Journal of Arid Environments (1985) **9**, 13–25

Variation of runoff with watershed area in a semi-arid location

W. C. Boughton* & J. J. Stone†

Accepted 6 January 1984

The effect of transmission loss in reducing the observed depth of runoff as catchment area increases is studied in a semi-arid location. Variation of mean annual runoff with catchment area, and variation in the frequency distribution of annual depths of runoff with catchment area, are evaluated; and the effect of transmission loss on the U.S. Soil Conservation Service Curve Number is reported.

Introduction

Since 1954 the Agricultural Research Service of the U.S. Department of Agriculture has made an intensive study of rainfall and runoff in the semi-arid Walnut Gulch experimental area near Tombstone in south-eastern Arizona. Dense networks of recording rain gauges and precalibrated runoff measuring structures have been used to clarify the characteristics of rainfall and runoff, and the hydrological processes of runoff generation in this area (Renard, 1970, 1977). The experimental area is located in an intermountain basin where air-mass thunderstorms dominate the annual precipitation. About two-thirds of the 355 mm (14 in) annual precipitation occurs during June–October from limited areal extent, high intensity thunderstorms (Renard & Brakensiek, 1976). Runoff is ephemeral and is highly variable in time and space.

In the 1960s, stepwise multiple regression analysis was used to relate runoff to catchment and meteorological variables. Schreiber & Kincaid (1967) used data from 1·83 m by 3·65 m (6– by 12–foot) plots and showed that average runoff increased as the quantity of precipitation increased, decreased as the crown spread of vegetation increased, and increased as antecedent soil moisture increased. These independent variables accounted for 72, 3 and 0·5 per cent of the variance in the runoff prediction equation developed. Osborn & Lane (1969) used data from four small catchments, 0·23–4·45 ha (0·56–11·0 acres) in area, to relate volume of runoff to total storm precipitation and to maximum 15-min precipitation during the storm. Small areas were used deliberately in these studies because it was known that transmission losses in the stream channel and spatial precipitation variability had a substantial effect on the amount of runoff observed from catchments of different sizes in this region. Renard (1970) reported that 'on-site' runoff (precipitation excess) on Walnut Gulch averaged about 50 mm (2 in) per year but only about 6 mm (0·25 in) per year of surface runoff emerged from the outlet of the 150 km^2 (58 m^2) experimental area. The remaining 44 mm (1·75 in) of on-site runoff was abstracted as transmission loss as runoff flowed through dry stream channels *en route* to the outlet. Several procedures have been developed to estimate transmission loss (*see*, for example: Lane, Diskin *et al.*, 1971; Lane, 1980; Lane, 1982).

---

* School of Australian Environmental Studies, Griffith University, Brisbane, Queensland 4111, Australia.
† USDA-ARS Southwest Rangeland Watershed Research Center, 2000 E. Allen Road, Tucson, Arizona 85719, U.S.A.

0140–1963/85/040013+13 $03.00/0

Sufficient data have now been collected in the Walnut Gulch area for direct frequency analysis of annual runoff volumes. This paper reports a study of the frequency distributions of runoff from catchments of different size at Walnut Gulch to show how catchment area affects the distribution of runoff.

Mean annual runoff vs. catchment area

Data from 12 gauged catchments in the Walnut Gulch experimental area (see Fig. 1 for location) were used in the study. The catchments ranged from 0·013 km^2 to 149 km^2 in area and the lengths of record ranged from 10 to 18 years.

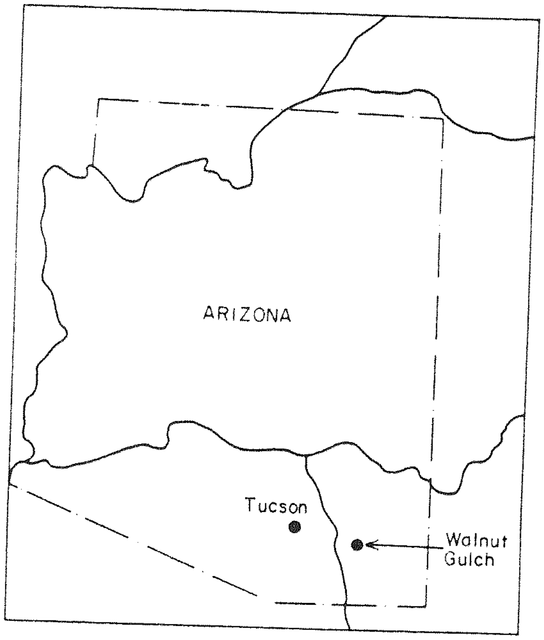

Figure 1. Location of study area.

