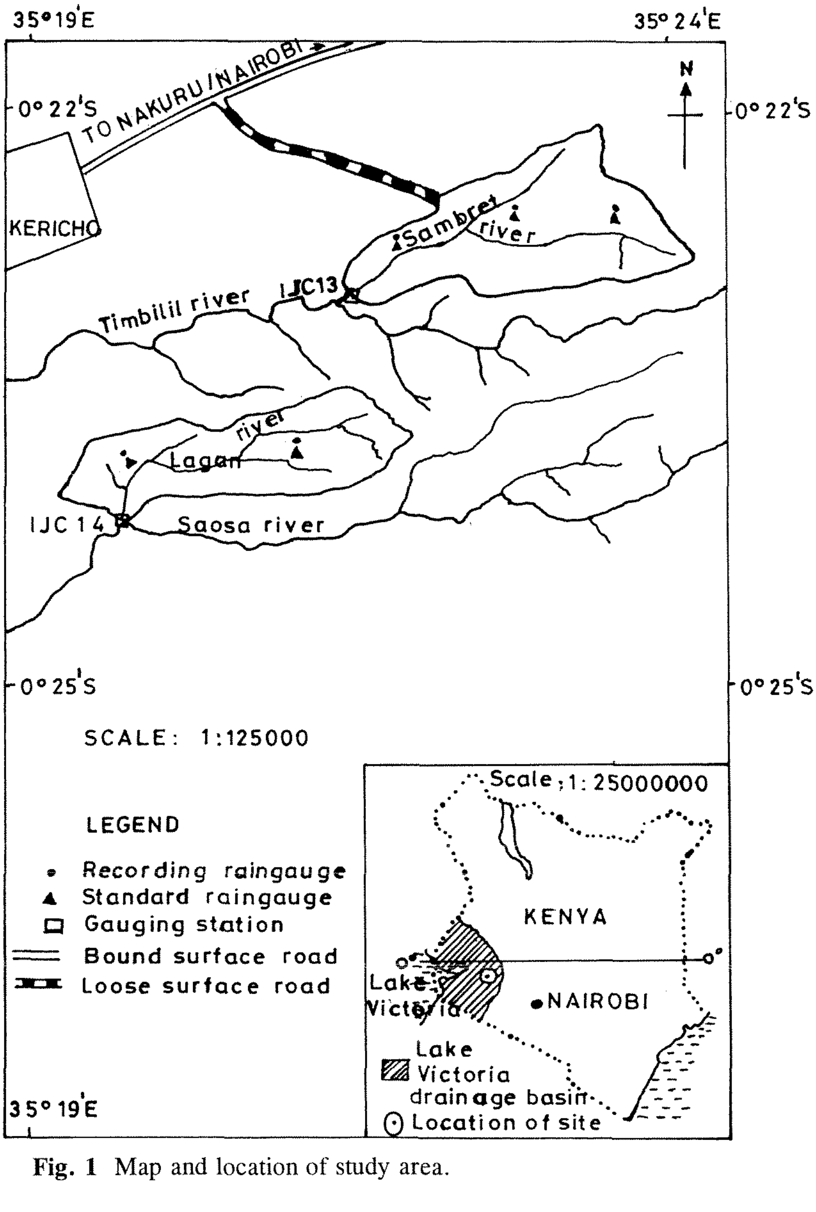

Fig. 1 Map and location of study area.

August-September. Most rainfall events are of short duration and high intensity followed by prolonged showers.

Both the Sambret and Lagan catchments were selected for the study because they had continuous hydrometeorological data from 1958 to 1980. The instrumentation was carried out by the East African Agricultural and Forestry Research Organisation (EAAFRO) in the late 1950s. Automatic water level recorders, compound weirs and staff gauges were installed at the gauging sites. Rainfall was monitored by both autographic rainfall recorders and standard rain gauges. From this intensive instrumentation, good quality data were obtained which provided a sound base for testing the models considered in this study. Details on instrumentation are well described by Edwards & Blackie (1979).

