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Including uncertainty in the unit hydrograph method

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The unit hydrograph method is reformulated into a stochastic integral equation for use in preparing probabilistic distributions of design criterion variable values (e.g., pipe size, basin volume, peak flow rate, etc.). By discretizing the ensemble of possible transfer functions (e.g., unit hydrographs) and weighting the resulting finite set of realizations, the stochastic integral equation can be more simply utilized in practical engineering problems. In this paper, a weighted set of mass curves are prepared for use in the Los Angeles, California, region. The weighted mass curves reflect the probabilistic weighting of the corresponding distribution of transfer functions used to convolute with effective rainfall (i.e., rainfall less losses) to produce runoff estimates.

INTRODUCTION

Recently, some attention has been paid in addressing the uncertainty in rainfall-runoff model predictions[1-7]. In Ref. 7, the well-known design storm approach to approximate T-year return frequency runoff criterion variables (e.g., pipe size, basin volume, peak flow rate, etc.) is examined with respect to the unit hydrograph method, and a stochastic integral equation is developed which relates a T-year effective rainfall event (i.e., rainfall less losses; rainfall excess) to T-year runoff quantities. A component of the stochastic integral equation formulation is the random variation in the transfer function used to convolute with effective rainfall to produce the runoff hydrograph estimate. In this note, the above random variation in the transfer function is approximated by a set of weighted mass-curves. The resulting set of weighting mass curves are similar in concept to the often used 'S'-graph representation of the unit hydrograph[9], and provide a discretized representation of the random transfer function identified in the stochastic integral equation formulation of the unit hydrograph method developed by Hromadka and Whitley[7]. The weighted mass curve set can then be regressed against catchment characteristics commonly used in the unit hydrograph method, such as catchment lag and ultimate discharge, in order to provide the ability to transfer the randomness in the S-graph (e.g., shape and magnitude) to ungauged catchments, analogous to the usual S-graph procedure itself. Use of the weighted mass curves enables the engineer to prepare a probabilistic distribution of design criterion variable values, in order to approximate design risk and uncertainty.

In the following analysis, a linear model of runoff with respect to effective rainfall, is used for mathematical development purposes. By introducing the concept of storm classes, wherein the space of effective rainfall realizations is partitioned into similarity classes, the linear runoff model becomes nonlinear over the total space, although it remains piecewise linear on a storm class basis. That is, that the unit-hydrograph (UH) model is assumed to be linear within a range of storms, and that the stochastic process in prediction can be approximated by use of a weighted set of UH realizations, as a substitution for the entire (and unknown) distribution of UH realizations.

MATHEMATICAL MODEL DEVELOPMENT

Hromadka and Whitley[7] developed a stochastic integral equation representation of the rainfall-runoff process which utilizes distributions of transfer functions to equate rainfall to runoff data for each storm event. For a free-draining catchment subdivided into m subareas linked together by quasi-linear unsteady flow routing algorithms (e.g., kinematic wave, convex, Muskingum, among others), Hromadka and Whitley[7] developed the link-node model representation, $M_m^i(t)$

$$M_m^i(t) = \int_{s=0}^{t} \mathrm{e}^i(t-s) \sum_{j=1}^{m} \sum_{\langle l \rangle_j} a^i_{\langle l \rangle_j} \sum_{k_j} \lambda^i_{jk} \phi^i_j(s - \theta^i_{jk} - \alpha^i_{\langle l \rangle_j})\, \mathrm{d}s \qquad (1)$$

where all parameters are evaluated on a storm by storm basis, i. Equation (1) describes a linear model which represents the total catchment runoff response based on variable subarea transfer functions (*TF*), for each subarea, j, $\phi^i_j(\cdot)$; variable effective rainfall distributions on a subarea basis with differences in magnitude (λ^i_{jk}), timing (θ^i_{jk}), and pattern shape as convoluted by the use of index k; and channel flow routing translation and storage effects (convolution parameters $a^i_{\langle l \rangle_j}$ and $\alpha^i_{\langle l \rangle_j}$) for $\langle l \rangle_j$ links from subarea j downstream to the point under study. All

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the above parameters are variable with respect to each storm event, i, and are hereafter considered to be mutually dependent random variables, conditioned according to the catchment rainfall loss function F used to develop the effective rainfall estimate, $e^i(\cdot)$.

