Nordic Hydrology, 8, 1977, 193-210

Estimation of Parameters of Converging Overland Flow Model

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The converging overland flow model contains five parameters, three geometric and two kinematic. An attempt is made in this study to estimate these parameters utilizing watershed topographic characteristics. By applying the model, with parameters estimated in the proposed fashion, to natural agricultural watersheds, its potential in the prediction of surface runoff is indicated.

Introduction

Watershed surface runoff models abound in the hydrological literature. A fundamental problem common to most models, however, is: How to estimate the model parameters from physically measurable watershed characteristics? A commonly used approach is to bypass this problem by optimizing the model parameters over some selected rainfall-runoff events of a given watershed, using a suitable optimization algorithm and an appropriate objective function. These optimized parameter values are then utilized in the model to predict surface runoff for the rainfall events of interest, not used in the optimization. This approach does not offer a solution to the basic problem and has some other serious limitations. For example, the optimized parameters can best represent the system only for the events used in the optimization; as the optimization set of events changes, so do the parameter values. This approach is not accessible to ungaged watersheds because of a lack of data. Equally important, optimization is an expensive proposition.

A logical approach to overcome this predicament is to relate the model parameters to those watershed characteristics which can be easily obtained from the topographic map. One obvious advantage of this approach is that it is readily applicable to ungaged watersheds or watersheds with insufficient data for optimization. An implicit assumption of this approach is that no changes take place in watershed physiography over the period in question. If changes do take place and are pronounced in scale, the determining equations will have to be rederived. Further, the watersheds, grouped together, must have similar geologic and physiographic features.

In a previous paper Singh and Woolhiser (1976) explored the possibility of estimating parameters of their converging overland flow model from watershed topography. Although not conclusive, their results were suggestive and looked promising. Their conclusions were: (1) the geometric parameters could be estimated from watershed topography, and (2) the estimation of kinematic parameters required further investigation. Encouraged by their study we decided to pursue the matter further. The present study is, therefore, an extension of the work by Singh and Woolhiser (1976). The objective here is to utilize the above approach to estimate the parameters of a converging overland flow model. By applying the model, with parameters estimated in the proposed manner, to natural agricultural watersheds the performance of the proposed approach is evaluated. At this point it is desirable to give a brief description of the model as deemed relevant in the present context.

Converging Overland Flow Model

The converging overland flow model considers surface runoff as gradually varied, unsteady free surface flow and approximates its dynamic behavior by kinematic wave theory (Lighthill and Whitham 1955). The complex geometry of a natural watershed is transformed into a simple linearly converging geometry as shown in Fig. 1. This transformation is based on the premise that the simplified geometry will have a hydrologic response similar to that of the natural geometry and is, hence, equivalent to some extent (Woolhiser 1969; Singh 1975a, 1976b).

From Fig. 1 it is clear that the converging section has four geometric parameters including L_O, r, θ and S_O, where L_O is the length of the section, S_O the slope, r a parameter related to the degree of convergence, and θ the interior angle. Because of radial symmetry θ does not affect the relative response characteristics; it depends on L_O and r only, since the watershed area must be preserved.

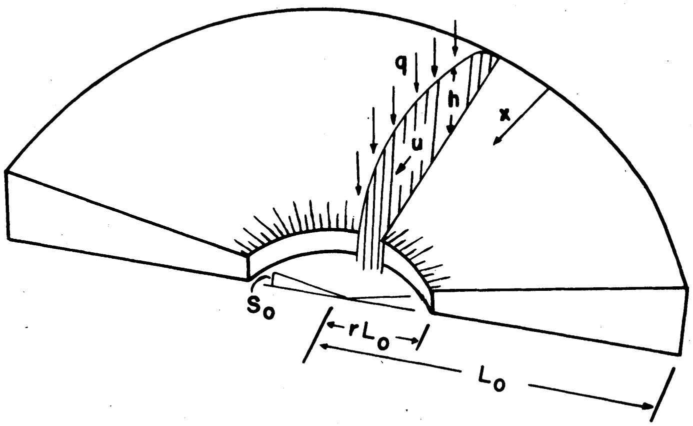

Fig. 1. Geometry of converging overland flow model.

The mathematical representation of the model consists of a continuity equation and a kinematic-momentum equation. These equations (Singh 1976a) can be written respectively as:

$$\frac{\partial h}{\partial t} + u\frac{\partial h}{\partial x} + h\frac{\partial u}{\partial x} = q(x,t) + \frac{uh}{(L_o - x)} \quad (1)$$

$$Q = \alpha h^n \quad (2)$$

where h is average local depth, u average local velocity, Q rate of outflow per unit width and equal to uh, $q(x, t)$ lateral inflow, L_O radius of the converging section, α, n parameters of friction relationship, x space coordinate, and t time coordinate.

Because of their nonlinear nature explicit analytical solutions of Eqs. (1) and (2), for space-time variable inflow $q(x, t)$, are not wieldly. However, numerical and hybrid solutions (Singh 1975a, 1975b, 1976a) are relatively simple to develop and were utilized in the present investigation. It is evident from Eq. (2) that the model has two kinematic parameters n and α. For an elaborate discussion of the model see the reference by Singh (1976b).

