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COMPARISON OF METHODS TO ESTIMATE RUNOFF FROM SMALL RANGELAND WATERSHEDS

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Introduction

Many methods have been used to estimate peak discharge and/or storm runoff volumes from small drainages in the United States (Chow 1962; Haan 1982). Most of these methods were developed for urban drainages, or were based on hydrologic data from the eastern and midwestern United States. Several methods have been suggested for possible use on small rangeland watersheds in the southwestern United States. Some, such as the Rational Formula, are easy to use but require subjective estimation of parameters and predict only peak discharge. Others predict both peak and volume, but may require more effort to use. In many cases, model use will determine the needed accuracy and required sophistication. In this paper, several models (methods) are compared and evaluated for use on rangeland watersheds using data from a very small gaged rangeland watershed.

Design of Experiment

The United States Department of Agriculture (USDA), Agricultural Research Service (ARS), Walnut Gulch Experimental Rangeland Watershed is located in southeastern Arizona, near Tombstone (Fig. 1). The 57-mi^2 watershed is divided into gaged subdrainages ranging from 0.4 acres to the entire watershed. The study described in this paper was carried out on a 0.45-acre subwatershed (63.105) located in the Lucky Hills research complex near Tombstone (Fig. 1). The small watershed is fenced and shrub-covered, and erosion pavement dominates the watershed surface. There is a well-defined, but shallow, channel draining the watershed, but channel abstractions were considered insignificant compared to watershed infiltration. The average watershed slope is 9 percent, and the channel slope is about 3 percent. There is a 6-hr weighing-type recording raingage on one edge of the watershed, and runoff is estimated from a FW-1 continuous water-level recorder mounted in a 3-ft H-flume.

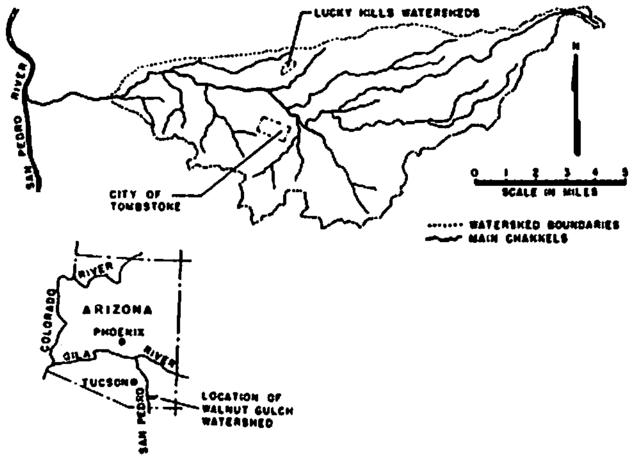

Figure 1. Location of the Walnut Gulch Watershed and the Lucky Hills experimental area on Walnut Gulch.

Six major runoff-producing events on 63.105 were chosen to compare the five methods. The events were selected to represent a range of temporal rainfall input and antecedent conditions. The models are compared on the basis of their relative accuracy in estimating peak discharge rates and runoff volumes of these storms.

Methods

The five methods discussed in this paper are linear regression, the Rational Method, Illinois Urban Drainage Area Simulator (ILLUDAS), two versions of the Santa Barbara Urban Hydrograph (SBUH), and the Kinematic Cascade Model (KINGEN). The Rational Formula (method) can be used only to predict peak discharge. Linear regression can be used to predict peak discharge and runoff volume separately. The other three methods include a hydrograph output, and can be used to estimate peak discharge, time to peak, flow duration, and storm runoff volume. ILLUDAS and SBUH were both designed for urban drainages, and we expected to make some adjustments in the program subroutines and parameters. KINGEN had been used on both urban and natural watersheds, and considerable information pertaining to rangeland use was already available. In some cases, we estimated the parameters a priori; in other cases, parameters were adjusted by trial and error based on comparisons of observed and computed runoff. In each case, we have adopted the author's notation; so several symbols are not unique in definition.