Equation (1) can represent most rainfall-runoff model structures in use today in that an arbitrary model employs some type of routing algorithm (that can be resolved into a convolution), a form of subarea runoff generator that can be resolved into an effective rainfall model and subarea transfer function, and a summation of runoff at concentration points. Of course, all these parameters and random variables are unknown for each storm event, i, which suggests use of a probabilistic model whose expected value equates to a deterministic model.

STOCHASTIC INTEGRAL EQUATION

The m-subarea model of equation (1) is rewritten as a stochastic integral equation which is equivalent to a single area model of the catchment, $M_1^i(\cdot)$, where

$$M_1^i(t) = \int_{s=0}^{t} e^i(t-s)\eta^i(s)\,ds \qquad (2)$$

where $\eta^i(\cdot)$ is the transfer function convoluted with $e^i(\cdot)$ to equate with $Q_g^i(\cdot)$. That is, in equation (2), $e^i(\cdot)$ is known from the function F and the data $P^i(\cdot)$; the $\eta^i(\cdot)$ is defined by means of setting $M_1^i(\cdot) = Q_g^i(\cdot)$ where $Q_g^i(\cdot)$ is a realization of stream guage data.

For the case of having available only a single rain gauge and stream gauge for data correlation purposes, the derived $\eta^i(\cdot)$ represents the several effects used in the development leading to equation (1), integrated according to the sampling from the several parameters' respective mutually dependent probability distributions. That is,

$$\eta^i(s) = \sum_{j=1}^{m} \sum_{\langle l \rangle_j} a^i_{\langle l \rangle_j} \sum_{k_j} \lambda^i_{jk}\phi^i_j(s - \theta^i_{jk} - \alpha^i_{\langle l \rangle_j}) \qquad (3)$$

STORM CLASSIFICATION SYSTEM (NONLINEARITY)

To proceed with the analysis, the full domain of effective rainfall realizations are categorized into storm classes, $\langle \xi_q \rangle$. Classification of storm classes depends on the quantity and quality of data available. As in any probabilistic setting, the more data assembled into each storm class, the more data are available for statistical analysis[7]. In this study, Los Angeles data were classified according to four classifications, minor, mild, major, severe. The severe storm class was then analyzed to develop the distribution of TF's. Any two elements of a class $\langle \xi_q \rangle$ are assumed to result in similar effective rainfall realizations, $e^i(\cdot)$, and hence one would 'expect' similar resulting runoff hydrographs at the stream gauge. However, the resulting runoff hydrographs differ and, therefore, the randomness of the effective rainfall distribution over R results in variations in the modelling 'best-fit' parameters in correlating the available rainfall-runoff data.

More precisely, any element of a specific storm class $\langle \xi_o \rangle$ has the same effective rainfall realization, $e_o(\cdot)$. That is, although $\langle \xi_o \rangle$ may contain several elements, each element equates to singleton, $e_o(\cdot)$. In correlating $\{Q_g^i(\cdot), e_o(\cdot)\}$, a different $\eta^i(\cdot)$ results due to the variations in the measured $Q_g^i(\cdot)$ with respect to the single $e_o(\cdot)$ realization. As a result, for k elements in $\langle \xi_o \rangle$, there are typically k distinct elements $\eta^i(\cdot)$ in $[\eta(\cdot)]_o$. It is seen that the number of storm classes, and the number of elements in any particular storm class, depends upon the mapping F used to transform $P^i(\cdot)$ into $e^i(\cdot)$. For example, if F maps $P^i(\cdot)$ into a unit pulse function for all storms i, then there would only be one storm class, and this class would contain n elements, where n is the total number of storms.