Parameter Estimation

Geometric Parameters

The transformation of the complex watershed geometry into a simplified converging geometry requires the determination of the geometric parameters L_O', r, θ and S_O; the parameter S_O does not enter explicitly into computations, but is embedded into the parameter α. These geometric parameters were estimated (Shelburne and Singh 1976) from topographic characteristics including width and area of the basin, and length of the mainstream. L_O was considered equal to the length of the mainstream along its course (Shelburne and Singh 1976). θ was defined as:

$$\theta = \arctan\left(\frac{W}{2L_O}\right) \quad (3)$$

where W is the horizontal projection of the watershed width. Then r was determined from the watershed area as:

$$A = \frac{\theta}{360}\,\pi L_O^2 \left(\frac{1+r}{1-r}\right) \quad (4)$$

It must be remarked that estimation of L_O and r is different here from that of Singh and Woolhiser (1976). They took L_O as the horizontal projection from the most remote point of the watershed to its outlet, and r as 0.01 for each watershed.

Kinematic Parameters

The parameter n reflects the degree of nonlinearity in runoff process. Although n may vary throughout the development of a runoff hydrograph, and may vary from event to event and from one watershed to another, it seems plausible that (1) its variance would not be large for watersheds in a certain area range, (2) it can be fixed at some suitable value between 1 and 3, and (3) this value of n would adequately account for the nonlinearity in the runoff process.

It seems that the parameter α accounts for both translation and attenuation effects, and consequently it may change considerably from one watershed to another. The topographic characteristics of a watershed may be the dominant factors in affecting the value of α. Although α will most likely change from event to event on the same watershed, this change hopefully will not be large. Moreover the dynamical basis of the parameter α strongly suggests that it has physical significance, and that it should be plausible to estimate it from physically measurable watershed characteristics. These plausible hypotheses will be explored in the ensuing discussion.

In a laboratory study (Singh 1975c) it was shown that n and were strongly correlated, and that it would be reasonable to keep n fixed at 1.5. Thus in the present study n was fixed at this value. To estimate α from topographic characteristics 38 natural agricultural watersheds were selected from several regions of the United States encompassing diverse geologic, topographic, hydrologic and climatic conditions. These watersheds are small in area varying from 0.5 to 3,055 ha. Two factors were considered in the selection of these watersheds: (1) rainfall-runoff data was adequate, (2) average watershed slope was reasonably steep. For a detailed description of these watersheds see the USDA publications (e.g., USDA 1963 and subsequent years).

Rainfall-runoff data for these watersheds were obtained from USDA publications entitled, »Hydrologic Data For Experimental Agricultural Watersheds In The United States.« These publications are released almost every year and generally contain one event per year on a watershed. This event is generally the largest runoff producing event in that year. Eight to twelve events per watershed were normally available; some watersheds had even fewer events.

The USDA publications usually list readings of only one raingage, although a watershed may have more raingages. This raingage is supposedly taken to represent the mean areal rainfall, a situation not often attained. For consistency this practice was followed for each watershed.

The conventional ϕ-index method was used to determine rainfall-excess. Although not accurate, this method is extremely simple, and its simplicity is the primary reason for its use in hydrologic modeling. A more accurate method of infiltration was desirable but was not used because of lack of information required to estimate its parameters.

The procedure to estimate α involved two operations: (1) optimization of α for a set of events for each watershed, (2) correlation of optimized α values with topographic characteristics by means of regression analysis.

The parameter α was optimized by the modified Rosenbrock algorithm (Rosenbrock 1960; Palmer 1969; Himmelblau 1972) using the objective function

$$f = \sum_{j=1}^{M} [Q_{p_o}(j) - Q_{p_e}(j)]^2 \Rightarrow \min \tag{5}$$

where f is objection function or an index of disagreement, $Q_{p_o}(j)$ observed hydrograph peak for the jth event, $Q_{p_e}(j)$ estimated hydrograph peak for the jth event, and M number of events in the optimization set. In optimization of α all rainfall events, that were available on a given watershed, were utilized. The optimized α values are given in Table 1.

To estimate α the following topographic characteristics were selected (Shelburne and Singh 1976), as given along with their units in Table 1.

Average Watershed Slope (SLOPE). Average watershed slope was obtained directly from the USDA publications. Slope was given in these publications for several portions of the watershed. An average slope was obtained by weighing each slope with respect to the proportionate area comprising this slope.

Basin Area (AREA), Basin Width (WIDTH) and Length of Mainstream (XLR). Area and width of the basin were given in the USDA publications. The length of the mainstream was defined as the distance from the gaging station to the upstream watershed boundary measured along its course.