The rainfall and runoff data used in the study were provided by the Ministry of Water Development of the Kenya Government. The runoff data were in the form of stage-time graphs from which discharge-time graphs were derived using rating equations. Direct runoff hydrograph parameters were subsequently determined after baseflow separation. The rainfall intensities were derived from the rainfall charts. The land use data were derived from topographic maps and documented literature (Edwards & Blackie, 1979). It was found that about half of the Sambret catchment consisted of tea plantations while the remaining portion was occupied by roads, forest and settlement areas. The Lagan catchment was entirely covered by indigenous forest. The Tea Research Foundation of the Kenyan Government made available the soils data. Texturally these soils have a high percentage of clay with a bulk density of about 1 g cm^{-3}. They are more than 3 m in depth, uniform and have a subangular blocky structure.

A total of 41 events were identified for the Sambret catchment of which 25 were used for model calibration and 16 for testing. Eighteen events from the Lagan data were used for model testing.

DATA ANALYSIS

The SCS curve number model for runoff volume estimation is expressed mathematically as follows:

$$Q = \frac{(P - I_a)^2}{(P - I_a + S)} \tag{1}$$

$$I_a = \phi S \tag{2}$$

$$S = \frac{25\ 400}{CN} - 254 \tag{3}$$

where Q = storm rainfall excess (mm), P = storm rainfall (mm), S = potential maximum soil water retention (mm), I_a = initial abstraction (mm), CN = runoff curve number and ϕ = coefficient of initial abstraction taken as

0.2. The application of this model relies on the determination of the curve number which is a function of land use, hydrological soil groups and antecedent moisture content. Values of *CN* are widely documented in the literature (Hromadka & Whitley, 1989; Chow *et al.*, 1988). An equation can also be derived from the simultaneous solution of the above three expressions which relates curve number to storm rainfall and runoff and is expressed as follows for $\phi = 0.2$:

$$CN = \frac{25\ 400}{254 + 5\left\{(2Q+P) - \left[(2Q+P)^2 - P(P-Q)\right]^{1/2}\right\}} \tag{4}$$

Equation (4) can also be presented in a nomographic form.

The Nash model used to generate a direct runoff hydrograph is a function of two parameters and takes the mathematical form:

$$h(t) = \frac{1}{k\Gamma n}\left[\frac{t}{k}\right]^{n-1} e^{-\frac{t}{k}} \tag{5}$$

where $h(t)$ = instantaneous unit hydrograph (IUH) ordinate (h^{-1}) at time t, n = number of linear reservoirs in cascade and k = storage constant (h). The values of n and k for the Sambret catchment were derived using the method of moments (Chow *et al.*, 1988) while for the Lagan catchment, geomorphic relationships (Shaw, 1983) were found satisfactory. The respective values of these parameters for the two catchments were 5 and 1.66 h, and 3 and 1.7 h.

Values of n and k for the Sambret catchment were also derived from geomorphic relationships and they were found to be 3 and 1.8 h respectively. The similarity of these values with those of Lagan is due to the similarity of the geomorphic features, namely slope and length of main stream channels. These features do not take into account the surface configuration of the catchments as modified by the structural conservation measures. Thus, this procedure did not give satisfactory results in the Sambret catchment; hence the use of the method of moments. In the Lagan catchment, there was less human intervention and therefore the geomorphic relationships used in deriving the parameters were more satisfactory.

Since the rainfall input into a catchment is a continuous process, direct runoff is suitably represented by the continuous convolution integral stated as:

$$q(t) = \int_0^t h(t-\tau)R(\tau)\,d\tau \tag{6}$$

where τ = dummy time variable of integration, $R(\tau)$ = excess rainfall intensity function and $q(t)$ = direct runoff rate (mm h^{-1}). In the present analysis the excess rainfall intensity (i_r) was regarded as constant for a period of T hours derived using a constant loss rate procedure (Shaw, 1983). In other words $R(\tau) = i_r$ for $0 < \tau \leq T$, $R(\tau) = 0$ for $\tau > T$ where T is the duration of the rainfall excess. Equation (6) therefore reduces to:

$$q(t) = i_r \int_0^T h(t-\tau)\mathrm{d}\tau \tag{7}$$

The analytical solution of equation (7) was determined with n equal to 5 for the Sambret catchment and n equal to 3 for the Lagan catchment. The resulting solutions:

$$q(t) = \frac{i_r}{24}\left[\mathrm{e}^{-f}(f^4+4f^3+12f^2+24f+24)\right]_{f_1}^{f_2} \tag{8}$$

and

$$q(t) = \frac{i_r}{2}\left[\mathrm{e}^{-f}(f^2+2f+2)\right]_{f_1}^{f_2} \tag{9}$$

were then used to derive direct runoff hydrographs for each of the two catchments where $f_1 = t/k$, $f_2 = (t - T)/k$, i_r = excess rainfall intensity (mm h^{-1}), T = duration of rainfall excess (h) and $q(0) = 0$. The value of T was 1 h for all the storms studied.