Table 1 shows details of the 12 catchments, the periods of record available for analysis, and the mean annual runoff in mm depth for each catchment based on the available record. The catchments are listed in the Table in increasing order of catchment size. The trend for decreasing annual runoff with increasing catchment area is evident from the tabulated figures and from Fig. 2 which shows the data plotted. The straight line on Fig. 2 is a linear regression of the logarithm of mean annual runoff on the logarithm of catchment area. The regression converts to the following equation:

$$Q = 11{\cdot}6\, A^{-0{\cdot}193} \qquad (1)$$

where Q represents mean annual runoff in mm and A represents catchment area in km^2. Equation (1) is similar to an earlier result for the same experimental area reported by Renard (1970). Converting Renard's equation from inches and acres to millimetres and square kilometres gives equation (2).

$$Q = 17{\cdot}0\, A^{-0{\cdot}151} \qquad (2)$$

The results obtained from equations (1) and (2) are compared in Table 2.

Catchm
identi

63·101
63·112
63·103
63·214
63·011
63·003
63·008
63·005
63·015
63·006
63·002
63·001

An e
the dif
1957–6
1968–7
of 4·7
whole
region
the var
records
adopte
danger
variatio
evaluati
climatic
Equa

Figure 2.

Table 1. *Mean annual runoff from twelve catchments in the Walnut Gulch experimental area.*

Catchment identity No.	Record		Area (km^2)	Mean annual runoff (mm/year)
	Years	Period		
63·101	13	1963–75	0·0130	27·6
63·112	13	1963–75	0·0186	22·2
63·103	13	1963–75	0·0368	23·6
63·214	15	1961–75	1·51	12·7
63·011	12	1963–74	8·24	15·1
63·003	17	1958–74	8·98	4·2
63·008	12	1963–74	15·5	8·2
63·005	15	1959–73	22·3	4·0
63·015	10	1965–74	23·9	5·1
63·006	13	1962–74	95·1	5·7
63·002	16	1959–74	114	4·8
63·001	18	1957–74	149	4·7

An examination of the records for the largest catchment (63·001) suggests a reason for the differences between the equations. Mean annual runoff from 63·001 over the period 1957–67 inclusive was 6·0 mm, while the mean annual runoff for the following 7 years 1968–74 inclusive was only 2·8 mm, compared with the mean based on the whole record of 4·7 mm. Renard used the early part of the record in deriving equation (2) while the whole record was used in deriving equation (1). The experimental area is located in a region that experiences very high variability in rainfall and runoff from year to year, and the variation between equations (1) and (2) is understandable with the relatively short records available. Equation (1) which is based on longer records than equation (2) is adopted here as the better estimate. The difference between the equations illustrates the danger of drawing conclusions from short records for climates where the coefficient of variation of annual rainfall is large. Knisel, Renard *et al.* (1979) describe some tests to evaluate objectively whether climatic records are of sufficient length to describe the climatic variability of a region.

Equation (1) shows that mean annual runoff reduces by 36 per cent for each tenfold

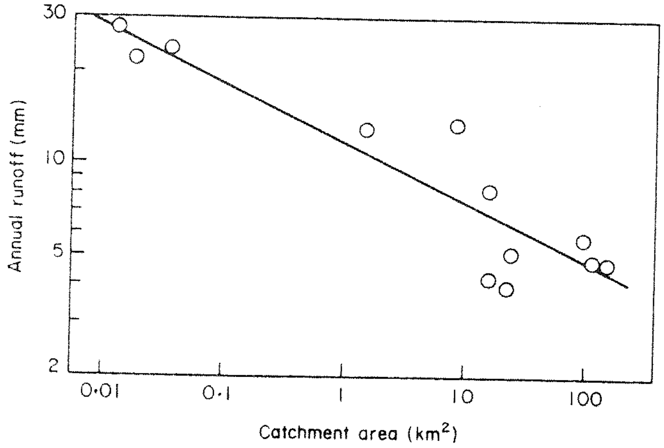

Figure 2. Effect of catchment area on mean annual runoff.