Drainage Density (DD). Drainage density was determined from the topographic map, and was defined as the cumulative length of all streams, shown in the drainage basin, divided by the basin area:

Table 1 - Watershed Characteristics and optimized model parameter

Location and Name	Watershed	Area (Ha.)	Width (Km)	Length of Mainstream (Km)	Slope (%)	Shape	Drainage Density (m^{-1})	Stream order	Slope of Mainstream (%)	No. of Events Used in Optimization	Model Parameter α
Albuquerque, N.M.	W-II	16.39	0.234	0.814	12.260	3.1752	0.0065	3	5.168	6	78.0000
Coshocton, Ohio	5	141.24	0.671	2.415	15.505	3.2431	0.0063	3	1.770	9	48.8750
	92	372.32	0.518	2.898	15.400	1.7716	0.0007	3	2.368	9	22.3750
	94	615.14	1.931	4.186	15.900	2.2372	0.0011	2	1.750	9	38.9500
	95	104.01	3.460	5.635	16.890	2.3978	0.0018	3	1.353	9	43.0937
	97	1,853.53	3.892	9.016	17.210	3.4444	0.0010	3	1.014	9	55.0624
	177	30.59	0.465	0.854	15.325	1.8707	0.0031	2	5.357	7	30.8000
Fennimore, Wisc.	W-1	133.55	0.914	1.768	5.975	1.8389	0.0022	2	1.724	10	52.3400
Hastings, Neb.	2-H	1.38	0.076	0.189	6.135	2.0395	0.0078	2	2.581		
	4-H	1.47	0.107	0.162	5.960	1.3921	0.0078	1	4.528	18	79.0690
	W-3	194.66	1.207	2.720	5.305	2.9861	0.0039	3	0.430	15	49.3749
	W-8	844.20	1.811	7.953	5.500	5.8850	0.0032	4	0.430	15	25.8750
	W-11	1,412.40	2.012	11.673	5.576	7.5793	0.0032	4	0.430	10	18.6609
Mo Credie, Mo.	W-1	62.32	0.415	1.036	3.420	1.3541	0.0028	3	1.176	9	15.7260
	W-10	7.97	0.305	0.323	1.620	1.0289	0.0041	1	1.500	8	10.1761
	Y	125.05	0.915	1.537	2.405	1.4830	0.0026	2	0.990	9	28.2910
	Y-2	53.42	0.854	1.000	2.585	1.4702	0.0027	2	1.220	9	15.7500
	Y-4	32.34	0.595	0.610	2.850	0.9031	0.0011	2	1.750	9	7.7789
	Y-6	8.46	0.259	0.338	3.225	1.0634	0.0015	1	1.804	9	3.6250
	Y-7	16.19	0.381	0.543	1.865	1.4289	0.0017	1	0.840	9	11.7937
	Y-8	8.42	0.183	0.244	1.945	0.5550	0.0016	1	1.100	8	7.3684
	Y-10	8.50	0.381	0.338	2.375	1.0584	0.0038	1	1.300	9	8.2937
	SW-12	1.20	0.119	0.116	3.950	0.8770	0.0171	1	2.894	5	8.7315
	SW-17	1.21	0.122	0.116	1.830	0.8712	0.0066	1	1.579	9	3.8516
Ralston Creek, Ia		781.07	1.463	5.796	10.250	3.3780	0.0085	4	0.550	11	36.0781
Watkinsville, Ga		7.77	0.274	0.381	10.625	1.4763	0.0114	2	4.161	9	15.1000
Oxford, Miss	W-5	457.31	2.347	2.415	7.720	1.0013	0.0009	1	0.630	13	21.5036
	W-10	2,238.00	4.829	6.440	10.140	1.4555	0.0010	3	0.700	9	54.0000
	W-24	206.80	1.207	2.012	12.420	1.5382	0.0038	3	3.030	9	12.2500
	W-35	3,055.48	3.621	8.855	7.550	2.0155	0.0014	4	0.689	8	14.5625
	WC-1	1.57	0.114	0.149	7.760	1.1163	0.0248	3	6.222	10	9.4359
	WC-2	0.59	0.084	0.092	7.130	1.1197	0.0146	1	6.667	10	4.9422
	WC-3	0.65	0.061	0.107	5.930	1.3725	0.0122	1	4.286	10	8.2000
	WP-4	1.22	0.076	0.134	9.380	1.1602	0.0138	1	5.682	7	8.6582
Riesel (Waco), Tx	C	234.32	1.402	2.366	2.040	1.8761	0.0023	3	0.570	9	16.0000
	D	449.22	1.982	3.567	2.100	2.2246	0.0022	3	0.510	8	16.7509
	G	1,772.59	2.592	7.329	2.055	2.7160	0.0020	4	0.389	9	20.0000
	W-1	71.23	0.610	1.646	2.180	2.9887	0.0029	2	0.833	8	38.0000
	W-2	52.61	0.823	0.945	2.550	1.3335	0.0034	2	1.290	8	15.4980
	W-6	17.12	0.457	0.445	2.020	0.9090	0.0129	2	1.370	8	9.8125

$$DD \equiv \frac{\Sigma L}{A} \tag{6}$$

where A is area of the basin and L lenght of the watercourses.

Shape Factor (SHAPE). The shape factor proposed by Chorley, Malm and Pagorzelski (1957) was utilized in this study:

$$Shape = \frac{\pi L^2}{4A} \tag{7}$$

where L is the length of the mainstream.

Stream Order (SO). The method of designating stream order, developed by Strahler (1957), was used. This method assumes that the channel-network map includes all intermittent and permanent flow lines located in clearly defined valleys. The smallest finger-tip tributaries are designated order 1; where two first-order channels join, a channel segment of order 2 is formed; where two channels of order 2 join, a segment of order 3 is formed; and so on. The mainstream through which all runoff passes is therefore the stream segment of the highest order.

