Storm Runoff Analyses on Three Semi-Arid Catchments

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Abstract

The objective of this study was to derive, by regression analysis, prediction equations for storm hydrograph characteristics of the Ecca River semi-arid research catchments near Grahamstown Independent variables included storm rainfall, rainfall duration, maximum intensity of rainfall, antecedent flow, and antecedent rainfall and moisture indices calculated by accumulating rainfall and potential evaporation over varying periods prior to storms. Log and cube root transformations were tested. Seven-day antecedent rainfall was generally the best index of catchment wetness at the beginning of a storm. This, together with storm rainfall, gave satisfactory prediction of storm flow volume. Storm flow peak and storm flow duration may further be predicted using the predicted storm flow volume, and a single relationship is adequate for all three catchments. The relationships are simple to derive and it is worthwhile extending the analysis to other catchments to test their generality and the possibility of including catchment area as an independent variable.

Introduction

Traditional methods of storm runoff prediction use two procedures: a volume of runoff or precipitation excess is estimated on the basis of infiltration capacity or loss rate and the time distribution of runoff is calculated, usually with some form of unit hydrograph. Peak flows are proportional to rates of rainfall excess, and if the procedures are considered representative of catchment processes there is an implicit assumption that rainfall, infiltration capacity and overland flow generation are spatially uniform.

Hewlett *et al.* (1977) found on a small forested catchment in a humid climate, that precipitation intensity variables were weakly correlated with peak flows and were of no practical value for predicting storm flow volumes. The most useful variables they found were storm rainfall, antecedent flow, season and storm duration. From experiments on an irrigated catchment in a similar environment, Lynch *et al.* (1979) report that storm flow response is very sensitive to antecedent soil water content. Relatively few results are available from semi-arid catchments. Arteaga and Rantz (1973) and Lane *et al.* (1978) describe rainfall-runoff analyses for small catchments in Arizona, based on a partial area interpretation of runoff generation. Overland flow is assumed to be generated by the mechanisms described by Horton (1933) and results support the idea that variable proportions of the catchment contribute runoff in each event. In a series of sprinkler experiments on plots in semi-arid Spain, Scoging and Thornes (1979) found saturation overland flow was the primary mechanism of runoff generation and they simulated overland flow hydrographs on this basis. Görgens (1980) compares storm flows from the Ecca catchments with those of other studies and although his largest storm has an estimated return period between 50 and 100 years, peak storm flows are significantly lower than Dunne (1978) gives as typical of areas with widespread Horton overland flow. The peak flows recorded correspond quite closely with the set Dunne uses to characterise areas where variable sources of runoff generation dominate.

This study is a statistical analysis of storm rainfall and flow data from the Ecca catchments. The objective is to identify simple prediction relationships for volume, peak, duration of storm flow hydrographs in terms of storm rainfall characteristics and simple indices of antecedent moisture conditions in the catchment. Because of a limited data base, the study must be seen as exploratory only, with the focus falling on the establishment of simple analysis procedures and objective definition of variables.

Study Area

Data for the analyses are the 1975 to 1979 records of rainfall, stream-flow and pan evaporation from three semi-arid Ecca River research catchments maintained by the Hydrological Research Unit, Rhodes University. Catchment A encloses catchments B and E (Figure 1) and the respective areas are 76 km^2, 10 km^2, and 24 km^2. Total basin relief is approximately 570 m and soils are shallow and stony on ridgetops, with deeper colluvial deposits in the valleys (Jolly, 1980). Vegetation is sparse, succulent woodland and scrub with a high proportion of bare ground through most of the year. All streams are ephemeral. Mean annual runoff for catchment A for the period of record is 2,477 x $10^6 m^3$ which represent about 7,5 per cent of the mean annual rainfall.

Methods

The approach to the analyses was dictated by a need to keep all methods and procedures as objective as possible. Streamflow hydrographs with a one hour time increment are separated into storm flows and delayed flow by the method of Hewlett and Hibbert (1967). Figure 2 depicts the way in which the various rainfall and runoff characteristics were defined. Note that the rainfall ordinates represent hourly totals, which was the finest time increment obtainable via the procedures used in the processing of raw data. A storm flow event begins when streamflow rises faster than the separation line (1,97 x 10^{-3} $mm.h^{-1}.h^{-1}$). Stream discharge at this time is the antecedent flow for the event. The separation line is projected at constant slope until it meets the falling limb of the hydrograph. Storm flow duration is

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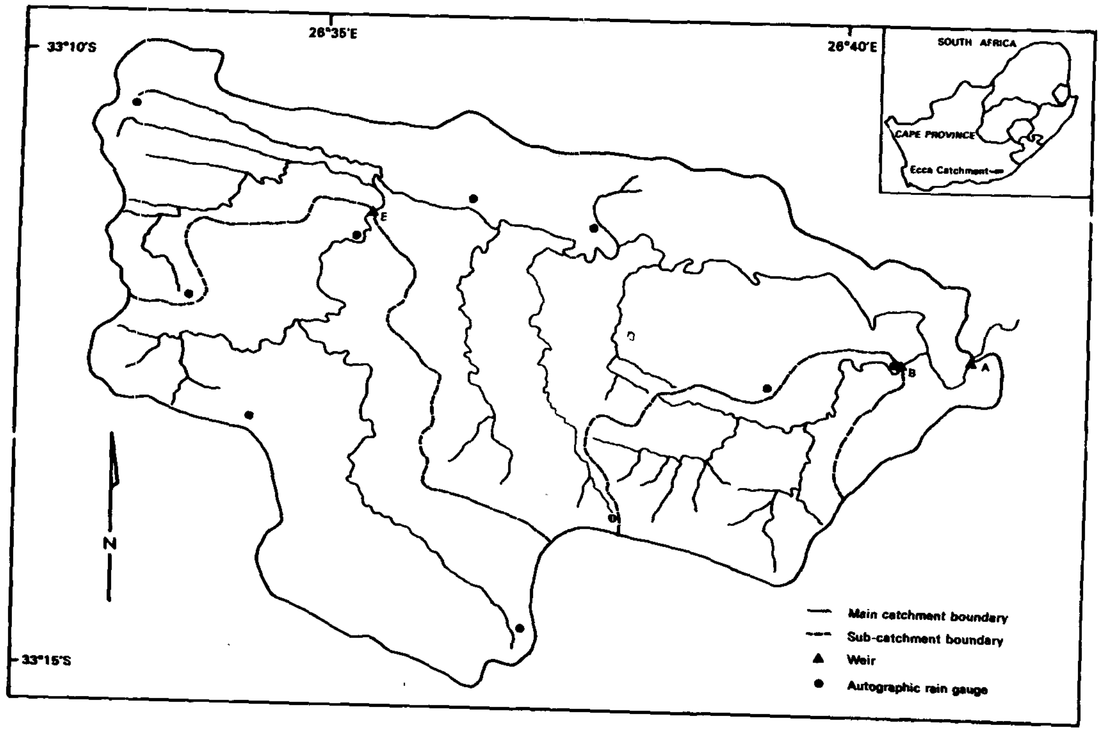