In the predictive mode, where one is given an assumed (or design) effective rainfall distribution, $e^D(\cdot)$, assumed to occur at the rain gauge site, the storm class of which $e^D(\cdot)$ is an element, is identified as $\langle \xi_D \rangle$, and the predictive output for the model input, $e^D(\cdot)$, must necessarily be the random distribution of outcomes,

$$M_1(t) = \int_{s=0}^{t} e^D(t-s)[\eta(s)]_D\,ds \qquad (4)$$

where $[\eta(\cdot)]_D$ is the distribution of $\eta^i(\cdot)$ transfer functions associated with storm class $\langle \xi_D \rangle$. However, there are insufficient rainfall-runoff data to derive a sufficiently unique set of storm classes, $\langle \xi_q \rangle$, and hence, additional assumptions must be used. For example, one may lower the eligibility standards for each storm class, $\langle \xi_q \rangle$, implicitly assuming that several storm class distributions of transfer functions, $[\eta(\cdot)]_q$, are identical; or one may transfer $[\eta(\cdot)]_q$ distributions from another rainfall-runoff data set, implicitly assuming that the two-catchment data set transfer function realizations are identical. A common occurrence is the case of predicting the runoff response from a design storm effective rainfall distribution, $e^D(\cdot)$, which is not an element of any observed storm class. In this case, another storm class distribution of $[\eta(\cdot)]_q$ may be used which implicitly assumes that the two sets of transfer function realizations are identical. Consequently, for a severe design storm condition, it would be preferable to develop transfer function realizations using the severe historic storms which have rainfall-runoff data available for analysis. For the severe storm class, $[\eta(s)]_D$ is based upon the TF's synthesized by equating known runoff data to assumed effective rainfall data, by use of equation (4).

EXPECTED VALUE ESTIMATES AND THE UNIT HYDROGRAPH METHOD

In practice, the well-known single area unit hydrograph (UH) model is frequently used to best fit (perhaps in a least squares norm) several record pairs of realizations $\{Q_g^i(\cdot), e^i(\cdot)\}$ from the same or similar storm class $\langle \xi_o \rangle$. Although the corresponding $\{\eta^i(\cdot)\}$ are often integrated and normalized, and the several normalizing parameters averaged together, the net effect of all this is finding the expected value of the distribution of transfer

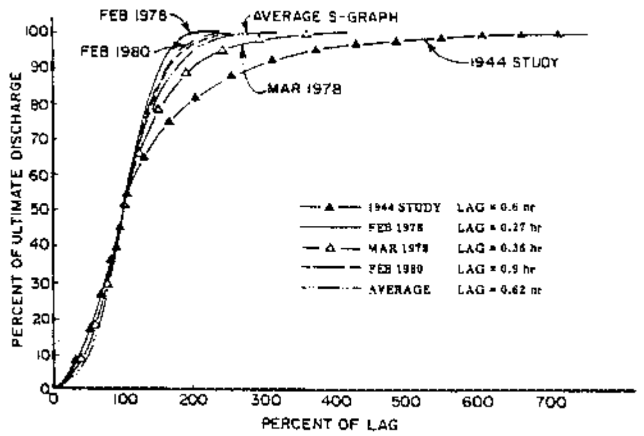

Fig. 1. Mass curves (S-graph, in units of percent of ultimate discharge versus time in percent of lag)

functions, denoted by $E[\eta(\cdot)]_o$. Then, the model used for predictive purposes (for storms in the same class, $\langle \xi_o \rangle$ used to develop $[\eta(\cdot)]_o$) is the expected distribution $E[M_1(\cdot)]$ given by

$$E[M_1(t)] = \int_{s=0}^{t} e^D(t-s)E[\eta(s)]_o \, ds \tag{5}$$

where $e^D(\cdot)$ is considered to be an element in $\langle \xi_o \rangle$.

Although the transfer function (or UH) is used in the convolution of equation (5), it is useful to represent the transfer function $\eta^i(\cdot)$ in terms of a mass curve. By normalizing each mass curve with respect to ultimate discharge (0 to 100− percent), and with respect to lag (100 percent lag equals the time to reach 50− percent of ultimate discharge), the average of the normalized mass curves, (i.e., the 'S'-graph) can be regressed to catchment characteristics such as are commonly employed in the UH method. Mass curves prepared from Los Angeles data are shown in Fig.1 for the Alhambra Wash catchment. Mean mass curves for several Los Angeles catchments are shown in Fig. 2. Tables 1 and 2 describe the Los Angeles catchments studied, and rain gauge data used.