Average Mainstream Slope (CSLOPE). The slope of the principal drainage channel was determined from the topographic map. The length of the mainstream was divided by the elevation difference between its upper and lower ends. Small basin areas and the relatively straight channel reaches justified this approach.

Regression analyses were performed to correlate α as dependent variable with aforementioned watershed characteristics as independent variables. Initially, a multiple linear regression analysis for all 38 watersheds was performed. The resulting correlation coefficient was 0.9523 and standard error of estimate 9.23. The regression equation can be written as:

$$\alpha \equiv 0.00942\,Area + 11.53795\,Width - 9.76167\,XRL + 1.94925\,Slope + 11.8994\,Shape + 175.32422\,DD + 0.89852\,SO - 4.687079\,C\,Slope \tag{8}$$

To check the reliability of this equation values of α computed by Eq. (8) were plotted against optimized values as shown in Fig. 2. It is clear that the linear relationship between α and watershed characteristics is relatively good, but not as good as we would like.

To improve the correlation the independent variables were first logarithmically transformed (to the base *e)* and then α was linearly correlated with transformed variables. The correlation coefficient and standard error of estimate were 0.9274 and 11.31 respectively. The logarithmic transformation obviously did not improve the correlation. It was then thought that the stratification of data on the basis of area might improve the correlation. Thus the watersheds were divided into the groups: (1) watersheds smaller than or equal to 75 ha, and (2) watersheds larger than 75 ha. The former group contained 20 watersheds and the latter 18 watersheds. Linear regression

analyses were performed for both groups. Correlation coefficient and standard error of estimates for the group of small watersheds were respectively 0.9932 and 2.29, and those for the group of large watersheds were respectively 0.9530 and 14.31. The regression equations can be written as:
For small watersheds,

$$\alpha \equiv -0.32453\,Area - 6.5572\,Width + 44.29964\,XLR + 1.08668\,Slope - 1.98314\,Shape + 427.48218\,DD - 2.45283\,SO - 1.02488\,C\,Slope \quad (9)$$

For large watersheds,

$$\alpha \equiv 0.01011\,Area + 12.6032\,Width - 10.50376\,XLR + 1.81744\,Slope + 12.20712\,Shape + 934.08984\,DD + 0.79896\,SO - 4.59683\,C\,Slope \quad (10)$$

Figs. 3 and 4 compare optimized α values with computed α values using Eqs. (9) and (10). It is clear that data stratification improved the correlation significantly.

To further improve the correlation for the group of large watersheds the functional relationship between α and each independent variable was investigated which would produce the highest correlation coefficient between them. Thus, by selectively combining the transformed independent variables in the regression analysis, the best equation was obtained for large watersheds with correlation coefficient of 0.9714 and standard error of estimate of 11.22. The regression equation can be written as:

$$\alpha = 0.01233\,Area + 11.82528\,Width - 10.50765\,SLR + 8.38607\ln Slope + 51.2758\ln Shape - 1.99823\ln DD - 7.06871\,SO - 2.51323\,CSlope \quad (11)$$

Fig. 5 shows optimized α values versus computed α values using Eq. (11). It is evident that Eq. (11) leads to an improved correlation.

Statistical F tests were applied to the regression equations to determine which variables did not contribute to correlation statistically significantly, and could therefore be deleted from the equation. Values of F were computed at each regression step, as shown in Table 2, using the following equation:

$$F = \frac{(SSR_1 - SSR_2)/P}{MSE_1} \quad (12)$$

where SSR_1 is the sum of squares due to regression from the full model, SSR_2 the sum of squares due to regression in the reduced model (when variables were deleted), P number of variables deleted, and MSE_1 the mean square error associated with devia-

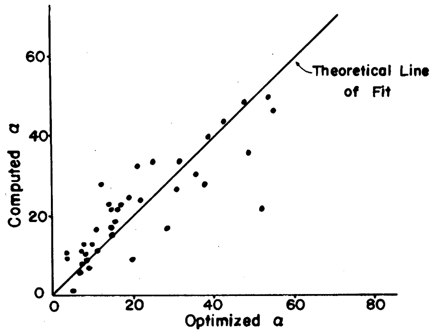

Fig. 2. Computed α vs. optimized α for Eq. (8).

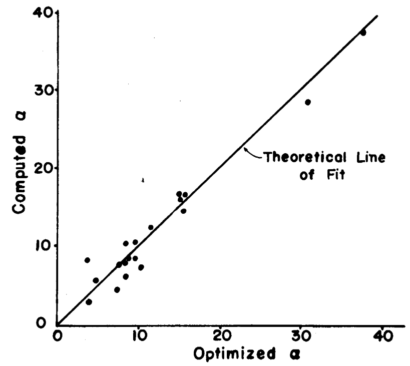

Fig. 3. Computed α vs. optimized α for Eq. (9).

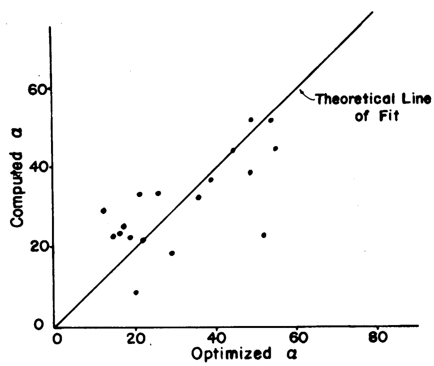

Fig. 4. Computed α vs. optimized α for Eq. (10).