Table 2. *Estimates of mean annual runoff for various catchment areas, based on equation (1) and (2).*

Catchment area (km^2)	Calculated mean annual runoff (mm)	
	Equation (1)	Equation (2)
0·01	28·3	34·1
0·1	18·1	24·1
1·0	11·6	17·0
10	7·4	12·0
100	4·8	8·5

increase in catchment area. For catchment areas greater than 0·1 km^2, transmission loss in the stream channels is undoubtedly the major cause of the reduction in runoff from the larger sizes of catchment. For catchment areas less than 0·1 km^2 (10 ha) it seems doubtful that transmission losses are significant even though Table 1 suggests that mean annual runoff continues to increase as catchment area decreases down to about 0·01 km^2. There is very high spatial variability in runoff from the experimental area, and the differences in runoff among the three smallest catchments in Table 1 could reflect merely the spatial variations in runoff and not a continuation of the runoff vs. area relationship down to areas of 1 ha.

Frequency distributions of annual runoff

Those involved with the practical use of runoff data from small semi-arid catchments are usually more interested in the amount of runoff which can be expected to be equalled or exceeded for 3 in 4 years or 4 in 5 years, rather than the mean annual runoff. For this reason, frequency distributions of annual runoff are of more interest than the mean values.

Although the lengths of available record, 10–18 years, are short for frequency analysis, the data are adequate to show the effects of catchment area on the frequency distributions of runoff even though the absolute accuracy of the individual fitted distributions is uncertain. The method used to estimate the effect of area is as follows.

The log-Boughton distribution (Boughton, 1980) was fitted to base 10 logarithms of the annual volumes of runoff, using the optimal fitting procedures developed by Boughton & Shirley (1983). Copies of the research report (Boughton, 1981) which includes the computer program used for fitting the distribution and operating instructions for running the program are available on request to the Director, Southwest Rangeland Watershed Research Centre, 2000 E. Allen Road, Tucson, Arizona 85719, U.S.A.

The fitted distributions were used to estimate annual runoff depths for exceedence probabilities of 0·01, 0·10, 0·20, 0·30, 0·50, 0·70, 0·80, 0·90 and 0·99 for each catchment. These estimates are set out in Table 3.

Over the whole range of exceedence probabilities, there is a trend for decreasing annual runoff with increasing catchment area; however, there are variations from the general trend in individual catchments because of the extremely high variability of rainfall and runoff which occurs in this location, and because the records which were available for analysis are short enough to contain significant sampling variability.

Figure 3 shows the general trends of decreasing runoff with increasing catchment area for 0·01 and 0·50 probabilities of exceedence. The straight lines through each set of data are linear regressions based on logarithms of both runoff and catchment area. Similar linear regressions were fitted to the data for each of the probabilities of exceedence shown

', transmission
ction in runoff
km^2 (10 ha) it
l suggests that
down to about
ental area, and
l could reflect
unoff vs. area

atchments are
be equalled or
noff. For this
ian the mean

ency analysis,
he frequency
ividual fitted
s as follows.
logarithms of
developed by
1981) which
nd operating
r, Southwest
izona 85719,

r exceedence
·99 for each

r decreasing
ons from the
variability of
which were
bility.
chment area
h set of data
rea. Similar
dence shown

Table 3. *Fitted frequency distributions of annual runoff.*

Catchment Identity No.	Annual runoff in millimetres for specified probability of exceedence								
	0·01	0·10	0·20	0·30	0·50	0·70	0·80	0·90	0·99
63·101	76·2	49·5	39·9	33·5	24·6	17·3	13·7	9·7	3·6
63·112	94·0	53·1	37·3	28·2	15·2	6·9	3.6	1·0	*
63·103	60·7	42·2	34·5	29·2	21·3	14·7	11·2	7·1	1·5
63·214	29·5	21·3	18·0	15·7	11·9	8·9	7·1	5·1	1·5
63·011	53·1	29·0	21·1	16·3	10·1	5·8	4·1	2·3	0·3
63·003	22·1	9·7	6·1	4·3	2·0	0·8	0·5	0·3	*
63·008	27·9	17·3	13·2	10·4	6·6	3·6	2·3	1·0	0·2
63·005	9·9	7·9	6·6	5·6	3·6	1·5	0·5	0·1	*
63·015	11·2	9·4	8·1	7·1	5·1	2·3	0·8	0·1	*
63·006	19·1	11·9	9·1	7·4	4·6	2·5	1·5	0·8	0·1
63·002	12·7	9·1	7·4	6·1	4·3	2·5	1·5	0·5	*
63·001	16·8	9·9	7·4	5·8	3·8	2·3	1·8	1·0	0·2

Note: * denotes less than 0·1 mm.