Figure 1
The Ecca research catchments near Grahamstown

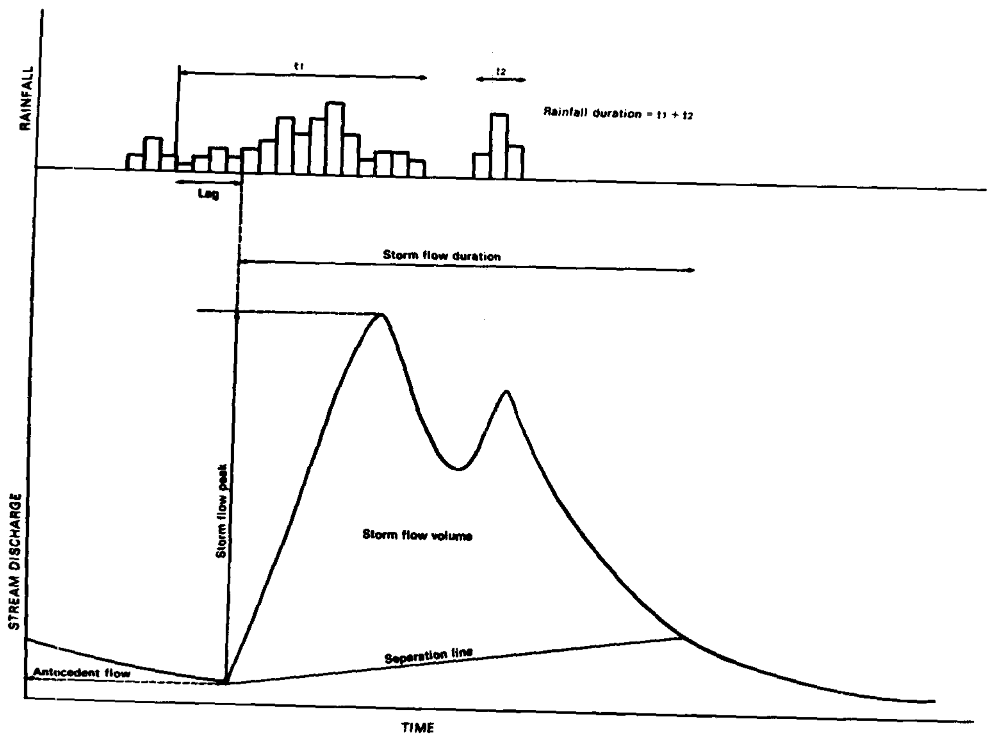

Figure 2
Definition of storm event variables

TABLE 1
STORM FLOW, RAINFALL AND ANTECEDENT RAINFALL FOR ECCA CATCHMENTS A, B, AND E

Date	Storm flow vol. mm	Storm flow peak mm/h	Storm flow duration h	Antecedent flow mm/h	Storm rainfall mm	Rainfall duration h	Maximum intens. mm/h	1-day antecedent rainfall (mm)	7-day antecedent rainfall (mm)	10-day antecedent rainfall (mm)
Catchment A										
21/3/76	0,011	0,0098	4,4	0,0019	13,6	8	3,6	16,4	36,5	40,5
21/3/76	3,998	0,3442	37,3	0,0086	40,1	22	8,2	23,3	50,2	54,2
29/3/76	0,015	0,0105	5,1	0,0060	14,4	10	3,1	0,0	1,6	72,0
27/2/77	0,022	0,0129	4,6	0,0001	30,8	4	16,8	0,0	3,3	21,9
28/2/77	0,281	0,0505	12,4	0,0008	27,9	15	7,8	30,8	34,1	52,7
6/3/77	0,483	0,1615	12,0	0,0002	7,0	5	3,6	5,5	64,2	64,9
7/5/77	0,216	0,0525	13,6	0,0027	21,5	8	9,4	33,8	42,2	42,3
1/12/77	0,028	0,0154	4,6	0,0012	15,8	2	14,5	5,0	42,5	42,5
30/12/77	0,033	0,0157	5,9	0,0019	11,4	12	2,5	35,9	63,1	63,6
10/1/78	0,028	0,0157	4,7	0,0001	19,5	4	16,6	0,4	2,9	21,1
11/1/78	0,031	0,0156	7,2	0,0044	8,0	4	4,1	19,6	22,6	27,7
4/2/78	0,001	0,0046	2,3	0,0019	22,4	2	16,6	0,0	7,1	21,9
20/4/78	0,041	0,0190	6,1	0,0004	33,7	12	6,5	11,8	19,6	20,1
21/4/78	0,886	0,1234	19,7	0,0032	36,3	15	9,9	33,2	54,7	54,7
28/2/79	0,014	0,0098	4,1	0,0000	26,9	5	27,1	27,1	61,2	61,7
21/7/79	24,615	1,5288	56,4	0,0001	125,4	27	15,4	28,9	29,4	29,4
24/7/79	5,819	0,5004	33,7	0,0751	29,0	24	4,0	1,4	155,6	156,1
20/8/79	36,054	1,6697	85,3	0,0041	105,2	55	5,1	0,0	5,9	12,3
26/8/79	0,051	0,0310	8,0	0,0686	4,9	4	2,2	0,0	105,2	110,0
15/9/79	0,002	0,0053	2,7	0,0158	5,8	7	2,2	15,4	15,4	16,0
Catchment B										
3/1/76	0,004	0,0063	2,0	0,0000	20,9	3	13,4	0,0	6,3	28,0
9/1/76	0,489	0,3168	4,2	0,0000	17,9	5	16,3	0,0	21,9	24,5
6/2/76	0,021	0,0163	3,3	0,0000	21,0	7	10,2	11,8	15,7	18,3
10/2/76	0,001	0,0034	1,6	0,0000	8,0	5	2,7	9,3	50,0	50,0
2/3/76	0,006	0,0078	2,2	0,0000	11,7	4	4,3	5,2	18,3	18,3
21/3/76	0,068	0,0437	6,2	0,0034	13,8	7	3,6	15,4	34,9	37,3
21/3/76	3,575	0,3784	32,2	0,0078	39,6	19	8,3	19,9	48,7	48,7
28/3/76	0,006	0,0070	2,4	0,0029	6,5	4	3,4	5,9	7,4	77,9
27/2/77	0,481	0,3168	5,8	0,0000	37,1	3	25,9	0,0	3,2	22,0
28/2/77	0,877	0,3135	15,8	0,0000	30,5	14	11,3	37,1	37,5	69,0
6/3/77	0,679	0,5172	6,8	0,0000	11,0	5	7,6	6,8	74,4	74,8
24/4/77	0,028	0,0215	3,2	0,0000	13,4	3	10,8	16,0	16,5	25,6
7/5/77	0,020	0,0182	3,6	0,0000	15,4	6	6,3	20,8	29,8	29,8
7/5/77	1,458	0,4496	18,1	0,0029	15,2	6	11,4	36,2	45,2	45,2