Linear Regression

Osborn and Lane (1969) developed linear regression equations to predict runoff volume and peak discharge from 63.105 and other Lucky Hills subwatersheds. With additional data, these equations have been modified for 63.105 (Osborn and Simanton, 1981) to the form:

$$Q_p = P_{15} - 0.68 \qquad (r^2 = 0.80) \qquad (1)$$

$$Q = 0.7P_{TOT} - 0.24 \qquad (r^2 = 0.78) \qquad (2)$$

where

Q_p = peak discharge (in/hr),
Q = total storm runoff (in),
P_{TOT} = total storm rainfall (in).

The equations were used to estimate peak and volume of discharge from the 6 selected events.

Rational Method

The Rational Method is still one of the most popular and simple methods for predicting peak discharge from an ungaged watershed. The equation is:

$$Q_p = CiA \qquad (3)$$

where

Q_p = peak discharge (cfs),
C = a constant based on watershed characteristics,
A = watershed area (acres), and
i = maximum rainfall (in/hr) for the time of concentration.

A TI-59* hand calculator program for using the Rational Method has been developed by B. C. Yen (1981). In the Yen adaptation of the Rational Method, there are two methods for determining the time of concentration. We determined the maximum average intensity based on the first method, Kerby's (1959) equation, in which:

$$T_{ck} = T_o + T_f \qquad (4)$$

where

T_{ck} = time of concentration by Kerby formula,
T_o = time of maximum overland flow from boundary to channel, and
T_f = time of flow through the channel.

The factors T_o and T_f are based on Kerby's coefficient, slopes, channel velocity, differences in elevation, and the lengths of overland and channel flows. These parameters must be entered into the program.

The second method for determining time of concentration, the Kirpich formula, did not give reasonable values for this watershed, and therefore cannot be recommended for use on such rangeland watersheds. The program TI-59 can be divided into three parts. First, the time of concentration is estimated using the Kerby formula. Second, precipitation intensity is determined by either assuming T_d (rainfall duration) = T_c for a statistical event (such as the 30-min, 100-yr storm), or by entering rainfall depth from an actual storm. Finally, peak discharges are obtained for each event.

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*Reference to a specific calculator program does not constitute endorsement of the brand.

ILLUDAS

The ILLUDAS model, developed by Terstriep and Stall (1969), is an objective method for the hydrologic design of storm drainage systems in urban areas. The model improves on a method described by Watkins (1962) for the urban drainage, and adds a grassed-area component. The intent of our study was to investigate the "grassed-area" component of the model for possible application to rangeland drainages. In ILLUDAS, an observed time-varying rainfall pattern is uniformly distributed over the basin. The basin can be divided into subbasins which produce hydrographs that are combined and routed downstream from one design point to the next until the outlet is reached. Detention storage can be included as part of the design in any subbasin.

Time versus area curve for each subbasin is represented as a straight line from the origin to a point where the entire subbasin is contributing. The time coordinate of this point is the time of concentration, which can be either entered directly or determined within the program with the following equations by Izzard (1946):

$$q_e = 0.0000231IL, \tag{5}$$

where

q_e = equilibrium overland flow (cfs per ft of width),
I = supply rate (in/hr), and
L = length of overland flow (ft),

and

$$t_e = 0.033KLq_e^{-0.67}, \tag{6}$$

where

t_e = time of equilibrium flow (min),

and

$$K = (0.0007I + C)S^{-0.33}, \tag{7}$$

where

S = surface slope (ft), and
C = cover coefficient = 0.046 (for bluegrass).

Standard infiltration curves were devised for soils by hydrologic group A, B, C, and D. These curves were calculated from the Horton equation as given by Chow (1964);

$$f = f_c + (f_0 - f_c)e^{-kt} \tag{8}$$

where

f = infiltration at time t,
f_c = final constant rate,
f_0 = initial infiltration rate (in/hr),
k = shape factor (given as 2 in this program), and
t = time from start of rainfall.

The program also requires selection of antecedent moisture conditions based on total rainfall during the five days preceeding the storm.

We found that, by changing a few data statements within the program, Izzard and Horton's equations could be easily changed to accommodate conditions other than bluegrass. For the very small watershed, 63.105, the travel times in the channel were so short that the routed hydrograph was the same as the watershed hydrograph.