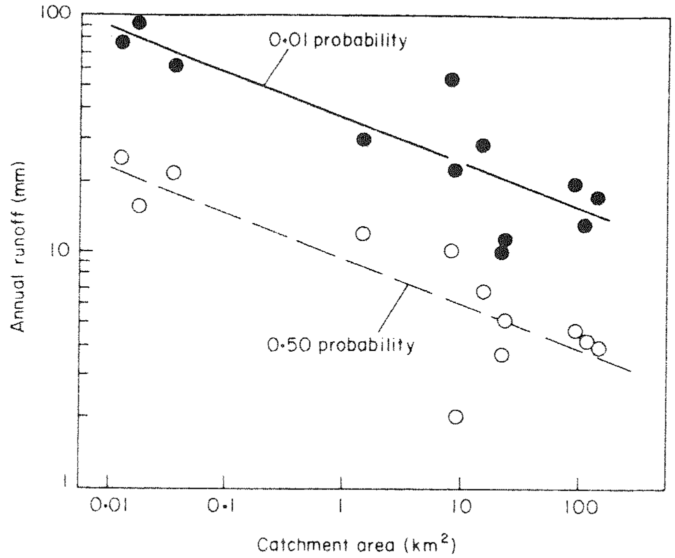

Figure 3. Decreasing runoff vs. increasing catchment area for 0·01 and 0·50 probabilities of exceedence.

in Table 3 (excluding 0·99), and the linear regressions were used to calculate the estimates of annual runoff shown in Table 4. The very low values of runoff, less than 0·1 mm, which occur in the 0·99 probability data made it impossible to derive any realistic regression and the column was omitted from the analysis.

The results in Table 4 show the general trend of decreasing runoff with increasing catchment area. These generalized results were compared to some of the original runoff data to see if any accuracy was lost in the smoothing process. Figure 4 shows the recorded data on catchment 63·002 (area = 114 km^2) compared to the estimated distribution from Table 4. Figure 4 shows the average of recorded data on the two smallest catchments, 63·101 and 63·112 (areas 0·0130 and 0·0186 km^2) compared to the average of their estimates in Table 4. It can be seen that the smoothing of the data has not introduced any errors of significance, and that the estimates in Table 4 give a good guide to the effect of catchment area on relative depths of annual runoff.

The results in Table 4 were generalized into an algebraic equation which evaluates the effects of both probability of exceedence and catchment size on annual runoff.

$$\text{Let} \quad K = 2{\cdot}5 + \frac{6{\cdot}54}{\ln\ln\left(\frac{T}{T-1}\right) - 2{\cdot}5}, \qquad (3)$$

where T represents the recurrence interval in years.

Using multiple linear regression, the following relationship was evaluated from the data in Table 4:

$$Q_T = 7{\cdot}0\, e^{1{\cdot}1K} A^{-0{\cdot}21}, \qquad (4)$$

where Q_T represents annual runoff in millimetres of recurrence interval T years, A represents catchment area (in square kilometres), and e = 2·71828 . . . .

Equation (4) is site specific for the Walnut Gulch geographic area and is not a universal relationship. It is worth noting that Murphey, Wallace *et al.* (1977) found that the mean volume of individual runoff events in this same area was proportional to $A^{-0{\cdot}2}$. Equation

Table 4. *Estimated frequency distributions of annual runoff based on regressions*

Catchment Identity No.	Annual runoff in millimetres for specified probability of exceedence							
	0·01	0·10	0·20	0·30	0·50	0·70	0·80	0·90
63·101	85·0	52·2	40·3	32·8	21·6	13·1	9·0	4·8
63·112	79·4	48·7	37·6	30·6	20·1	12·2	8·3	4·4
63·103	69·6	42·8	33·1	26·9	17·6	10·5	7·1	3·6
63·214	34·2	21·2	16·4	13·2	8·6	4·8	3·0	1·3
63·011	24·7	15·3	11·9	9·6	6·2	3·3	2·0	0·8
63·003	24·3	15·1	11·7	9·4	6·1	3·3	1·9	0·8
63·008	21·9	13·6	10·5	8·5	5·5	2·9	1·7	0·7
63·005	20·4	12·7	9·8	7·9	5·1	2·7	1·6	0·6
63·015	20·1	12·5	9·7	7·8	5·0	2·7	1·5	0·6
63·006	15·4	9·6	7·5	6·0	3·8	2·0	1·1	0·4
63·002	14·9	9·3	7·2	5·8	3·7	1·9	1·1	0·4
63·001	14·2	8·9	6·9	5·5	3·5	1·8	1·0	0·4