Another approach is to use the kinematic wave model. This is the simplest distributed flow model derived from the Saint-Venant equations. Chow *et al.* (1988) present the linear form of the numerical solution of this model which was used in the computations and is expressed as:

$$q_{(i,j)} = \frac{\dfrac{\Delta t}{\Delta x} + \sigma\beta q_{(i,j-1)}\left[\dfrac{q_{(i,j-1)}+q_{(i-1,j)}}{2}\right]^{\beta-1} + \Delta t\left[\dfrac{q_{s(i,j)}+q_{s(i,j-1)}}{2}\right]}{\dfrac{\Delta t}{\Delta x} + \sigma\beta\left[\dfrac{q_{(i,j-1)}+q_{(i-1,j)}}{2}\right]^{\beta-1}} \tag{10}$$

where Δx = space grid interval (m), Δt = time grid interval (s), t = time coordinate (s), x = space coordinate (m), q_s = lateral inflow ($\mathrm{m}^3\ \mathrm{s}^{-1}\ \mathrm{m}^{-1}$), σ, β = kinematic wave parameters, q = direct runoff flow rate ($\mathrm{m}^3\ \mathrm{s}^{-1}$), i = counter for distance and j = counter for time. Routing of the flow was done on a space-time grid representation of the catchments (Fig. 2). The catchments were divided into imaginary flow planes within which the overland flow was assumed to be uniform and having equal depth as generated by rainfall excess while in the side channels the discharge was concentrated within the channel geometry and routing proceeded in a similar manner as for the main channel.

The parameter σ was obtained from equation (11) which incorporates the Manning roughness formula:

$$\sigma = \left[\frac{n_c p^{2/3}}{\sqrt{s}}\right]^{0.6} \tag{11}$$

where n_c = Manning's roughness coefficient for channel flow, p = wetted

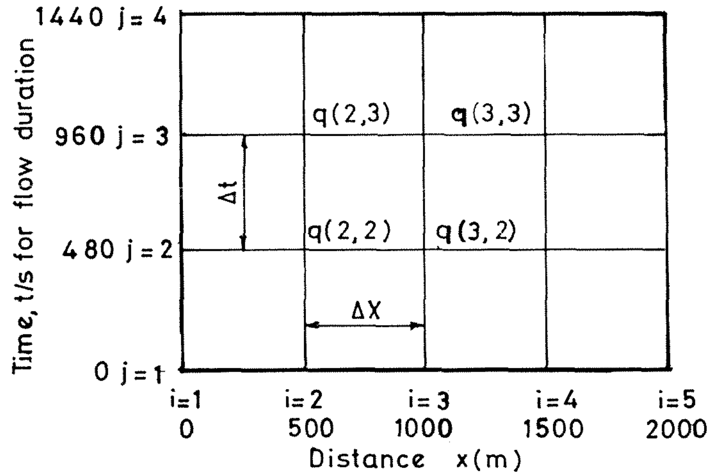

Fig. 2 Space-time grid representation for the kinematic wave model.

perimeter (m) and s = channel slope. The exponent β in equation (11) was taken as 0.6 while σ for the Sambret catchment was 0.68 for the main channel and 0.52 for the side channels. For the Lagan catchment, σ was 0.53. The grid spacing (Fig. 2) was determined by first assuming a value of Δx and then calculating the corresponding time interval Δt using the Kirpich formula as recommended by Brakensiek & Comer (1965). Optimization was then done using calibration storms by varying the grid intervals to determine the appropriate values of Δt and Δx. The linear form of the kinematic wave model, equation (10), converges unconditionally and when routing was done, with the various combinations of Δx and Δt tested, gave peak runoff rates which compared well with the observed values for the calibration storms. By using grid spacings of 500 m and 480 s, the predicted peak runoff rates compared well with the observed values. This number of grid intervals is not excessive and does not make the computations unnecessarily lengthy. The same space-time grid was therefore used with the test storms in both catchments. The routing process was accomplished by assuming dry initial conditions for both the overland flow planes and channels (Rastogi & Jones, 1969). Collector channels were ignored because the catchments were small and well conserved, although Lagan had a relatively higher drainage density.