SBUH Method

The current method for generating a complete hydrograph for retention/detention basin design for storm water management in Santa Barbara County (California) is the Howard Needles version of the Santa Barbara Urban Hydrograph Method (HNV-SBUH), originally developed by J. M. Studchaer of the Santa Barbara County Flood Control and Water Conservation District (Golding 1980). The final design hydrograph is obtained by routing the rainfall excess for each time period through an imaginary linear reservoir with a routing constant equivalent to the time of concentration of the basin.

The model can be described in three parts: (1) calculation of runoff depths, (2) computation of rainfall excess, and (3) routing the rainfall excess through an imaginary linear reservoir. Runoff depths for each time period R(t), are calculated using the following equations:

$$R(0) - I \times P(t) \tag{9}$$

$$R(1) = P(t)(1-I) - f(1-I_t) \tag{10}$$

$$R(t) = R(0) + R(1) \tag{11}$$

where

$P(t)$ = rainfall depth during time increment Δt (in),
f = infiltration during time increment Δt (in),
I_t = total impervious portion of drainage basin (decimal),
I = directly connected impervious drainage (decimal), and
Δt = incremental time period (hr).

The rainfall excess, I(t)(cfs), is computed in the second step by multiplying the total runoff depth, R(t), for each time period, t, by the drainage basin area, A (acres), and dividing by the time increment Δt:

$$I(t) = R(t) \times \frac{A}{\Delta t} . \qquad (12)$$

In the third part, the design hydrograph is obtained by routing the rainfall excess with a time delay equal to the time of concentration of the drainage basin:

$$Q(t) = Q(t-1) + \bar{K}\ [I(t) + I(t-1) - 2Q(t-1)] \qquad (13)$$

where

$$\bar{K} = \frac{\Delta t}{2T_c + \Delta t} \qquad (14)$$

As was the case with ILLUDAS, the infiltration, f, is computed by the Horton equation (Eq. 8).

The program is also similar to ILLUDAS in that the standard infiltration curves established by Terstriep and Stall (1969) which adjust f_0 in equation (8) are used to compute infiltration. Again, the infiltration parameters can be changed to accommodate specific soil types.

The original program was written for an HP-67* programmable calculator and used a numerical integration scheme in the infiltration routine. With the help of Dr. Donald Ross Davis, Department of Hydrology, University of Arizona, the program was rewritten for a TI-59* calculator (DRD-SBUH), and the infiltration curve solved in closed form. Both methods were used in the study.

KINGEN

Program KINGEN is a modified version of the Kibler-Woolhiser (1970) kinematic cascade model for routing overland flow over a cascade of planes and through trapezoidal channels (Lane and Woolhiser 1977). Input to the program is rainfall excess based on the Phillip (1969) equation:

$$f = 1/2\ st^{-1/2} + A \qquad (15)$$

where

s = sorptivity of the soil, and
A = steady state infiltration rate.

The program can be operated in either a simulation or optimization mode. Given slopes and channel characteristics, the program computes flow area, hydraulic radius, velocity, and shear stress for the channel segments. Output is a complete storm hydrograph from which peak time, discharge rate, and volume of runoff are obtained.

Comparison of Methods

Hydrographs were simulated for 6 selected runoff-producing events on subwatershed 63.105, and compared to actual data (Fig. 2-6). Peaks and volumes of simulated and actual events were also compared (Tables 1 and 2). Both peaks and volumes tended to be overpredicted with ILLUDAS, and peaks underpredicted with either version of SBUH (Fig. 2-4). Both ILLUDAS and SBUH badly underpredicted runoff from the high-intensity, short-duration rainfall of 5 July, 1975. KINGEN generally gave a better "fit" of the data, including the 5 July, 1975 event (Fig. 5-6). We could have improved the "fit" of the actual and simulated peaks from the Rational Method by simply changing the "C" value. Since we had followed the instructions for estimating peak discharge for an ungaged watershed, we felt the strong tendency to overpredict should be noted. The ILLUDAS and SBUH methods were adjusted based on early fittings, and the hydrographs in Fig. 2-4 are based on parameter adjustments. The hydrographs developed with KINGEN are without adjustment. At this point, we clearly have more confidence in KINGEN than in the other methods. However, KINGEN is, by far, the most complex of the methods.