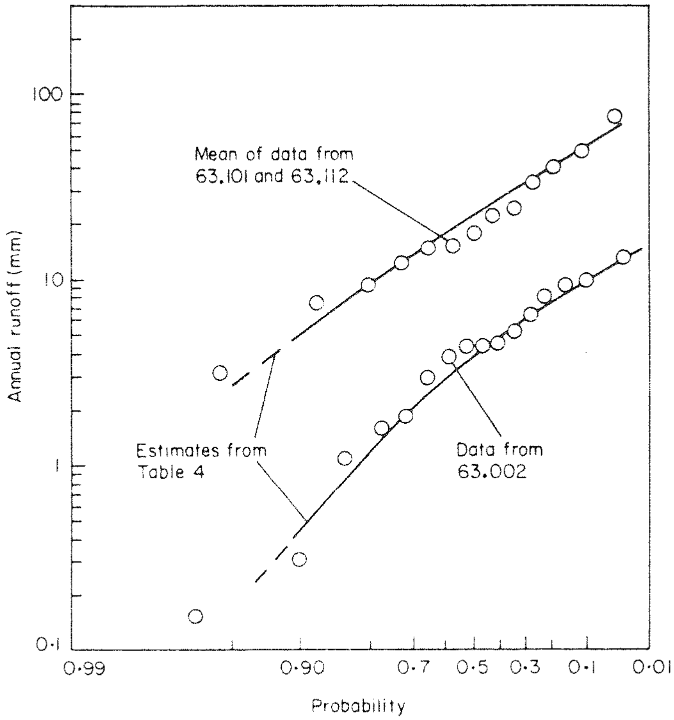

Figure 4. Comparisons of fitted distributions and original data for the smallest and largest catchments.

(4) confirms this result and defines the effect of recurrence interval on annual runoff. To facilitate interpretation, values of $e^{1 \cdot 1K}$ are tabulated in Table 5. The value of $e^{1 \cdot 1K}$ is 1·0 for the mean annual runoff, hence the values in the right hand column of Table 5 are multipliers of the mean annual runoff.

Effect of area on SCS curve numbers

The runoff equation of the U.S. Soil Conservation Service, commonly called the curve number method, for estimating runoff from rainfall, came into common use in the mid-1950s. Since then, its use has become widespread, particularly on ungauged catchments, because of its simplicity. Rallison (1980) documented the origin and evolution of the method up to 1980.

Table 5. *Values of* $e^{1 \cdot 1K}$ *for probability of exceedence* (P_e) *or recurrence interval* T *years*

P_e	T (years)	$e^{1 \cdot 1K}$
0·01	100	5·68
0·10	10	3·44
0·20	5	2·59
0·50	2	1·27
0·80	1·25	0·45
0·90	1·11	0·21
0·99	1·01	0·01

The standard meth
Handbook, Section 4,
there are variations of
curve numbers for
determined, the basic
National Engineering
recommendations for
of the south-west US
with the Handbook re
In the Handbook a
land use, conservation
Section 4 of the Ha
evaluated. The altern
percentage ground cov
In the present study
were used to compar
number method. The
transmission loss on th
Gulch experimental a
runoff made from the
catchments have the sa
the same for each catch
For these catchmen
Handbook method are
Malone's method are

Table 6 compares ann
63·103, ranked in orde
method. The estimate

Table 6. *Ra*

Rank Na	Ob
	63·101
1	66·8
2	48·8
3	41·1
4	37·1
5	26·7
6	26·2
7	22·4
8	19·3
9	18·5
10	16·0
11	15·0
12	14·2
13	6·1

The standard method in most common use is described in the *National Engineering Handbook*, Section 4, *Hydrology*, of the U.S. Soil Conservation Service (1972). However, there are variations of the basic method, usually concerned with estimating appropriate curve numbers for ungauged catchments. Once the curve numbers have been determined, the basic method of estimating runoff from rainfall, as described in the *National Engineering Handbook*, is generally used. One of these variations, which gives recommendations for curve numbers on catchments in the arid and semi-arid rangelands of the south-west USA (Malone, 1972), was used in the present study for comparison with the Handbook recommendations.