RESULTS AND DISCUSSIONS

The determination of curve numbers from the catchment characteristics gave three values representing dry, average and wet moisture conditions over the catchments. The runoff volumes estimated using these values deviated from the observed ones by a wide margin (Table 1).

The discrepancies observed in Table 1 occurred due to the discrete nature of the relationship between the curve numbers and the soil moisture index of

Table 1 Predicted and observed runoff volumes from the study catchments

Sambret				Lagan			
P	Q_o	Q_p	Q_p'	P	Q_o	Q_p	Q_p'
11.6	0.113	0.146	6.254	43.1	0.572	0.633	0.375
14.8	0.143	0.224	5.089	12.6	0.130	0.167	0.167
16.8	0.185	0.249	1.459	19.4	0.288	0.276	4.853
50.1	1.026	0.899	21.04	21.8	0.265	0.322	4.139
26.9	0.344	0.410	5.787	10.5	0.162	0.130	1.302
29.3	0.641	0.487	0.841	10.0	0.129	0.110	8.299
19.5	0.177	0.233	3.624	32.4	0.495	0.484	7.262
14.0	0.141	0.182	5.367	33.7	0.400	0.453	7.971
19.6	0.227	0.244	2.437	31.7	0.202	0.477	0.830
22.6	0.369	0.408	3.688	30.2	0.410	0.378	2.127
19.3	0.271	0.265	2.323	18.0	0.155	0.207	5.299
30.5	0.569	0.484	1.232	13.0	0.187	0.184	7.082
15.2	0.183	0.219	4.953	14.5	0.242	0.190	0.520
22.8	0.258	0.380	2.759	32.3	0.481	0.472	0.929
17.6	0.128	0.186	4.305	15.0	0.196	0.197	6.333
20.3	0.354	0.300	2.711	33.8	0.435	0.464	1.197
				32.6	0.221	0.405	1.684
				14.1	0.072	0.193	6.664

P = storm rainfall; Q_o = observed runoff volumes; Q_p = predicted runoff volumes based on curve numbers from curve number *vs* storm rainfall relationship; Q_p' = predicted runoff volumes based on curve numbers estimated from catchment factors.

the catchments. Similar results were reported by Hawkins (1979). Further investigations to derive continuous curve numbers were carried out using equation (4) which relates curve numbers to storm rainfall and direct runoff. The calibration data from the Sambret catchment were used with equation (4) to determine the corresponding curve numbers for each event. On plotting these values against the storm rainfall, the points were found to fall uniquely on the curve shown in Fig. 3. Hawkins (1979) also found a similar relationship. This curve implies that storm rainfall has an influence on the curve numbers and subsequent curve numbers for the test storms were derived directly from Fig. 3. These values were used with equations (1) to (3) to determine the runoff volumes and the results are shown in Fig. 4 for the test events on the Sambret catchment. Due to the similarity in storm and catchment characteristics, the same curve was applied in the neighbouring Lagan catchment to derive the curve numbers and the corresponding predicted runoff volumes shown in Fig. 4. By visual inspection, the results were found to be satisfactory with most points lying close to the 1:1 line. However, more scatter was observed for the Lagan catchment. Further verification of the findings was performed using statistics such as percentage error ($\%E$) and R^2 proposed by Nash & Sutcliffe (1970) and recommended by the ASCE Task Committee (1993). The tangent of the zero-intercept regression line (McCuen & Snyder, 1986) and the t statistic were also included (Table 2) for evaluating the performance of the models. The t-test was preferred because both means and variances of the sample data were estimated (Steel & Torrie, 1981).