26/11/77	0,014	0,0133	3,0	0,0000	15,0	5	10,9	14,5	14,5	16,2
1/12/77	0,415	0,2560	5,9	0,0000	19,8	2	18,7	6,5	41,1	41,1
30/12/77	0,137	0,0471	6,9	0,0000	41,5	10	11,0	23,7	25,4	25,4
30/12/77	0,001	0,0022	1,1	0,0126	7,9	4	2,6	56,8	58,0	58,5
1/1/78	0,001	0,0030	1,5	0,0044	2,5	4	1,0	10,9	78,9	79,4
9/1/78	0,159	0,1127	4,2	0,0000	20,6	3	16,6	0,1	2,9	64,3
20/4/78	0,077	0,0378	6,2	0,0000	23,9	10	6,4	20,0	27,3	27,8
21/4/78	0,907	0,1625	15,9	0,0000	38,2	11	11,8	20,3	55,7	55,7
2/11/78	0,009	0,0097	2,6	0,0000	15,5	6	10,2	7,0	7,0	21,5
21/2/79	0,001	0,0044	2,1	0,0000	16,7	6	6,8	16,5	16,8	18,7
28/2/79	0,197	0,1046	4,4	0,0000	27,1	5	12,7	11,9	15,6	49,1
20/7/79	23,610	1,6702	59,1	0,0000	126,7	25	14,8	29,5	30,3	30,3
24/7/79	0,406	0,6032	35,6	0,0775	29,4	23	4,1	1,4	157,5	158,4
11/8/79	0,001	0,0036	1,8	0,0041	3,5	4	2,5	1,9	1,9	1,9
20/8/79	0,001	0,0041	2,1	0,0019	21,2	6	4,9	7,7	13,5	20,2
20/8/79	21,287	0,7423	79,2	0,0060	79,5	44	5,3	18,5	24,2	31,0
26/8/79	0,086	0,0409	7,2	0,0545	3,7	3	2,2	0,0	98,0	102,5
31/8/79	0,001	0,0074	5,0	0,0319	7,4	5	2,9	0,0	3,7	26,2
15/9/79	0,023	0,0145	6,1	0,0226	14,9	9	4,5	0,0	0,0	0,6
Catchment E										
21/3/76	1,650	0,1667	24,3	0,0000	27,5	11	6,9	32,5	70,5	70,5
28/3/76	0,005	0,0085	4,1	0,0025	14,5	9	3,0	0,0	0,6	77,7
7/5/77	0,214	0,0879	7,6	0,0000	19,7	4	11,3	46,8	55,6	55,7
3/2/78	0,007	0,0083	2,2	0,0000	23,4	3	14,5	0,0	4,2	21,7
21/7/79	14,774	1,4839	45,3	0,0000	95,3	19	16,4	57,1	57,7	57,7
23/7/79	5,372	0,5518	34,1	0,0521	29,9	21	4,2	1,7	154,2	154,8
20/8/79	14,650	0,8304	80,4	0,0000	109,9	49	4,5	0,0	4,7	11,4
26/8/79	0,132	0,0290	8,7	0,0583	5,8	4	2,9	0,0	99,9	114,6
31/8/79	0,007	0,0142	5,9	0,0235	7,8	5	3,3	0,0	5,8	35,4
1/9/79	0,001	0,0041	2,1	0,0251	6,5	7	2,7	0,0	7,8	13,7
15/9/79	0,001	0,0023	1,1	0,0080	14,7	5	6,4	0,0	0,0	0,6
15/9/79	0,004	0,0058	2,8	0,0134	4,2	5	3,4	14,7	14,7	19,5
15/9/79	0,005	0,0072	3,6	0,0188	5,4	5	2,0	18,9	18,9	19,5
10/10/79	0,018	0,0102	5,1	0,0000	11,8	5	4,4	5,5	7,0	7,0
19/10/79	0,003	0,0044	2,2	0,0004	8,8	5	3,3	0,1	7,5	26,2

the time between these two points. The volume of storm flow is the volume of water contained between the total streamflow hydrograph and the separation line. Storm flow peak is the difference between maximum discharge during the event and antecedent flow. A variable, termed total flow, was defined by a horizontal line projected from the point where storm flow begins (Lynch *et al.*, 1979) but correlations were unremarkable and it was eliminated after initial analyses.