In the Handbook approach, curve number is evaluated as a function of soil group, land use, conservation treatment, and hydrological condition. Chapters 7, 8, 9 and 10 of Section 4 of the Handbook include detailed descriptions of how these factors are evaluated. The alternative procedure used by Malone (1972) uses vegetation type, percentage ground cover and soil group to evaluate curve number.

In the present study, data from two of the smaller catchments, 63·101 and 63·103, were used to compare observed runoff with estimates of runoff made by the curve number method. The small catchments were chosen specifically to avoid any effect of transmission loss on the results. These two catchments are close together in the Walnut Gulch experimental area and are served by the same rain gauge, hence estimates of runoff made from the rainfall data should apply equally to either catchment. The two catchments have the same soil group, land use, vegetation etc. so that curve numbers are the same for each catchment.

For these catchments, the curve numbers estimated by the *National Engineering Handbook* method are $K1 = 62$, $K2 = 79$, and $K3 = 90$; and curve numbers estimated by Malone's method are $K1 = 74$, $K2 = 87$ and $K3 = 94$.

Optimized curve number

Table 6 compares annual depths of runoff in millimetres from catchments 63·101 and 63·103, ranked in order of magnitude, with estimates of runoff by the SCS curve number method. The estimates of runoff were calculated on a daily basis, using daily rainfalls,

Table 6. *Ranked order of annual runoff in millimetres. Comparison of observed runoff with SCS curve no. estimates*

Rank Na	Observed runoff Na		Estimated runoff (mm)		
			NEH4	Malone	(mm) Optimized
	63·101	63·103	$K2 = 79$	$K2 = 87$	$K2 = 93$
1	66·8	60·5	27·7	43·9	67·3
2	48·8	50·3	3·0	12·4	37·8
3	41·1	28·2	2·5	11·7	31·2
4	37·1	26·9	1·3	8·1	26·4
5	26·7	22·4	1·3	6·4	22·9
6	26·2	22·1	1·0	6·1	22·1
7	22·4	20·3	0·5	5·3	20·1
8	19·3	17·3	0·5	4·3	19·6
9	18·5	16·5	0·3	4·3	19·3
10	16·0	14·5	0·3	3·8	16·3
11	15·0	13·7	0·3	3·0	14·5
12	14·2	9·9	0	1·8	13·7
13	6·1	3·8	0	0	2·5

accumulated into annual totals, and the annual totals ranked in order of magnitude for comparison with the observed data.

The estimates of runoff produced by the curve numbers recommended in the *National Engineering Handbook*, Section 4 *Hydrology*, are shown under the heading 'NEH4 $K2$ = 79' in Table 6. The estimates of runoff produced by the curve numbers recommended by Malone are shown under the heading 'Malone $K2$ = 87'. It can be seen that both of these recommendations give estimates of runoff that are significantly lower than observed runoff on either catchment. Mean annual runoff on 63·101 is 27·6 mm and on 63·103 is 23·6 mm. The average of these two values is 25·6 mm p.a. Using the *National Engineering Handbook* curve numbers ($K2 = 79$), estimated runoff averaged only 3·0 mm p.a., some 12 per cent of observed runoff. Using Malone's recommendations ($K2 = 87$), estimated runoff averaged 8·5 mm p.a., some 33 per cent of observed runoff.

Higher values of curve number were tested, and it was found by trial and error that the set of curve numbers, $K1 = 83$, $K2 = 93$, $K3 = 97$ gave an estimate of runoff that best matched the ranked order of observed runoff from the two catchments. This estimate is shown in Table 6 under the heading '$K2$ = 93'. This estimate averaged 24·1 mm p.a. compared to 25·6 mm p.a. measured. Also, the ranked order of estimated runoff matches well with corresponding values of observed runoff from the highest to the lowest values.

Effect of transmission loss on curve numbers

Using the regressions illustrated in Fig. 3, which were used to estimate the tabulated values in Table 4, estimates were made of the frequency distributions of runoff for catchment sizes of 0·01, 0·1, 1·0 and 10 km^2. These are shown in Table 7(a). Frequency distributions were also fitted to the annual totals of runoff estimated by the SCS curve number method with several sets of curve numbers. These distributions are shown in Table 7(b).