The statistical results (Table 2) further verify that the SCS curve number model satisfactorily estimated the runoff volumes. However, the results from

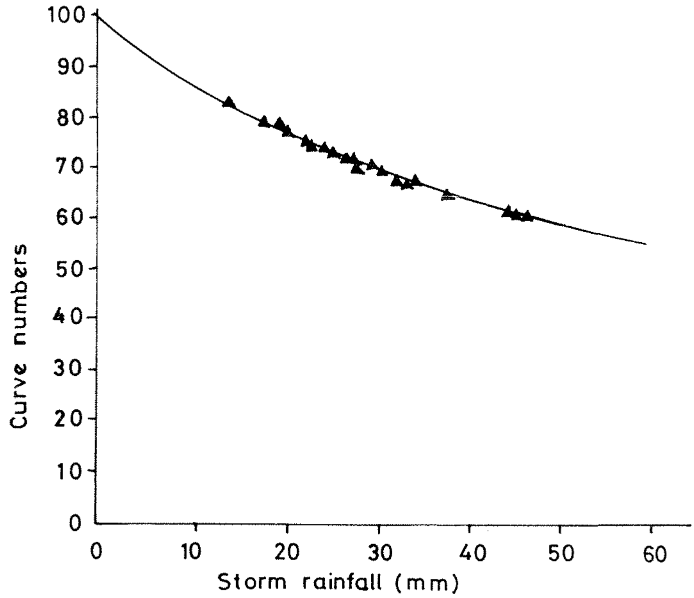

Fig. 3 Curve number storm rainfall relationship.

Table 2 Statistical comparison of the results

	Sambret			Lagan		
	Curve number	Nash model	Kinematic wave model	Curve number	Nash model	Kinematic wave model
Mean %*E*	16.4	26.6	−25.1	23.8	2.1	−52.7
R^2	0.90	0.88	0.69	0.61	0.56	−0.64
Slope	0.93	1.05	0.93	1.09	0.99	0.55
t_{cal}	0.145	0.57	0.68	0.760	0.000	3.567
t_{tab}	2.042	2.042	2.042	2.110	2.110	2.110
		(5%, 30 df)			(5%, 34 df)	

%*E* = percentage error; df = statistical degrees of freedom; t_{cal} = calculated value of *t* statistic; t_{tab} = value of *t* statistic from the table.

the Lagan catchment, although acceptable, were less accurate as indicated by the mean percentage error. The tangent of the zero-intercept regression line and the R^2 statistic further confirmed this observation while the *t* statistic indicated that there was no significant difference between the predicted and the observed runoff volumes at the 5% significance level in both catchments. The discrepancy observed in the runoff volumes for the Lagan catchment can be ascribed to the difference in conservation activities compared to those in the Sambret catchment where structural soil conservation practices are in use. These include terraces and cut-off drains within the tea zone of the Sambret catchment. Such structural measures were not undertaken in Lagan as the catchment is entirely covered by indigenous forest. It should also be noted that curve numbers were calibrated in Sambret and applied in Lagan.