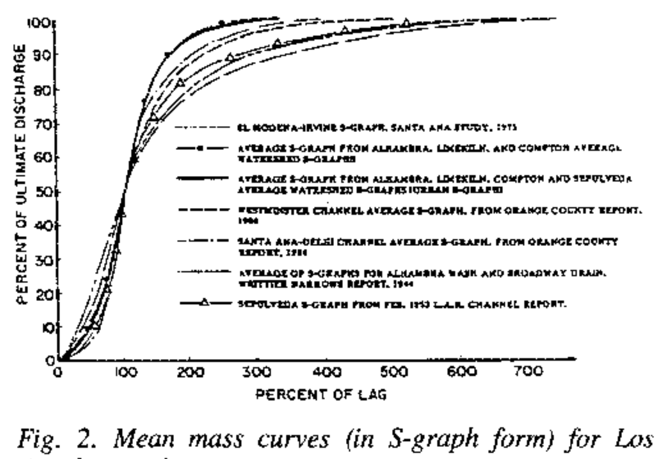

Fig. 2. Mean mass curves (in S-graph form) for Los Angeles catchments

WEIGHTED MASS—CURVES FOR LOS ANGELES, CALIFORNIA

Using catchment unit hydrograph reconstitution data prepared from several catchments in Los Angeles, California[8], a discretized representation of the random mass curve stochastic process can be made to simplify the analysis. Figure 3 shows the weighted mass curves prepared from the Los Angeles rainfall-runoff data, Figs 1 and 2, using the convolution integral model of equation (2), and a loss function, F, where F: $P^i(\cdot) \rightarrow P^i(\cdot) - \Phi$, where Φ is the constant phi-index. (Use of other loss functions will result in a variation in the resulting mass curves or transfer functions, and hence a different set of mass curves.) Shown in the figure is an averaged mass-curve (or S-graph), representing the expected value of the stochastic process. This average realization (S-graph) is characterized by means of catchment lag as discussed by Hromadka *et al.*[9], and provides for the so-called 'calibrated' unit hydrograph model transfer function for the region considered.

ESTIMATING DESIGN VARIABLE UNCERTAINTY

Directly analogous to the well-known unit hydrograph method, the weighted mass curves or transfer functions can be correlated to catchment lag and ultimate discharge (or other catchment variables) for use at ungauged catchments. Figure 4 shows a probabilistic distribution in peak flow rate estimates for a specific design rainfall event at an ungauged catchment design point in Los Angeles. A frequency distribution of peak flow rate values is developed simply by using each mass curve shown in Fig. 3, adjusted according to catchment lag and ultimate discharge (just as one would use an 'S'-graph to develop a basin UH). The resulting set of peak flow rates, estimated by convoluting each of the weighted transfer functions with the effective rainfall, are then weighted according to the respective mass curve weightings. Figure 5 shows a detention basin design volume distribution of values also based upon the weighted mass curves of Fig. 3. Each mass curve is linearly adjusted by rescaling Fig. 3 according to the catchment's lag and ultimate discharge, and the transfer functions subsequently derived for convolution with the effective rainfall to produce a set of weighted runoff hydrographs. The well-known unit hydrograph convolution procedure and methods commonly used to develop effective rainfall are presented in Ref. 9.