The two sets of distributions of annual runoff in (a) and (b) of Table 7 do not provide an exact correspondence of curve number with a specific size of catchment. The estimated runoff from $K2 = 93$ corresponds with a catchment size of 0·01 km^2 in the lower range (probability 0·90–0·50), and with a catchment size of 0·10 km^2 in the higher range (probability 0·10–0·01). Nevertheless, the figures show that an increase in catchment size of two orders of magnitude (e.g. from 0·1 to 10 km^2) would be reflected by a reduction of about five in optimized curve number, because of the lesser observed runoff due to transmission loss.

None of the published procedures for estimating curve numbers for use on ungauged catchments takes account of transmission loss or makes any allowance for a decrease in runoff with increasing size of catchment. Some of the problems associated with estimating the appropriate value of curve number, in the absence of data for calibration, can be attributed to transmission loss.

A second factor which contributes to the effect of catchment area on runoff in semi-arid areas is the very large spatial variability of rainfall when thunderstorms are the main source of rain. Hjelmfelt (1980) related the frequency distribution of runoff to the frequency distribution of point rainfall using SCS curve number method for five catchments in the United States having significantly different climatic and physiographic characteristics. The technique appeared to work well except for the semi-arid catchment in Arizona where transmission losses and spatial variability of rainfall distort the relationship. Renard (1981), in commenting on this paper, pointed out that the use of a single rain gauge will not provide an adequate representation of the input to the 544 km^2 catchment because of transmission losses and rainfall variability. More recently, Lane (1982) produced a distributed model in which runoff on upland source areas is calculated using the SCS curve number method and then transmission losses are calculated for the movement of water through the absorbing channel network to give the runoff volume at the outlet of the catchment.

Table 7

(a) Variation of annual runoff with catchment area

ıitude for

: *National*
H4 *K*2 =
ıended by
h of these
observed
63·103 is
National
y 3·0 mm
(2 = 87),

ır that the
' that best
stimate is
mm p.a.
ɛd runoff
he lowest

tabulated
unoff for
requency
CS curve
shown in

ıt provide
ent. The
m² in the
he higher
crease in
reflected
observed

ungauged
ɛcrease in
ıted with
libration,

f in semi-
the main
ıff to the
for five
iographic
atchment
ıstort the
e use of a
: 544 km²
tly, Lane
alculated
ɛd for the
volume at

Table 7

(a) Variation of annual runoff with catchment area

Catchment area km²	Annual runoff in millimetres for specified probability of exceedence							
	0·01	0·10	0·20	0·30	0·50	0·70	0·80	0·90
0·01	89·4	54·8	42·3	34·4	22·7	13·9	9·6	5·2
0·10	57·5	35·4	27·4	22·2	14·5	8·5	5·6	2·7
1·0	37·0	22·9	17·7	14·3	9·3	5·2	3·3	1·5
10.0	23·8	14.8	11·4	9·2	6·0	3·2	1·9	0·8

(b) Variation of annual runoff with SCS curve number

SCS curve number	Annual runoff in millimetres for specified probability of exceedence							
	0·01	0·10	0·20	0·30	0·50	0·70	0·80	0·90
K2 = 93	50·0	39·6	34·4	30·5	23·6	16·5	12·4	7·2
K2 = 90	31·4	24·2	20·6	17·8	12·9	8·0	5·2	2·1
K2 = 87	19·4	14·1	11·6	9·8	6·7	4·0	2·5	1·0

Concluding comments

Because of the sparseness of hydrological data in the arid and semi-arid areas of the world, there is value in the results of any hydrological investigations undertaken in arid areas. The hydrological research undertaken by the USDA Agricultural Research Service in the Walnut Gulch experimental area in Arizona is particularly valuable because of the intensity and quality of data collection which has continued for over two decades.

The results obtained in the present study show how transmission loss can affect the probability of obtaining various amounts of annual runoff. In areas where transmission loss in stream channels is of the same magnitude as in the Walnut Gulch experimental area, size of catchment area should be taken into account when estimating the amount of runoff. In this case, mean annual runoff reduces by about 38 per cent for each tenfold increase in catchment area.

This research was undertaken while the senior author was at the USDA Southwest Rangeland Watershed Research Center, on study leave from Griffith University. We acknowledge with thanks the opportunity given by the University for the leave, and the cooperation of the U.S. Department of Agriculture in making data and facilities available for the research.

References

Boughton, W. C. (1980). A frequency distribution for annual floods. *Water Resources Research*, **16** (2): 347–354.