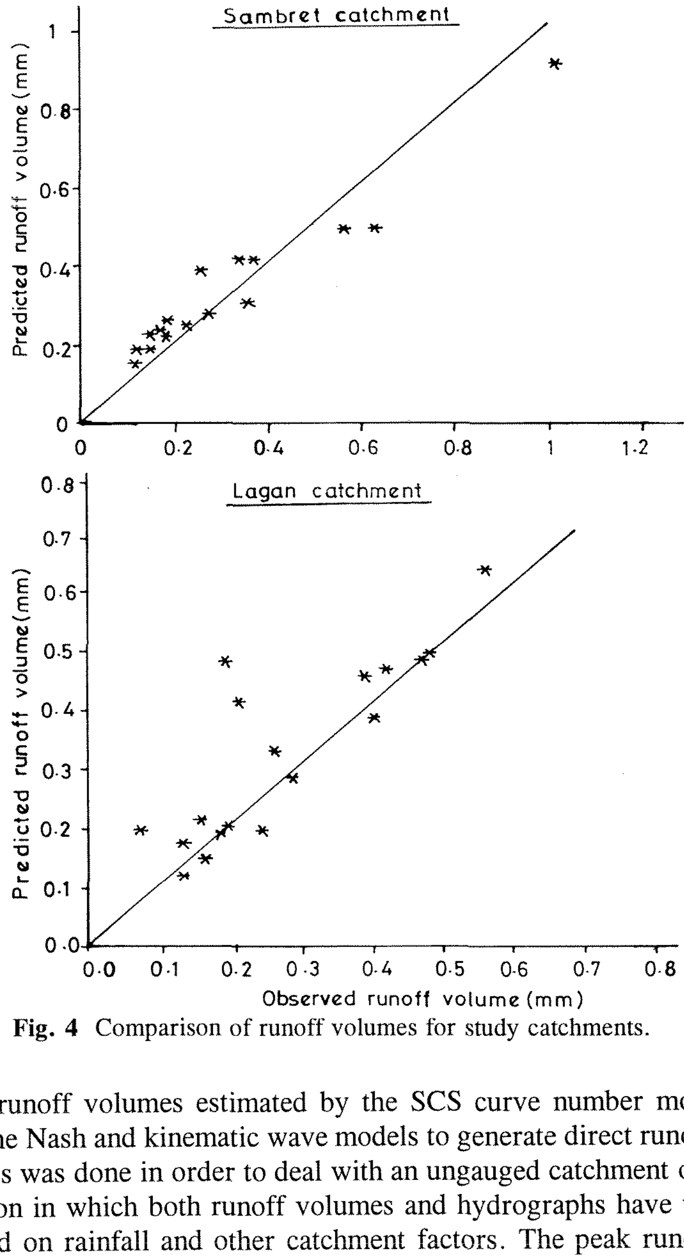

Fig. 4 Comparison of runoff volumes for study catchments.

The runoff volumes estimated by the SCS curve number model were input into the Nash and kinematic wave models to generate direct runoff hydrographs. This was done in order to deal with an ungauged catchment or missing data situation in which both runoff volumes and hydrographs have to be predicted based on rainfall and other catchment factors. The peak runoff values determined are shown in Fig. 5. The statistical results are tabulated in Table 2.

The study indicated that the Nash model satisfactorily predicted the peak runoff rates in both the Sambret and Lagan catchments as indicated by both Fig. 5 and the statistical parameters. However, in the Lagan catchment, the points were more scattered. The kinematic wave model gave acceptable results in the Sambret catchment, while in the Lagan catchment the peak rates were significantly different from the observed values as shown for example, by the t statistic (significant at the 5% level). This is further shown by the negative value of R^2 which indicated poor prediction by the model. In both catchments,

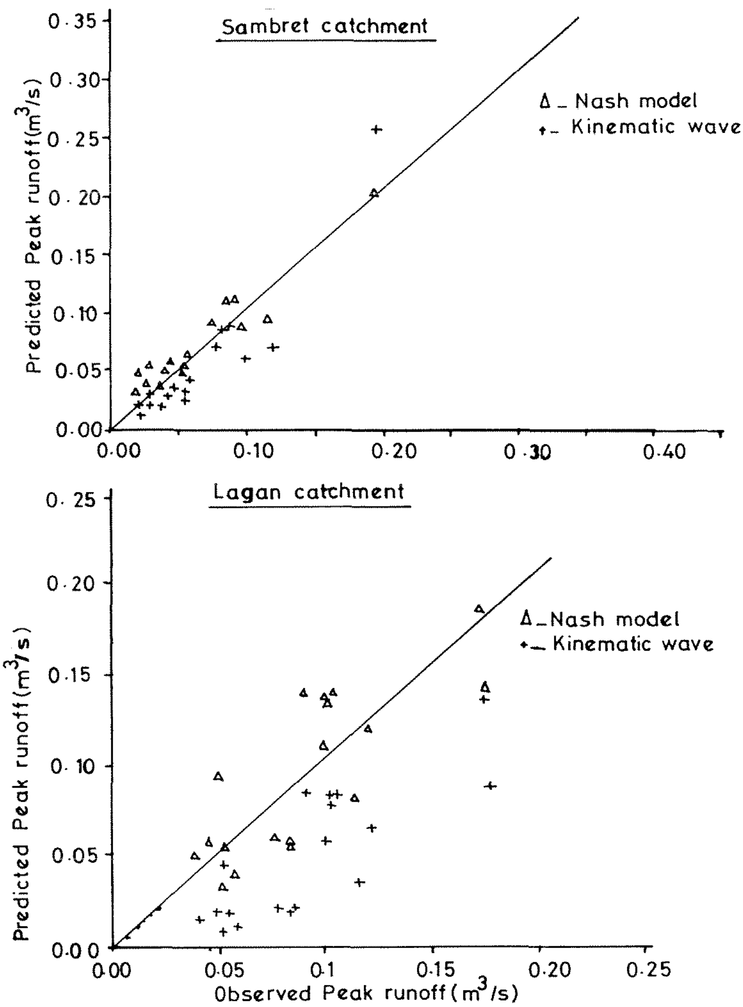

Fig. 5 Comparison of runoff peaks (m^3 s^{-1}) for study catchments.

the kinematic wave model showed a tendency to under-estimate the peak runoff rate.