Discussion

Regression equations are easy to develop when rainfall and runoff data are available, and they can be used on similar ungaged watersheds. However, there are several assumptions which limit the value of such equations. First, watershed characteristics such as size, slope, and drainage density must not differ significantly between "similar" gaged and ungaged watersheds. Second, rainfall is assumed uniform over the watershed, both in time and space. Third, rainfall intensity within the assumed constant

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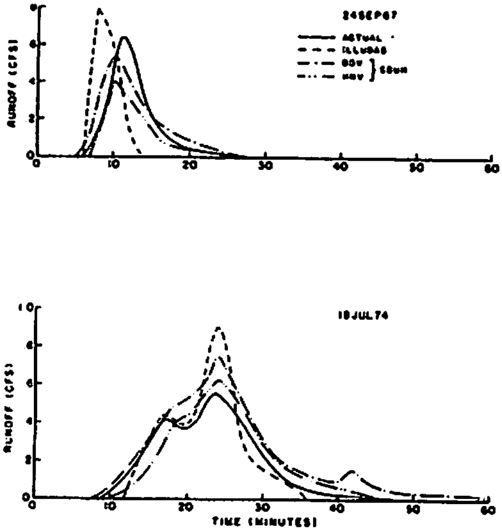

Figure 2. Comparison of three methods for estimating runoff for storms of 24 Sep 67 and 19 July 74.

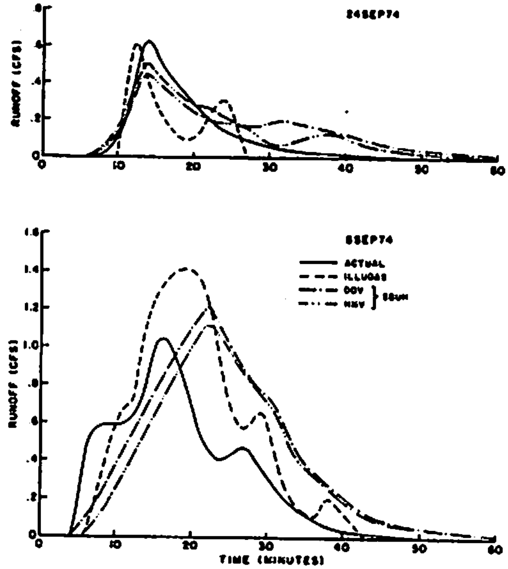

Figure 3. Comparison of three methods for estimating runoff for storms of 24 Sep 74 and 8 Sep 70.

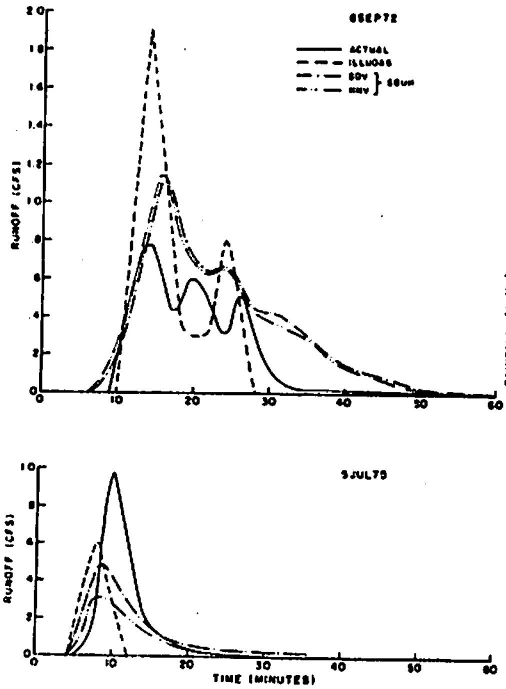

Figure 4. Comparison of three methods for estimating runoff for storms of 6 Sep 72 and 5 July 75.