Boughton, W. C. (1981). The log-Boughton distribution for frequency analysis of annual floods. Research paper No 409, USDA Southwest Rangeland Watershed Center, 2000 E. Allen Road, Tucson, Arizona, 85719, 19 pp.

Boughton, W. C. & Shirley, E. D. (1983). Fitting procedures for the log-Boughton distribution. *Journal of the Hydraulics Division, American Society of Civil Engineers*, **109** (4): 579–589.

Hjelmfelt, A. T. (1980). Empirical investigations of curve number technique. *Journal of the Hydraulics Division, American Society of Civil Engineers*, **106** (4): 579–589.

Knisel, W. G., Renard, K. G. & Lane, L. J. (1979). Hydrologic data collection: how long is long enough? *ASCE Irrigation and Drainage in the Nineteen-Eighties, Speciality Conference Proceedings*, pp. 238–254.

Lane, L. J. (1980). Transmission losses. In *National Engineering Handbook*, Section 4, *Hydrology*. Washington D.C.: USDA Soil Conservation Service, 32 pp.

Lane, L. J. (1982). Distributed model for small semi-arid watersheds. *Journal of the Hydraulics Division, American Society of Civil Engineers*, **108** (HY10): 1114–1131

Lane, L. J., Diskin, M. H. & Renard, K. G. (1971). Input–output relationships for an ephemeral stream channel system. *Journal of Hydrology*, **13**: 22–40.

Malone, J. M. (1972). Hydrologic design manual for drainage areas under 25 square miles. Phoenix, Ariz.: USDA Soil Conservation Service.

Murphey, J. B., Wallace, D. E. & Lane, L. J. (1977). Geomorphic parameters predict hydrograph characteristics in the south-west. *Water Resources Bulletin*, **13** (1): 25–38.

Osborne, H. B. & Lane, L. J. (1969). Precipitation–runoff relationships for very small semi-arid rangeland watersheds. *Water Resources Research*, 5 (2): 419–425.

Rallison, R. E. (1980). Origin and evolution of the SCS runoff equation. In '*Symposium on Watershed Management*, Vol. II, pp. 912–924' New York: ASCE.

Renard, K. G. (1970). The hydrology of semi-arid rangeland watersheds. ARS 41–162, Washington D.C.: USDA Agricultural Research Service. 26 pp.

Renard, K. G. (1977). Past, present and future water resources research in arid and semi-arid areas of the southwestern United States. *Institution of Engineers, Australia, Hydrology Symposium 1977*: 1–29.

Renard, K. G. (1981). Discussion of 'Empirical investigation of curve number technique' (Hjelmfelt, 1980), *Journal of the Hydraulics Division, American Society of Civil Engineers*, **107**: (HY5): 651–653.

Renard, K. G. & Brakensiek, D. L. (1976). Precipitation on inter-mountain rangeland in the western United States. In Heady, H., Falkenborg, D. & Riley, J. (Eds), *Watershed Management*

l semi-arid areas of the
:ions undertaken in arid
Agricultural Research
icuarly valuable because
:d for over two decades.
ssion loss can affect the
reas where transmission
nut Gulch experimental
:stimating the amount of
ɔer cent for each tenfold

;DA Southwest Rangeland
'e acknowledge with thanks
ion of the U.S. Department

. *Water Resources Research*,

:y analysis of annual floods.
:enter, 2000 E. Allen Road,

log-Boughton distribution.
·s, **109** (4): 579–589.
r technique. *Journal of the*
)–589.
collection: how long is long
peciality Conference Proceed-

·ing Handbook, Section 4,
: pp.
ds. *Journal of the Hydraulics*
31
:lationships for an ephemeral

eas under 25 square miles.

ırameters predict hydrograph
25–38.
hips for very small semi-arid

equation. In '*Symposium on*

watersheds. ARS 41–162,

:ch in arid and semi-arid areas
ı, Hydrology Symposium 1977:

›f curve number technique'
ociety of Civil Engineers, **107:**

:r-mountain rangeland in the
(Eds), *Watershed Management*

on Range and Forest Lands, pp. 39–59. Logan, Utah: Utah Water Research Laboratory, Utah State University.

Schrieber, H. A. & Kincaid, D. R. (1967). Regression models for predicting on-site runoff from short-duration convective storms. *Water Resources Research*, **3** (2): 389–395.

United States Soil Conservation Service (1972). *National Engineering Handbook*, Section 4, *Hydrology*. Washington D.C.: Department of Agriculture.