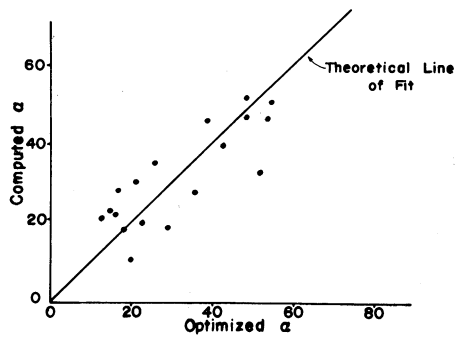

Fig. 5. Computed α vs. optimized α for Eq. (11).

tions from regression in the full model. Calculated F values (see Table 2) at each step of regression were compared with tabulated F values, $F_{0.05}$ $(P, n - k - 1)$, where n is the sample size and k degree of freedom due to regression. By deleting relatively noncontributory variables the degrees of freedom were increased. The final regression equation for small watersheds is:

$$\alpha = -0.45817\,Area - 9.54289\,Width + 50.53227\,XLR + 0.59317\,Slope - 3.13773\,Shape + 148.47112\,DD \qquad (13)$$

with correlation coefficient of 0.9905 and standard error of estimated 2.49. Fig. 6

Table 2 - Statistical F tests in regression analysis.

	Small Watersheds				Large Watersheds		
Step	Variable To Be added	Calculated F	Tabulated F $F_{05}(p,n\text{-}k\text{-}1)$	Step	Variable To Be Added	Calculated F	Tabulated F $F_{05}(p,n\text{-}k\text{-}1)$
1	SHAPE	-	-	1	SLOPE	-	-
2	XLR	17.83	4.45	2	DD	18.38	4.67
3	SLOPE	5.04	4.49	3	CSLOPE	8.16	4.75
4	AREA	4.98	4.54	4	XLR	7.93	4.84
5	WIDTH	4.72	4.60	5	SHAPE	6.53	4.96
6	DD	4.69	4.67	6	WIDTH	5.98	5.12
7	SO	1.31	4.75	7	AREA	5.08	5.32
8	CSLOPE	0.19	4.84	8	SO	4.83	5.59

shows computed versus optimized values of α for Eq. (13). A comparison of Figs. 3 and 6 shows that Eqs. (9) and (13) produce essentially the same results although two variables have been deleted from Eq. (13).

The final regression equation for large watersheds is:

$$\alpha = 10.91814\,Width - 6.96391\,XLR + 10.764\ln Slope + 28.933\ln Shape - 0.70065\ln DD - 5.89831\,C\,Slope \quad (14)$$

with correlation coefficient of 0.9625 and standard error of estimate of 11.69. Fig. 7 shows computed versus optimized values of α for Eq. (14). A comparison of Figs. 4 and 7 shows that Eqs. (10) and (14) lead essentially to the same results although two variables have been deleted from Eq. (14). Henceforth, we will use Eqs. (13) and (14) to estimate α.

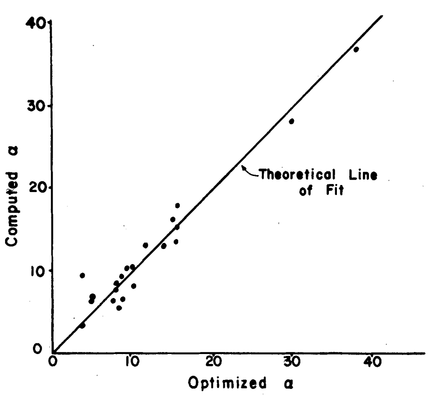

Fig. 6. Computed α vs. optimized α for Eq. (13).

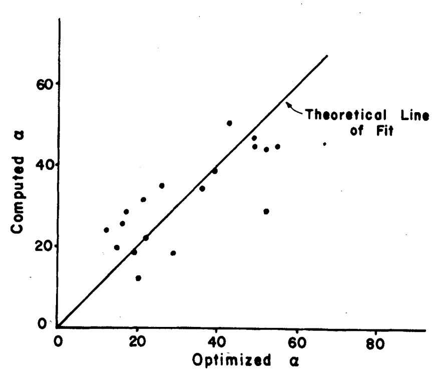

Fig. 7. Computed α vs. optimized α for Eq. (14).

Hydrograph Prediction

Hydrographs were predicted for several events, using Eqs. (13) and (14). Tables 3 and 4 provide a comparison of observed and predicted hydrograph peak characteristics. For two sample events hydrograph predictions are shown in Figs. 8-9. On comparing observed and predicted hydrograph peak and its time it is seen that the model, with parameters estimated as described above, performed quite well. Three hydrograph features were especially important: (1) hydrograph peak, (2) time to peak and (3) hydrograph shape. All three features were well predicted. It should be remarked that although the peak matching criterion (Eq. (5)) does not include the time component explicitly, time to peak was predicted reasonably well.