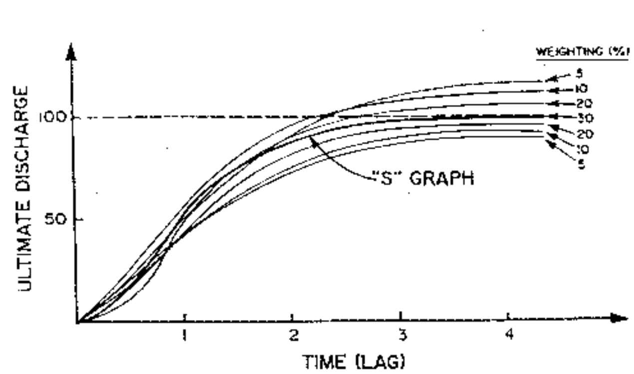

Fig. 3. Weighted mass curves for Los Angeles, California

Table 1. Watershed characteristics

	Watershed Geometry							Calibration Results		
Watershed Name	Area (mi^2)	Length (mi)	Length of centroid (mi)	Slope (ft/mi)	Percent impervious (%)	Tc (Hrs)	Storm date	Peak F_P (inch/hr)	Lag (hrs)	Basin factor
Alhambra Wash[1]	13.67	8.62	4.17	82.4	45	0.89	Feb. 78 Mar. 78 Feb. 80	0.59, 0.24 0.35, 0.29 0.24	0.62	0.015
Compton 2[1]	24.66	12.69	6.63	13.8	55	2.22	Feb. 78 Mar. 78 Feb. 80	0.36 0.29 0.44	0.94	0.015
Verdugo Wash[1]	26.8	10.98	5.49	316.9	20	–	Feb. 78	0.65	0.64	0.016
Limekiln[1]	10.3	7.77	3.41	295.7	25	–	Feb. 78 Feb. 80	0.27 0.27	0.73	0.026
San Jose[2]	83.4	23.00	8.5	60.0	18	–	Feb. 78 Feb. 80	0.20 0.39	1.66	0.020
Sepulveda[2]	152.0	19.0	9.0	143.0	24	–	Feb. 78 Mar. 78 Feb. 80	0.22, 0.21 0.32 0.42	1.12	0.017
Eaton Wash[1]	11.02[4] (57%)	8.14	3.41	90.9	40	1.05	–	–	–	0.015[7]
Rubio Wash[1]	12.20[5] (3%)	9.47	5.11	125.7	40	0.68		–	–	0.015[7]
Arcadia Wash[1]	7.70[6] (14%)	5.87	3.03	156.7	45	0.60		–	–	0.015[8]
Compton 1[1]	15.08	9.47	3.79	14.3	55	1.92		–	–	0.015[8]
Dominguez[1]	37.30	11.36	4.92	7.9	60	2.08		–	–	0.015[8]
Santa Ana Delhi[3]	17.6	8.71	4.17	16.0	40	1.73		–	–	0.053[9] 0.040[10]
Westminster[3]	6.7	5.65	1.39	13	40	–		–	–	0.079[9] 0.040[10]
El Modena-Irvine[3]	11.9	6.34	2.69	52	40	0.78		–	–	0.028[9]
Garden Grove–Wintersberg[1]	20.8	11.74	4.73	10.6	64	1.98		–	–	–
San Diego Creek[1]	36.8	14.2	8.52	95.0	20	1.39		–	–	–

Notes
1: Watershed Geometry based on review of quadrangle maps and LACFCD strom drain maps.
2: Watershed Geometry based on COE LACDA Study.
3: Watershed Geometry based on COE Reconstitution Study for Santa Ana Delhi and Westminster Channels (June, 1983).
4: Area reduced 57% due to several debris basins and Eaton Wash Dam reservoir, and groundwater recharge ponds.
5: Area reduced 3% due to debris basin.
6: Area reduced 14% due to several debris basins.
7: 0.013 basin factor reported by COE (subarea characteristics, June, 1984).
8: 0.015 basin factor assumed due to similar watershed values of 0.015.
9: Average basin factor computed from reconstitution studies.
10: COE recommended basin factor for flood flows.
11: COE = U.S. Army Corps of Engineers.
12: LACDA = Los Angeles County Drainage Area Study by COE.
13: LACFCD = Los Angeles County Flood Control District.

CONCLUSIONS

A procedure to present uncertainty in design value estimates developed from the unit hydrograph rainfall-runoff model is examined. The technique is easy to use, and provides the engineer with a method for evaluating risk, in engineering design and planning of flood control systems. Application of the procedure is analogous to the classic unit hydrograph procedure, except that a set of weighted mass curves are used to develop a set of weighted transfer functions for convolution with the prescribed effective rainfall.

Table 2. Precipitation gauges used in Los Angeles county flood reconstitutions

Stream gauge location	Storm reconstitution	LACFCD Rain gauge No. #
Alhambra Wash near Klingerman Street	Feb 78	191, 303, 1114B
	Mar 78	191, 303, 1114
	Feb 80	191B, 235, 280C, 1014
Compton Creek near Greenleaf Drive	Feb 78	116, 291
	Mar 78	116, 291
	Feb 80	116, 291, 716
Limekiln Creek above Aliso Creek	Feb 78	57A, 446
	Feb 80	259, 446
San Jose Creek Channel above Workman Mill Rd.	Feb 78	92, 1078, 1088X
	Feb 80	96CE, 347E, 1088
Sepulveda Dam (inflow)	Feb 78	57A, 292DE, 446, 735H
	Mar 78	57A, 435, 762
	Feb 80	292, 446, 735
Verdugo Wash at Estelle Ave.	Feb 78	280C, 373C, 498, 758