In semi-arid environments there are storms for which there is no runoff and similarly there are storms where runoff begins only after several hours of rainfall; consequently, an objective distinction between storm rainfall and antecedent rainfall had to be made via a simple lag analysis. (Hewlett *et al.*, 1977) The modal value of time between peak rainfall and intensity (centre of the peak hour) and peak runoff rate for all storms in each catchment is subtracted from the time when storm flow begins (Figure 2). This procedure allows for the effects of both the usual response lag phenomena in a catchment and possible clock errors in the raw data. (Modal lags were used, because the predominance of long duration antecedent rainstorms with uniform intensities made the definition of a representative mean lag impossible). Storm rainfall is the observed depth from this time to the end of the storm flow event and rainfall duration is the number of hours in which rainfall is recorded. Maximum intensity is the highest hourly rainfall total during the storm. With storm rainfall defined, an alternative dependent variable to storm flow volume is calculated by expressing storm flow volume as a percentage of storm rainfall (Dickinson and Whiteley, 1970). The variable is termed hydrological response (HR).

Analyses of catchment B data showed that accumulated rainfall for periods up to 8 days before a storm event could improve prediction equations (Van Wyk, 1980). Accumulated rainfalls for from one to ten days before storm events give 10 antecedent rainfall variables. These are based on daily rainfalls except for the one-day antecedent value which is the total rainfall in the 24 h prior to the beginning of the storm event. Ten more antecedent variables (antecedent moisture index) were calculated as the differences between antecedent rainfall and corresponding accumulated daily potential evapotranspiration based on U.S. Weather Bureau Class A pan evaporation data. Statistical independence cannot be assumed within or between the two sets of antecedent variables; the object of their inclusion is to select the most suitable variable as an index of catchment wetness for the prediction equations. The use of standard antecedent moisture indices, such as weighted antecedent rainfalls, was considered, but rejected in order to restrict subjectivity in the analysis procedure as much as possible.

Objective application of the storm flow definitions gives 20, 33, and 15 events in catchment A, B and E respectively. Storm rainfall and flow variables for all events are shown in Table 1. Antecedent variables shown are restricted to one-day, 7-day, and 10-day antecedent rainfalls to save space. In all three catchments the record is dominated by two events, in July and August 1979. These gave by far the highest flows of the five year period, and during the subsequent recession there are several events when quite small rainfalls on wet catchments gave marked rises in flow. This is particularly so for catchment E where 11 of the 15 events occur in 1979. The very small events at this and other times are retained in the analysis because it is quite clear that they are responses to rainfall and the already small sample sizes would be unacceptably reduced if some threshold criterion of size was enforced.

Analyses of the data include calculation of correlation matrices for each catchment, and then derivation, by multiple regression, of equations to predict storm flow variables. Since several prediction variables are highly correlated, some were discarded during the execution of the multiple regression analyses, which then became a search for the "best" two or three independent variables describing the storm and catchment condition. Furthermore, the search has not been for the best prediction equation for each catchment, rather it was for a single set of variables that was best over all three catchments, thus imparting some small degree of regional generality to the derived relationships. The possibility of a single relationship for all catchments was also tested at each stage.

Raw data, log base (base 10) and cube root transformations were all tested, the last being advantageous when zero and negative (in the antecedent moisture indices) values appear in the raw data set. Cube root transformations for rainfall data have been employed successfully by, for example, Hogg *et al* (1978) and Howell (1965).

Results

The correlation matrices showed only weak association between peak flow and maximum intensity, but there are satisfactory correlations on all catchments between storm flow volume and both storm flow peak and storm flow duration. The log transformation of the last three variables improved correlations and distributions of the data, and so linear relationships, between the transformed variables, were derived to predict peak and duration of storm flow from storm flow volume (Table 2). All regression coefficients are significantly different from zero at the 5% level. Figures 3 and 4 show plots of the transformed data and a single relationship for all three catchments is not unreasonable. Catchment B may be under-estimated in peaks and over-estimated in durations at high storm flow volumes by this combined equation. In view of the limited sample used, an extended investigation using data from other semi-arid catch-

TABLE 2
STATISTICS FROM LINEAR REGRESSIONS OF STORM FLOW PEAK AND STORM FLOW DURATION ON STORM FLOW VOLUME, ALL VARIABLES WITH LOG. TRANSFORMATION

Catchment	Regression slope b	Coefficients intercept a	Explained variance r^2
Peak as dependent variable			
A	0,60	−0,80	0,97
B	0,59	−0,63	0,94
E	0,56	−0,77	0,96
pooled	0,58	−0,72	0,94
Duration as dependent variable			
A	0,34	1,30	0,97
B	0,30	1,12	0,82
E	0,34	1,30	0,95
pooled	0,32	1,22	0,88