For most events relative error, (observed quantity - predicted quantity)/observed quantity, stayed below 30%; in some cases it was much higher, however. An examination of rainfall-runoff record indicated that in those cases error was primarily due to two reasons: (1) synchronization between rainfall and runoff observations was poor, (2) ϕ-index did not estimate time distribution of infiltration well, and consequently rainfall excess was not computed properly. To examine the role of infiltration further, hydrographs were predicted, using Philip's equation (Philip 1957), for the same events on the same watersheds. It is seen from Tables 5 and 6 that error in both runoff peak and its time is consistently smaller for predicted hydrographs utilizing Philip's equation.

Conclusions

The parameters of converging overland flow model have been determined from watershed characteristics. By applying the model to natural agricultural watersheds it has been shown that the parameters can be estimated satisfactorily in the proposed manner. Further, the method of determining rainfall-excess is crucial in prediction of surface runoff.

Acknowledgement

The work upon which this study is based was supported in part by funds provided through the New Mexico Resources Research Institute by the Department of Interior, Office of Water Research and Technology, as authorized under the Water Resources Research Act of 1964, Public Law 88-379 as amended, under project number 3109-206.

Table 3 - Comparison of observed and predicted hydrograph peak and its timing for small agricultural watersheds.

Converging Overland Flow Model: ϕ-index for infiltration

Watershed Riesel (Waco) Texas	Date	Observed Hydro-graph Peak (cm/hr)	Predicted Hydro-graph Peak (cm/hr)	Relative Error (%)	Observed Hydro-graph Peak Time (min)	Predicted Hydro-graph Peak Time (min)	Relative Error (%)
Y-2	3-26-1946	1.270	0.993	21.85	66.0	50.9	22.85
	6-23-1949	2.022	1.337	33.86	84.0	112.7	- 34.17
	4-24-1957	4.267	5.293	-24.05	37.0	48.0	- 29.73
	5-13-1957	3.150	3.681	-16.87	35.0	46.0	- 31.46
	6- 4-1957	4.547	3.990	12.25	34.0	43.3	- 27.47
	7-16-1961	0.183	0.134	26.89	79.0	89.0	- 12.72
	6-25-1961	0.643	0.497	22.74	84.0	66.4	21.00
	6- 9-1962	2.284	1.693	25.85	49.0	64.9	- 32.42
Y-10	5- 6-1955	1.511	0.538	64.37	12.0	50.1	-317.16
	6- 4-1957	6.096	5.873	3.65	26.0	32.8	- 25.97
	6-23-1959	1.786	1.723	3.49	70.0	102.6	- 46.64
	5-25-1961	0.930	0.264	71.57	17.0	56.1	-229.87
	6-15-1961	0.858	0.216	74.90	26.0	67.2	-158.33
	4-24-1957	6.858	6.648	3.07	35.0	36.7	- 4.82
	5-13-1957	4.851	4.698	3.16	26.0	35.9	- 38.05
	6- 9-1962	1.001	1.129	-12.77	38.0	46.4	- 22.13
	3-29-1965	6.925	7.781	-12.36	69.0	81.2	- 17.69
W-10	3-12-1953	2.718	1.128	58.50	49.0	42.0	14.20
	6- 4-1957	2.167	1.308	39.62	48.0	52.4	- 9.07
	4-24-1957	7.087	6.243	11.90	28.0	34.8	- 24.38
	4-24-1957	7.087	5.607	20.88	28.0	34.9	- 24.61
	5-22-1961	1.072	0.352	67.18	41.0	64.4	- 57.05
	6-25-1961	0.838	0.551	35.03	41.0	66.4	- 62.07
	6- 9-1962	2.093	1.706	18.51	32.0	41.0	- 28.04
	6-23-1959	4.978	3.822	23.23	63.0	56.0	11.11
	3-29-1965	4.495	6.387	-42.09	71.0	75.3	- 6.09

Table 4 - Comparison of observed and predicted hydrograph peak and its timing for large agricultural watersheds.

Converging Overland Flow Model: ϕ-index for infiltration

Watershed Name	Date	Observed Hydro-graph Peak (cm/hr)	Predicted Hydro-graph Peak (cm/hr)	Relative Error (%)	Observed Hydro-graph Peak Time (min.)	Predicted Hydro-graph Peak Time (min.)	Relative Error (%)
Hastings W-3	6-10-43	0.884	1.537	-73.93	35.0	47.1	-34.50
	5-27-44	1.194	0.981	17.80	29.0	53.0	-82.76
	5-20-49	0.528	0.719	-36.13	99.0	106.1	- 7.16
	7-10-51	4.420	3.686	39.23	41.0	80.0	95.12
	5-21-52	1.466	1.065	27.35	40.0	53.0	32.50
	6-26-52	1.455	2.261	-55.36	50.0	47.4	5.18
	6- 7-53	1.824	2.526	-38.52	40.0	49.9	-24.82
	6-15-57	2.997	2.451	18.22	62.0	61.0	1.61
	7- 3-59	5.080	4.729	6.92	34.0	38.0	-11.76
	9- 5-46	1.298	0.993	23.53	146.0	177.6	-21.61
	5- 6-49	0.358	0.290	19.08	74.0	87.0	-17.57
	6-25-51	1.697	1.194	29.64	129.0	176.7	-36.97
	7-13-52	3.378	4.120	-21.96	124.0	129.0	- 4.03
	6-15-57	2.487	2.753	-10.69	64.0	84.0	-31.25
	6-16-57	1.727	1.542	10.74	154.0	162.4	- 5.49
W-11	5-11-44	0.285	0.002	99.94	145.0	250.0	-72.41
	9-19-50	0.527	0.201	61.87	316.0	375.0	-18.67
	7-10-51	0.663	0.951	-43.38	189.0	296.0	-56.63
	5-22-54	0.721	0.292	59.52	214.0	300.0	-40.19
	6-14-61	0.257	0.222	13.19	212.0	300.0	-41.51
	6- 1-51	0.831	0.258	68.90	247.0	400.0	-61.94
	6-26-52	0.205	0.204	0.29	555.0	386.7	30.33
	7-13-52	0.772	0.485	37.20	256.0	378.2	-47.73
	6-16-57	0.582	0.587	- 0.74	349.0	342.0	2.01
	5-21-65	1.064	1.393	-30.92	560.0	249.7	55.42