*No.	Station name	Lat.	Long.	Elev.	Type
L057A	Camp Hi Hill (OPIDS)	34-15-18	118-05-41	4240	SR
L0092	Claremont-Pomona College	34-05-48	117-42-33	1185	SR
L0096CE	Puddingstone Dam	34-05-31	117-48-24	1030	SR
L0116	Inglewood Fire Station	33-47-53	118-21-22	153	SR
L0191(B)	Los Angeles-Alcazar	34-03-46	118-11-54	400	SR
L0235	Henninger Flats	43-11-38	118-05-17	2550	SR
L0259	Chatsworth-Twin Lakes	34-16-43	118-35-41	1275	SR
L0280C	Sacred Heart Academy	34-10-54	118-11-08	1600	R
L0291	Los Angeles-96th & Central	33-56-56	118-15-17	121	R
L0292(DE)	Encino Reservoir	34-08-56	118-30-57	1075	SR
L0303	Pasadena-Cal Tech	34-08-14	118-07-25	800	SR
L0347E	Baldwin Park-Exp. Station	34-05-56	117-57-40	384	SR
L0373C	Briggs Terrace	34-14-17	118-13-27	2200	SR
L0435	Monte Nido	34-04-41	118-41-35	600	SR
L0446	Aliso Canyon-Oat Canyon	34-18-53	118-33-25	2367	SR
L0498	Angeles Crest Hwy-Drk Cny Tr	34-15-21	118-11-45	2800	R
L0716	Los Angeles-Ducommun Street	34-03-09	118-14-13	306	SR
L0735(H)	Bell Canyon	34-11-40	118-39-23	895	R
L0758	Griffith Park-Lower Spr Cyn	34-08-02	118-17-27	600	R
L0762	Upperstone Canyon	34-07-27	118-27-15	943	R
L1014	Rio Hondo Spreading	33-59-57	118-06-04	170	SR
L1078	Covina-Griffith	34-04-10	117-50-47	975	SR
L1088(X)	LaHabra Hts-Mut Water Co	33-56-55	117-57-51	445	SR
L1114(B)	Whittier Narrows Dam	34-01-29	118-05-02	239	SR

S = Standard 8" raingauge (non-recording)
R = Recording raingauge

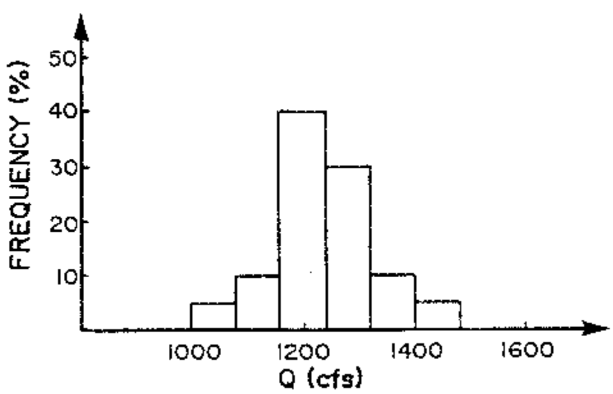

Fig. 4. Distribution of peak flow rates developed by use of Fig. 3

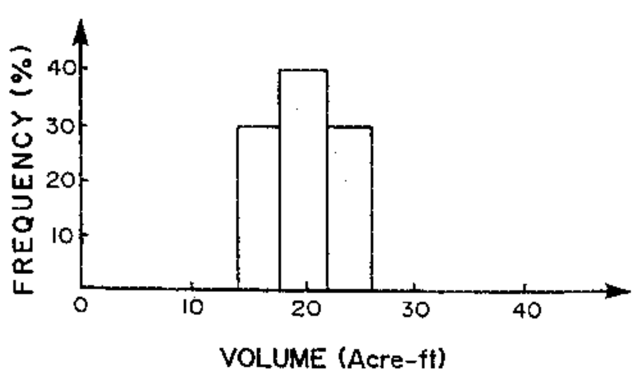

Fig. 5. Distribution of detention basin volume developed by use of Fig. 3

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