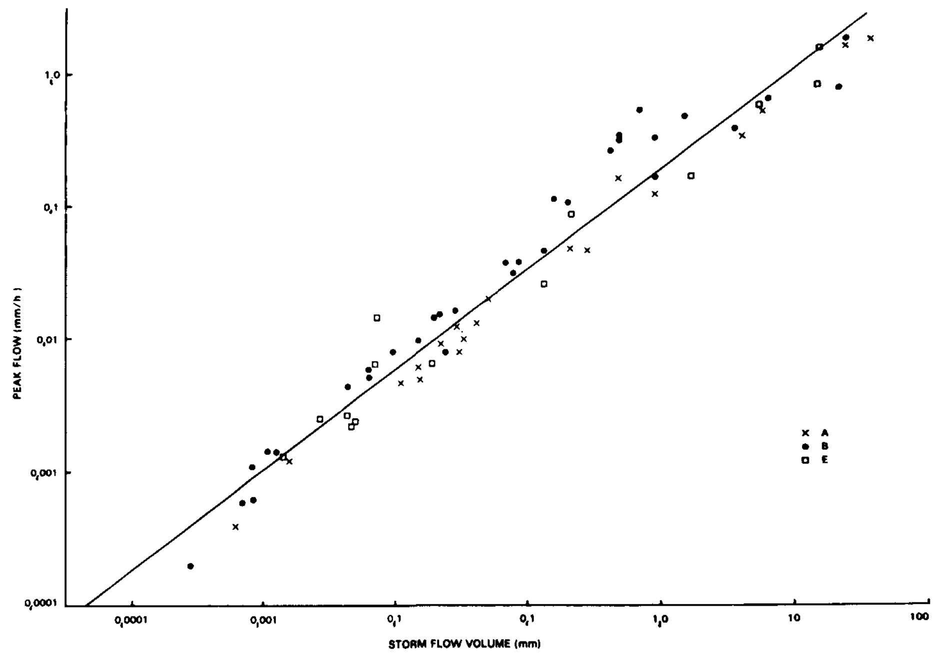

Figure 3
Regression of peak flow on storm flow volume

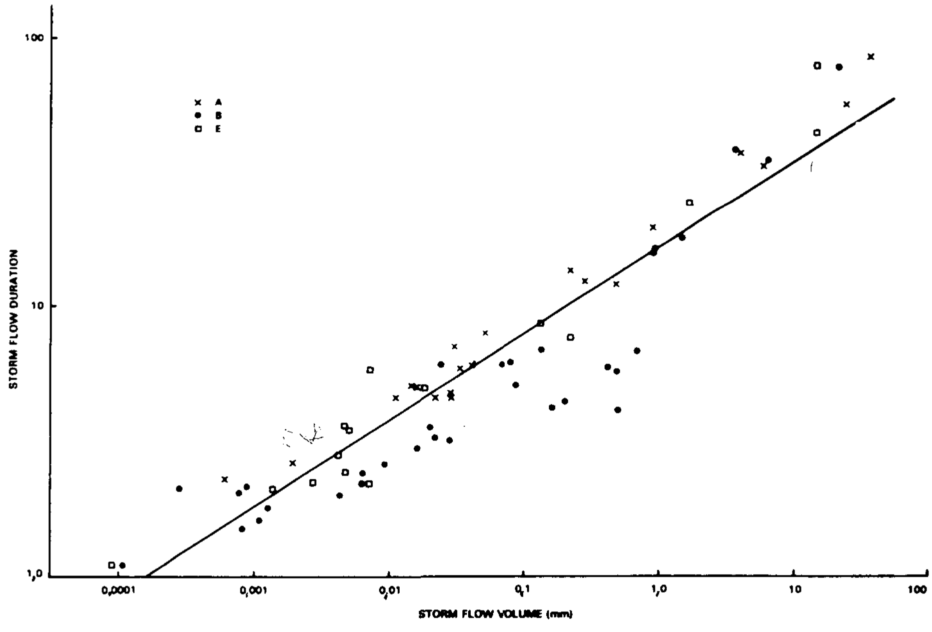

Figure 4
Regression of storm flow duration on storm flow volume

ments would be worthwhile to determine the generality of the relationship.

Subsequent analyses were aimed at finding suitable prediction equations for storm flow volume. Initial trials showed maximum intensity and antecedent flow were going to be of little use in increasing explained variance of storm flow volume. In several cases their regression coefficients were negative which does not accord with accepted conceptualisations of the runoff process and so both variables were deleted from further analyses. The choice of suitable dependent and independent variables involves four interrelated questions:

1. Which of storm flow volume and hydrological response is the better dependent variable for prediction of storm flow peak?

2. Should magnitude of storm be described by storm rainfall or rainfall duration? As the two are strongly correlated, both cannot be included in regression equations.

3. Which, if any, of the catchment antecedent wetness indices should be included?

4. Are the transformations of any assistance in developing precise prediction equations?

With respect to the variables of questions 1 and 2, transformations are of little value (Table 3). The correlation coefficients show that of the four possible combinations, two appear about equally favourable: storm flow volume with storm rainfall, and hydrological response with rainfall duration tend tc give higher correlation coefficients than the other two combinations. Simple correlations, however, are not necessarily a measure of how a combination of two independent variables will correlate with a dependent variable. Therefore the four possible combinations of the two dependent and independent variables of questions 1 and 2 are grouped with all the antecedent variables in separate, stepwise, multiple regression analyses. Three independent variables made significant contributions to explained variance in only a few cases, mostly only two independent variables met the significance criterion. Neither transformation consistently improved coefficients of determination and so raw data are preferred for the equations.

By successive elimination, 7-day antecedent rainfall and 7-day antecedent moisture index are selected as the two best indicators of catchment wetness at the beginning of an event. This was not entirely consistent over all catchments. In the first set of regression analyses 7-day antecedent rainfall or moisture index was chosen more frequently than any other single antecedent varible. In cases where the 7-day value was not chosen, however, a recalculation, with it as a compulsory selection, only slightly reduced the explained variances. Table 4 shows coefficients of determination from regressions, with either 7-day antecedent rainfall or 7-day antecedent moisture as the second independent variable. Since the two appear quite similar in their effects, the former is selected on the basis of simplicity. Table 4 also shows that the two best combinations of dependent variables and storm magnitude in simple regressions are still superior in multiple regression equations. On catchments A and B hydrologic response with storm duration is marginally better,

TABLE 3
SIMPLE CORRELATION COEFFICIENTS FOR 4 VARIABLES, AND 2 TRANSFORMATIONS

Catchment	Transformation / Dependent variable	Raw data: Storm rain.	Raw data: Storm dura.	Cube Root: Storm rain.	Cube Root: Storm dura.	Log (base 10): Storm rain.	Log (base 10): Storm dura.
A	Storm flow volume mm	0,91	0,90	0,82	0,86	0,64	0,80
	Hydrolog. Response %	0,79	0,92	0,64	0,81	0,58	0,78
B	Storm flow volume mm	0,89	0,86	0,80	0,81	0,70	0,58
	Hydrolog. Response %	0,70	0,89	0,63	0,70	0,63	0,55
E	Storm flow volume mm	0,97	0,86	0,91	0,89	0,75	0,74
	Hydrolog. Response %	0,77	0,76	0,77	0,80	0,70	0,71

TABLE 4
COEFFICIENTS OF DETERMINATION (r^2) WITH 2 INDEPENDENT VARIABLES: 7-DAY ANTECEDENT RAINFALL/ MOISTURE INDEX, AND STORM RAINFALL/DURATION