The direct runoff hydrographs generated by the models more closely approximated the observed ones in the Sambret catchment than in the Lagan catchment. Fig. 6 shows representative hydrographs for one of the events in each catchment. In all the observed hydrographs, the baseflow was separated by first plotting the recession limb on semi-logarithmic paper and the end of the direct runoff contribution was marked at the point where the recession curve changed to a straight line. This point, when joined to the point of rise of the hydrograph, marked the baseflow separation line (Shaw, 1983).

The Nash model performed consistently better in both the Sambret and Lagan catchments. The kinematic wave model gave good results in the Sambret, while in the Lagan it significantly under-predicted the peak discharges. This anomaly is associated with a higher drainage density in the Lagan

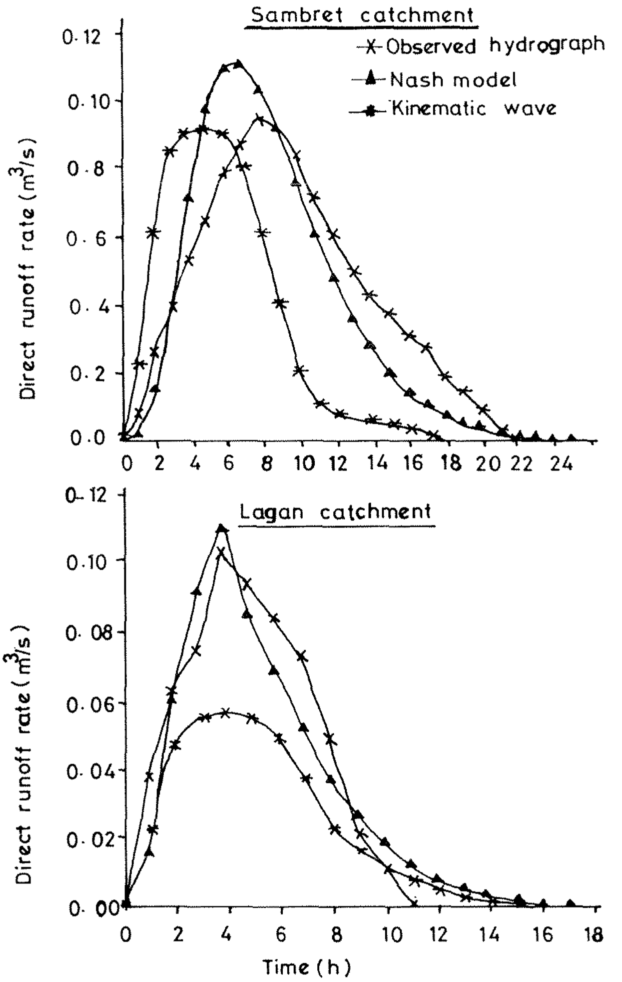

Fig. 6 Comparison of storm runoff hydrograph for study catchments.

catchment which, although assumed to be insignificant, implies more collector channel flow. In the Sambret catchment, structural soil conservation practices within the tea zone delayed the flow of direct runoff. This caused differences in the hydrological response between the two catchments hence limiting the direct extrapolation of the calibrated model from the Sambret to the Lagan. It is therefore essential that the model be calibrated separately in the Lagan catchment for future prediction of runoff hydrographs.

CONCLUSIONS

The use of the SCS curve number model with curve numbers determined using storm rainfall and runoff data, gave satisfactory results compared to the poor results from curve numbers derived from catchment characteristics documented in the literature. The success of the model in the Lagan catchment showed that the model can be easily extrapolated into neighbouring catchments for estimating runoff volumes. However, the model requires some rainfall-runoff data for parameter estimation.

The use of the method of moments in the Nash model for parameter estimation was found satisfactory in the Sambret catchment while in the Lagan catchment geomorphic relationships were found superior. Although the former required some data, the latter enabled the model to be applied in ungauged catchments. The kinematic wave model performed well in the Sambret but less satisfactorily in the Lagan. This indicated that it required calibration in a catchment where it is intended for use. Although both models can be used for direct runoff hydrograph generation, the Nash model seemed more accurate and versatile than the kinematic wave model as indicated by the results of this study.

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