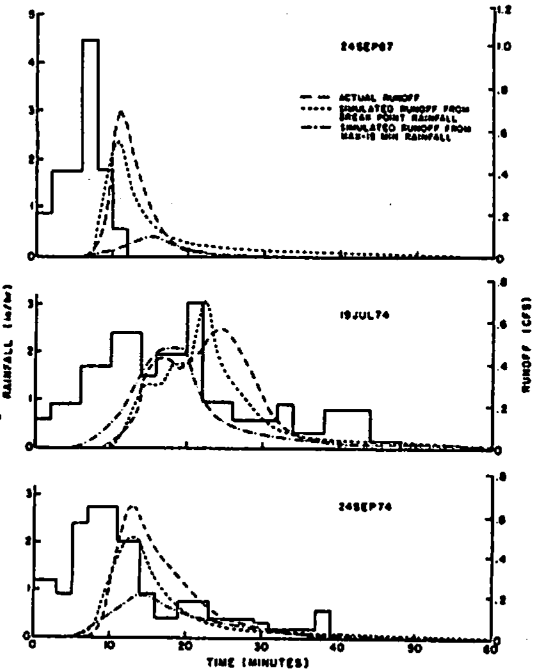

Figure 5. Comparison of estimated runoff using breakpoint and maximum 15- min rainfall in a kinematic cascade model (KINGEN) with actual rainfall and runoff data for three storms (from Osborn and Simanton, 1981).

regression rainfall duration must not significantly affect the estimate of peak and volume of runoff. Because of the extreme variability in rainfall, both in time and space, and the non-homogeneity of rangeland watersheds, linear regression is generally limited to very small rangeland watersheds of no more than a few tens of acres. Regression equations can be used to predict time to peak and flow duration also, but generally with considerably less accuracy than peak discharge and runoff volume.

Table 1. Comparison of estimated peak discharges for 5 methods and 6 selected events on subwatershed 63.105.

Storm date	Rainfall		Peak Discharge (cfs)						
	Total	Maximum intensity (2 min)	Actual	Regression	Rational	ILLUDAS	SBUH DDV	SBUH HNV	KINGEN
	(in)	(in/hr)							
24 Sep 67	0.39	4.50	0.64	0.40	0.59	0.70	0.53	0.40	0.45
8 Sep 70	1.14	4.20	1.04	1.08	2.24	1.45	1.20	1.13	.99
6 Sep 72	.79	3.90	.78	.77	1.38	1.90	1.14	1.12	.89
19 Jul 74	.94	3.00	.55	.63	1.36	.90	.68	.62	.67
24 Sep 74	.47	2.70	.64	.55	.91	.64	.49	.44	.45
5 Jul 75	.59	5.12	.98	.40	.62	.60	.48	.30	1.26

Table 2. Comparison of predicted storm runoff for 5 methods and 6 selected events on subwatershed 63.105.

Storm date	Rainfall		Storm runoff (in)						
	Total	Maximum intensity (2 min)	Actual	Regression	Rational	ILLUDAS	SBUH DDV	SBUH HNV	KINGEN
	(in)	(in/hr)							
24 Sep 67	0.39	4.50	0.12	0.04	--	0.11	0.15	0.11	0.14
8 Sep 70	1.14	4.20	.61	.56	--	.85	.88	.74	.59
6 Sep 72	.79	3.90	.37	.31	--	.46	.66	.63	.38
19 Jul 74	.94	3.00	.31	.42	--	.30	.45	.32	.28
24 Sep 74	.47	2.70	.20	.09	--	.14	.31	.23	.17
5 Jul 75	.59	5.12	.21	.18	--	.10	.14	.09	.25
Average	.72	--	.30	.27	--	.33	.43	.36	.30

In this study, the regression coefficients were determined from runoff events for a 15-yr period and used to predict the 6 selected events, so the fit of actual and estimated volumes was as good as those based on KINGEN, and the fit of actual and predicted peaks as good as all but those based on KINGEN.

The Rational Method is limited to predicting peak discharge independently of peak time and volume. It is a simple method to use, and it is indeed rational in that the units are proper, and the peak discharge depends upon rainfall intensity for the time of concentration. However, like linear regression, rainfall is assumed uniform, both in time and space, and the watershed is considered homogeneous. The "C" value must be representative of the runoff-producing features of the watershed, and is determined, to a large degree, subjectively. Time of concentration must be accurately estimated, and if the rainfall is too variable within the time of concentration, the predicted peaks may be in considerable error. The Rational Method is also limited to very small areas (in terms of acres).

As stated earlier, adjustments were made on the ILLUDAS and SBUH programs, both initially and as the study progressed. It became apparent early in the study that peak discharge and time to peak were extremely sensitive to the infiltration subroutine. Both ILLUDAS and SBUH were developed for urban drainages, with routines for both pervious and impervious areas within the same drainage. We found that the infiltration parameters, which were based on grassed urban areas, did not represent rangeland soils. We had to adjust the parameters considerably to reduce the infiltration for more and faster runoff. In most cases, we predicted no runoff with the original grassed-area infiltration parameters.