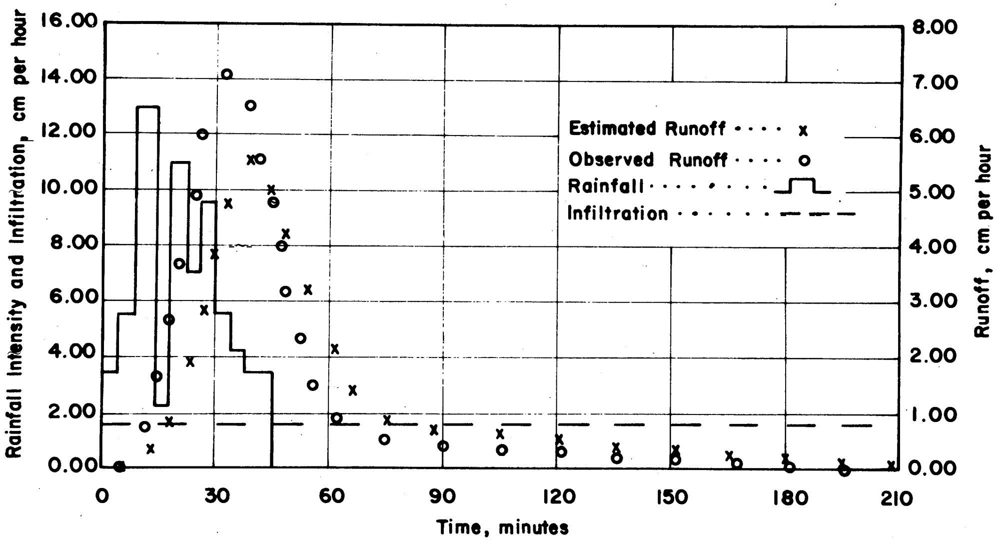

Fig. 8. Hydrograph prediction by Model, using ϕ-index, for rainfall event of 4-24-57 on watershed W-10, Riesel (Waco), Texas.

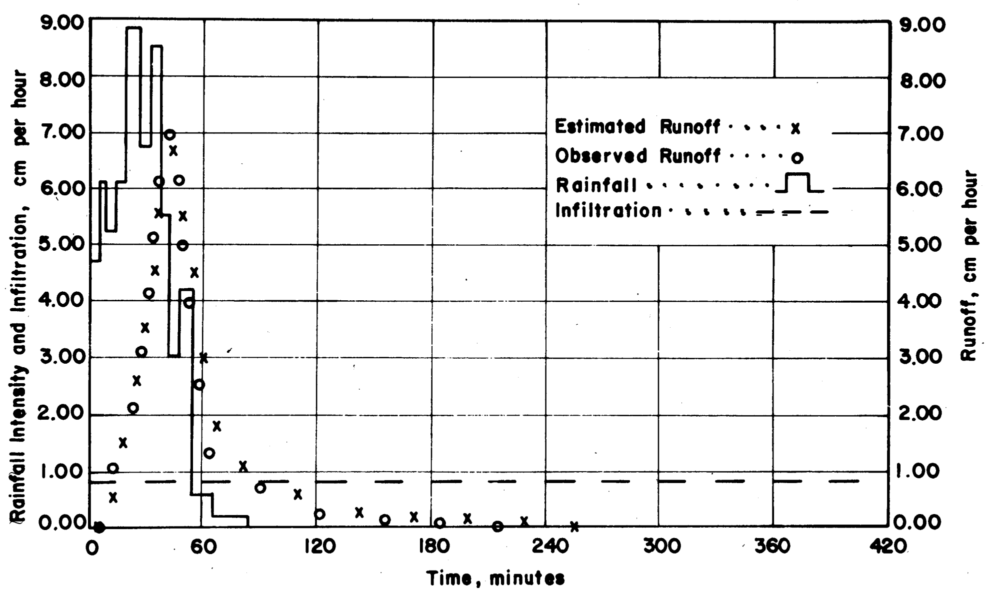

Fig. 9. Hydrograph prediction by Model, using ϕ-index, for rainfall event of 4-24-57 on watershed Y-10, Riesel (Waco), Texas.