Catchment	Dependent variable	Independent variable (other than 7-day index): Antecedent Rainfall: Storm rain.	Antecedent Rainfall: Storm dura.	Antecedent Moist. Index: Storm rain.	Antecedent Moist. Index: Storm dura.
A	Storm flow volume	0,83	0,83	0,83	0,83
	Hydrol. Response	0,73	0,87	0,74	0,87
B	Storm flow volume	0,82	0,75	0,83	0,75
	Hydrol. Response	0,69	0,85	0,73	0,85
E	Storm flow volume	0,96	0,75	0,97	0,75
	Hydrol. Response	0,90	0,85	0,90	0,85
Combined	Storm flow volume	0,80	0,75	0,81	0,75
	Hydrol. Response	0,71	0,82	0,73	0,82

TABLE 5(a)
REGRESSION COEFFICIENTS FOR PREDICTING HYDROLOGICAL RESPONSE FROM 7-DAY ANTECEDENT RAINFALL AND RAINFALL DURATION

$Y_1 = a_1 + b_1x_1 + b_2x_2 \pm$ Error

Y_1 is hydrological response (%)

X_1 is storm duration (hours)

X_2 is seven-day antecedent rainfall (mm)

Catchment	a_1	b_1	b_2	r^2	Standard Error
A	−5,00	0,68	0,04	0,87	3,02
B	−3,81	0,65	0,05	0,85	4,03
E	−2,68	0,37	0,07	0,85	2,39
Pooled	−3,79	0,58	0,05	0,82	3,68

TABLE 5(b)
REGRESSION COEFFICIENTS FOR PREDICTING STORM FLOW VOLUME FROM 7-DAY ANTECEDENT RAINFALL AND STORM RAINFALL

$Y_2 = a_2 + b_3x_3 + b_4x_4 \pm$ Error

Y_2 is storm flow volume (mm)

X_3 is storm rainfall (mm)

X_4 is seven-day antecedent rainfall (mm)

Catchment	a_2	b_3	b_4	r^2	Standard Error
A	−5,17	0,28	0,01	0,83	3,90
B	−3,77	0,21	0,02	0,82	2,49
E	−1,97	0,15	0,01	0,96	1,04
Pooled	−3,60	0,22	0,01	0,80	3,05

while on catchment E storm volume with storm rainfall has the highest coefficient of determination. Pooling data from all catchments gives slightly lower explained variances, and hydrologic response with storm duration is the best combination, reflecting the influence of the larger sample sizes of catchment A and B. Regression coefficients for the two pairs of variables with 7-day antecedent rainfall as the second independent variable in both cases are shown in Table 5. Since the data do not meet all the requirements for regression analysis, significance tests for regression coefficients and constants were not made, but the relationships for catchment E appear different from those of the other two catchments. Figure 5 shows observed and predicted hydrological response calculated from the equations of Table 5(a), and also reveals the effects of the small number of large events. The position of the regression surface is strongly influenced by these extreme values. On catchment E the response to one of the two large storms appears quite different from response on the other catchments and this has altered the regression coefficients considerably.

When rainfall duration is plotted against hydrological response (Figure 6) the low response of catchment E to the longest storm is evident. For all catchments the diagram shows an apparent threshold of storm duration of about 12 h, above which hydrological response increases, but shows no easily discernable pattern. For durations less than 12 h hydrological response varies widely and includes many zero and near zero values. It was expected that for short duration storms the antecedent rainfall variables would be more important but a regression analysis of only events with storm durations less than 12 h gave very poor correlations.

Since the data for these analyses are selected on the basis of flow events, there will be many other storms in the record *with no flow response*. It is possible, though unlikely, that some of these could have rainfall durations greater than 12 h. Furthermore, while it is conceivable that a low intensity, long duration storm may not cause a flow response, any very high intensity storm is almost certain to produce runoff. Thus there are intuitive difficulties with storm duration as a predictor variable. The alternative pairing of dependent-independent variables is preferred: storm flow volume is the dependent variable, with storm rainfall and 7-day antecedent rainfall as the independent variables. Coefficients for these equations, by catchments and pooled, are shown in Table 5(b).

The prediction equations for storm flow peak and duration given in Table 2 were derived from observed storm flow volumes (Table 1). The question now arises how the predictive performance of these equations is affected by using *predicted* storm flow volumes (Table 5(b)) as independent variables, as opposed to *observed* values. The former case is, after all, the typical procedure in a design situation. Table 6 casts some light on this question.

Both statistics used in this test as fitting criteria, i.e. the

TABLE 6
DETERIORATION IN PREDICTIVE PERFORMANCE OF STORM FLOW PEAK AND DURATION EQUATIONS WHEN USING PREDICTED INSTEAD OF OBSERVED STORM FLOW VOLUMES AS THE INDEPENDENT VARIABLE

Catchment	Standard error		Coefficient of efficiency	
	Observed case	Predicted case	Observed case	Predicted case
Storm flow peak as dependent variable				
A	0,13	0,24	0,93	0,77
B	0,17	0,22	0,74	0,57
E	0,20	0,23	0,79	0,72
Pooled	0,14	0,21	0,87	0,73
Storm flow duration as dependent variable				
A	4,49	14,75	0,96	0,53
B	10,85	12,42	0,61	0,48
E	8,42	11,95	0,86	0,72
Pooled	9,07	12,76	0,79	0,58