The ILLUDAS and SBUH methods are somewhat similar, using the same infiltration equations as well as similar routine techniques. Both are designed for use on larger watersheds, at least up to several square miles. Unlike the Rational Method and linear regression, rainfall can be varied in time, which improves the accuracy of estimation. However, neither program can handle spatial variability, which limits their usefulness for larger watersheds. ILLUDAS does include infiltration from subbasins within the drainage, which allows for non-homogeneous watersheds. We have not, as yet, investigated the sensitivity of shape factor, K, in the Horton equation.

Both ILLUDAS and SBUH were fitted to the 6 selected events. Each had infiltration parameters derived from infiltrometer data rather than the standard curves provided. Initial runs of both SBUH and ILLUDAS produced almost no runoff, because Izzard's equation gave a time of concentration four times longer than was reasonable. On subsequent runs, the time of concentration was entered directly.

The output for the 6 events from KINGEN are as shown. We used both breakpoint data and the maximum 15-min rainfall to better illustrate the need for breakpoint input. The program parameters were entered based on previous knowledge from other watershed studies. The parameters were not adjusted to improve the fit of actual and predicted peaks. In this test, KINGEN, with breakpoint data, clearly outperformed ILLUDAS and SBUH, but KINGEN had been used on other rangeland watersheds; whereas, we were starting from scratch with ILLUDAS and SBUH.

Summary

Several suggested methods for estimating runoff from rangeland watersheds were compared using six selected events from a very small gaged watershed on the USDA experimental watershed. These methods included linear regression, the Rational Formula, ILLUDAS (Illinois Urban Drainage Area Simulator), two versions of the SBUH (Santa Barbara Urban Hydrograph) method, and KINGEN (a kinematic cascade model). KINGEN was the most complex of the models, the Rational Formula the simplest. Estimates of both runoff peaks and volumes, based on KINGEN, were significantly more accurate than those from the other methods. Although the linear regression estimates were as accurate as those from ILLUDAS and SBUH, regression equations are not easily transferred to ungaged watersheds. ILLUDAS and SBUH were both designed for urban drainages, but were developed for use on ungaged watersheds. Neither method gave particularly good estimates in this test, but they may be applicable to other watersheds with revisions to accommodate spatial rainfall variability and/or time of concentration. The Rational Method can only be used to make quick peak estimates on very small watersheds. At this point, we have more confidence in KINGEN than in the other methods tested.

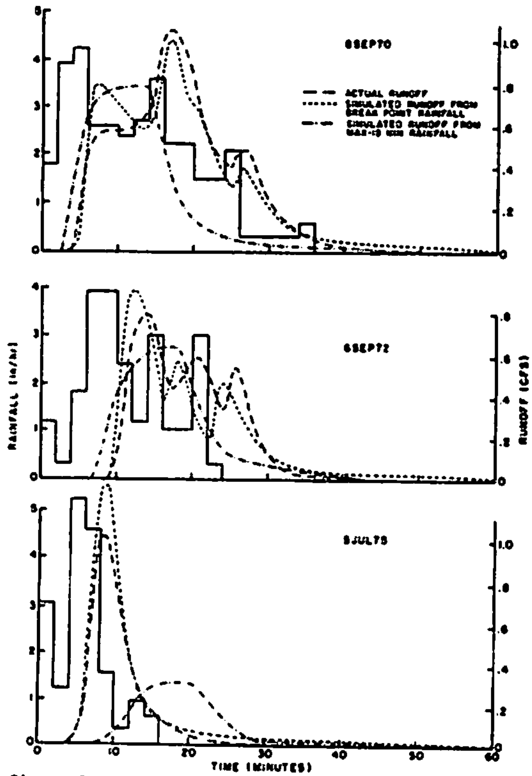

Figure 6. Comparison of estimated runoff using breakpoint and maximum 15-min rainfall in a kinematic cascade model (KINGEN) with actual rainfall and runoff for three storms (from Osborn and Simanton, 1981)

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