Table 5 - Comparison of observed and predicted hydrograph peak and its timing for small agricultural watersheds.

Converging Overland Flow Model: Philip equation for infiltration

Watershed Riesel (Waco) Texas	Date	Observed Hydro-graph Peak (cm/hr)	Predicted Hydro-graph Peak (cm/hr)	Relative Error (%)	Observed Hydro-graph Peak Time (min)	Predicted Hydro-graph Peak Time (min)	Relative Error (%)
Y-2	3-26-1946	1.270	1.284	- 1.07	66.0	47.8	27.56
	4-24-1957	4.267	4.993	-17.01	37.0	48.0	- 29.73
	5-13-1957	3.150	3.600	-14.16	35.0	46.1	- 31.69
	6- 4-1957	4.547	3.951	13.11	34.0	43.0	- 26.45
	6-23-1959	2.022	2.289	-13.22	84.0	101.0	- 20.24
	7-16-1961	0.183	0.167	8.93	79.0	86.6	- 9.62
	6-25-1961	0.643	0.482	25.04	84.0	74.5	11.32
	6- 9-1962	2.282	1.800	21.22	49.0	65.3	- 33.21
Y-10	5- 6-1955	1.511	0.589	61.00	12.0	42.2	251.36
	6- 4-1957	6.096	6.217	- 1.99	26.0	31.0	- 19.23
	6-23-1959	1.786	2.494	-39.66	70.0	87.2	- 24.58
	5-25-1961	0.930	1.004	- 7.99	17.0	39.8	-133.85
	6-15-1961	0.858	0.236	72.50	26.0	58.8	-126.21
	4-24-1957	6.858	6.806	0.76	35.0	35.0	0.00
	5-13-1957	4.851	4.705	3.03	26.0	35.8	- 37.62
	6- 9-1962	1.001	1.258	-25.68	38.0	45.4	- 19.52
	3-29-1965	6.925	7.842	-13.25	69.0	81.0	- 17.40
W-10	3-12-1953	2.718	1.158	57.39	49.0	41.8	14.64
	6- 4-1957	2.167	1.367	36.90	48.0	50.6	- 5.51
	4-24-1957	7.085	6.280	11.39	28.0	34.8	- 24.37
	4-24-1957	7.085	5.564	21.49	28.0	36.8	- 31.44
	5-22-1961	1.072	0.358	66.61	41.0	52.3	- 27.67
	6-25-1961	0.848	0.578	31.85	41.0	70.5	- 71.86
	6- 9-1962	2.093	1.700	18.79	32.0	43.9	- 37.04
	6-23-1959	4.978	4.431	10.99	63.0	58.2	7.61
	3-29-1965	4.495	6.448	-43.47	71.0	75.3	- 6.07

Table 6 - Comparison of observed and predicted hydrograph peak and its timing for large agricultural watersheds.

Converging Overland Flow Model: Philip Equation for Infiltration

Watershed	Date	Observed Hydrograph Peak (cm/hr)	Predicted Hydrograph Peak (cm/hr)	Relative Error (%)	Observed Hydrograph Peak Time (min.)	Predicted Hydrograph Peak Time (min.)	Relative Error (%)
Hastings W-3	6-10-43	0.884	1.512	-71.02	35.0	46.1	-31.69
	5-27-44	1.194	0.980	17.91	29.0	53.0	-82.76
	5-20-49	0.528	0.685	-29.59	99.0	80.5	18.72
	7-10-51	4.420	5.284	-19.56	41.0	46.1	-12.42
	5-21-52	1.466	1.066	27.24	40.0	53.0	-32.50
	6-26-52	1.455	1.894	-30.13	50.0	47.8	4.45
	6- 7-53	1.824	2.346	-28.61	40.0	52.7	-31.68
	6-15-57	2.997	2.635	12.07	62.0	66.1	- 6.68
	7- 3-59	5.080	4.789	5.73	34.0	42.0	-23.53
	9- 5-46	1.298	1.538	-18.47	146.0	161.0	-10.27
	5- 6-49	0.358	0.292	18.52	74.0	87.0	-17.57
	6-25-51	1.697	1.319	22.25	129.0	169.7	-31.57
	7-13-52	3.378	4.240	-25.50	124.0	128.9	- 3.98
	6-15-57	2.487	2.524	- 1.52	64.0	62.6	2.18
	6-16-57	1.727	1.575	8.84	154.0	162.3	- 5.39
W-11	5-11-44	0.285	0.062	78.08	145.0	250.0	-72.41
	9-19-50	0.527	0.445	15.66	316.0	357.0	-12.97
	7-10-51	0.663	0.954	-43.87	189.0	233.4	-23.47
	5-22-54	0.721	0.303	58.03	214.0	300.0	-40.19
	6-14-61	0.257	0.221	13.94	212.0	300.0	-41.51
	6- 1-51	0.831	0.279	66.36	247.0	400.0	-61.94
	6-26-52	0.205	0.204	0.54	555.0	419.2	24.47
	7-13-52	0.772	0.488	36.86	256.0	338.5	-32.22
	6-16-57	0.582	0.584	- 0.19	349.0	342.0	2.01
	5-21-65	1.064	1.403	-31.81	560.0	249.4	55.46

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Received: 6 June, 1977

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