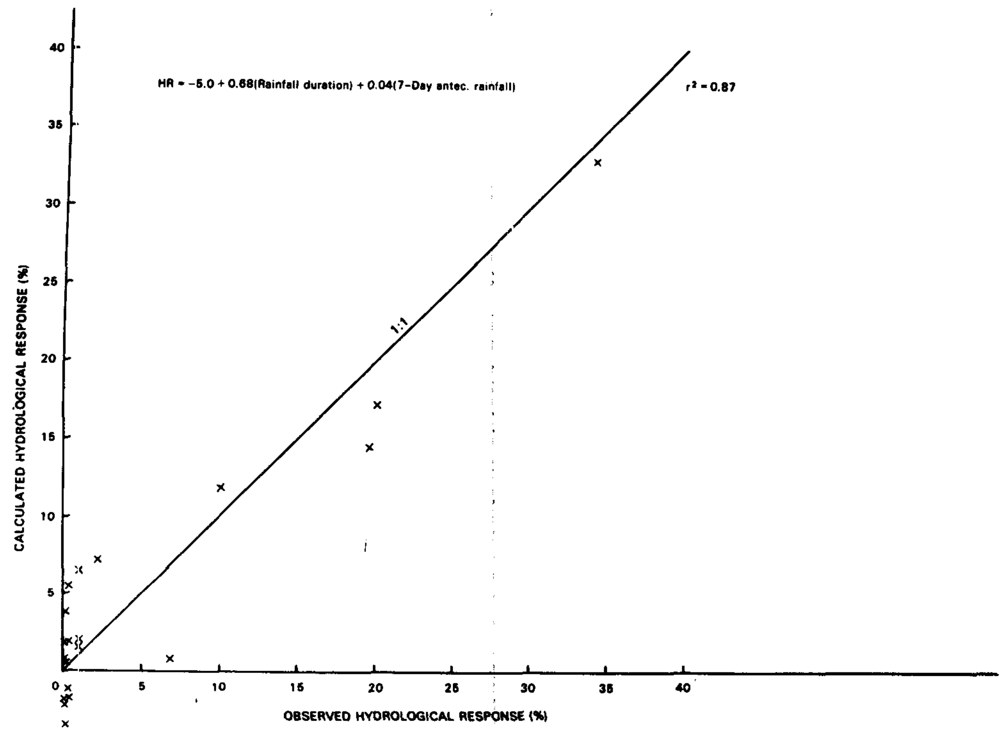

Figure 5(a)
Catchment A: Observed and calculated hydrological response.

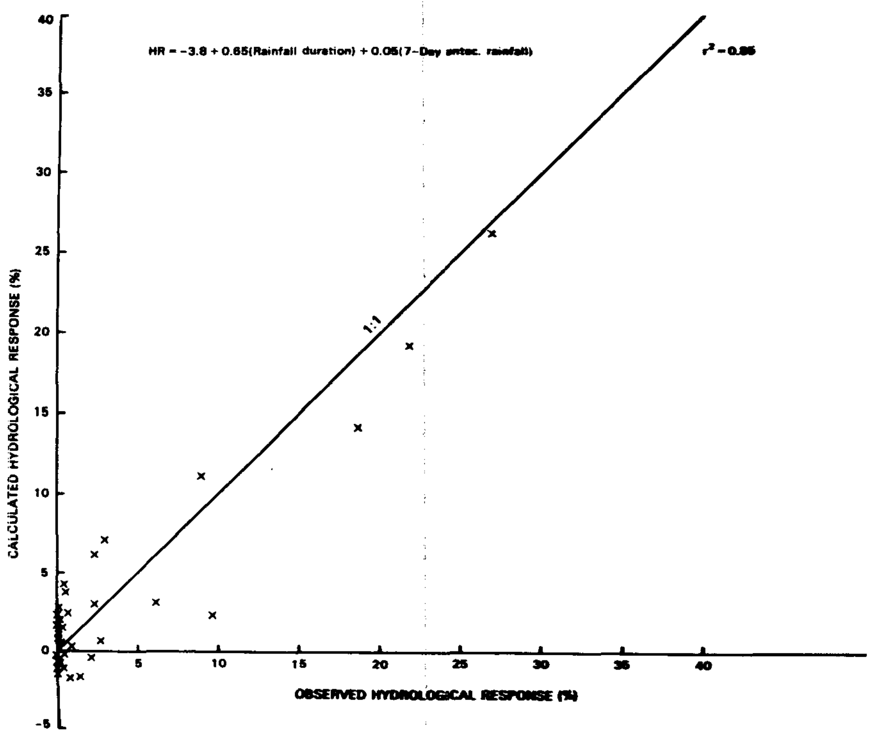

Figure 5(b)
Catchment B: Observed and calculated hydrological response

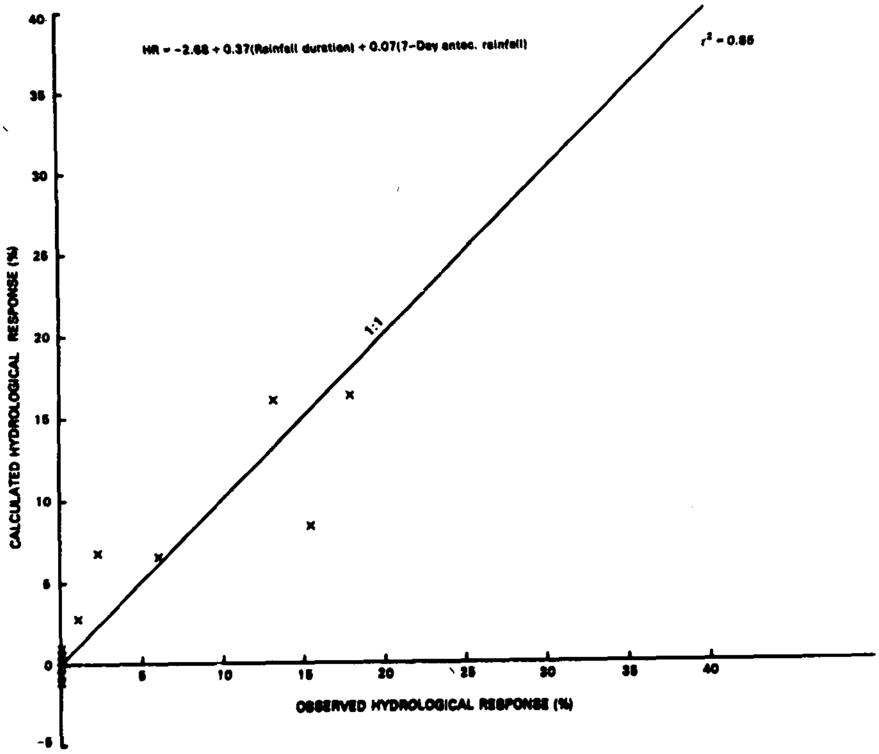

Figure 5(c)
Catchment E: Observed and calculated hydrological response

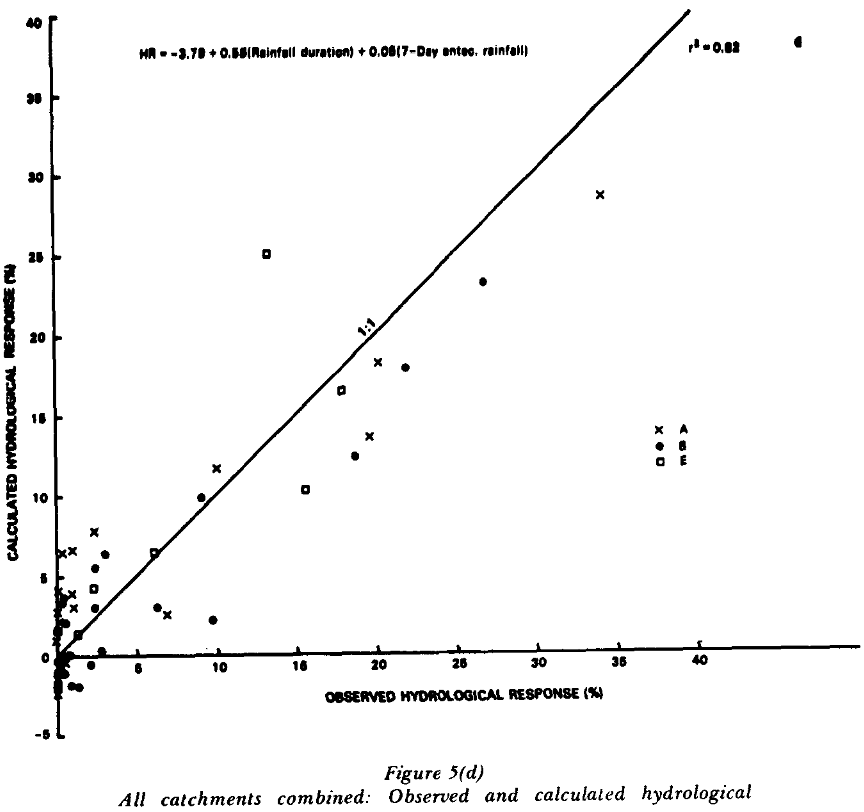

Figure 5(d)
All catchments combined: Observed and calculated hydrological response

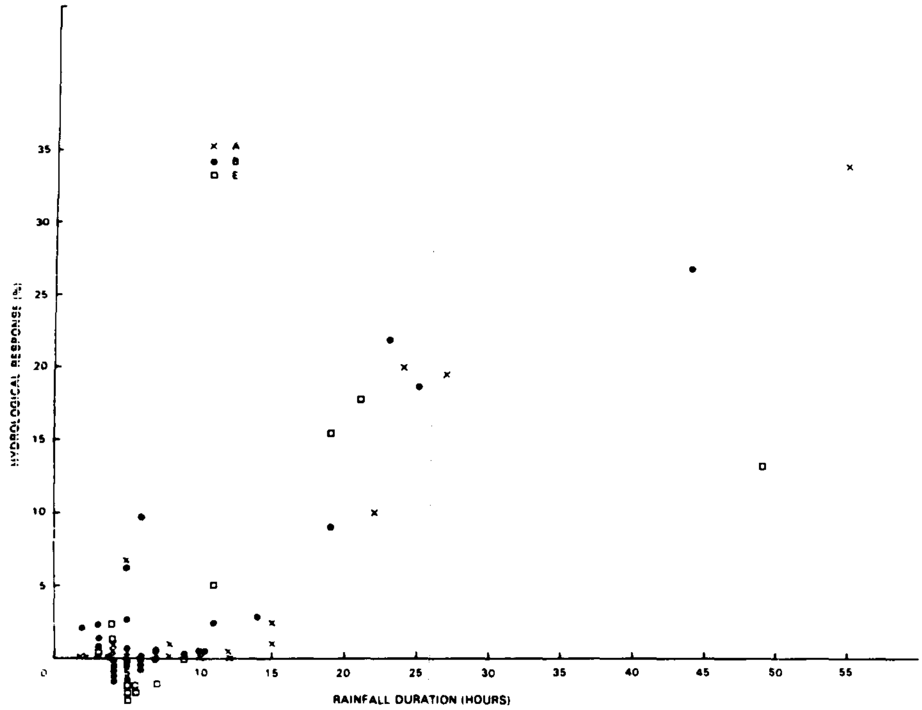

Figure 6
Variation of hydrological response with rainfall duration

standard error (Haan, 1977) and the coefficient of efficiency (Aitken, 1973), showed marked deterioration while changing from the observed independent variable case to the predicted independent variable case. Closer investigation revealed that this deterioration was mostly caused by negative storm flow volumes predicted for the majority of the small storms. However, the high storm flow peaks and long durations were generally satisfactorily predicted, and the storm flow peak equations seem more robust than the duration equations. The inconclusiveness of this test again points to the need for a larger data base containing more runoff events of larger magnitude before a set of robust prediction equations can be developed. In the semi-arid environment this may take many years to accomplish.

Conclusions

1. Storm flow volume and hydrological response can be predicted using storm rainfall and rainfall duration respectively, with 7-day antecedent rainfall as a second independent variable in the equations for both cases. Pooling data for all catchments give only a small reduction in the level of explanation of the equation.

2. On the Ecca catchments storm flow peak and duration may be predicted from storm flow volume. A single relationship for all three catchments is suitable for peak flows but is less adequate for duration of storm flow and further investigations are required on other semi-arid catchments.

3. In all cases the regression coefficients have been strongly influenced by data from two large storms and the rather limited sample size. For this reason the prediction equations must be regarded as provisional only.

4. In view of the simplicity, and ease of derivation of the variables used and the relatively high levels of explanation achieved, it is worthwhile extending the analyses to other semi-arid catchments. Relationships independent of catchment area or including area as an independent variable, would be of considerable value in applied hydrology in this environment.

Acknowledgements

This project is part of continuing research funded by the Water Research Commission. The senior author expresses his gratitude to the Commission for supporting his visit to South Africa. Diagrams were drawn by Mrs. D. Joustra of the Hydrological Research Unit.

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