Application of an electronic analog computer to the evaluation of the effects of urbanization on the runoff characteristics of small watersheds

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ABSTRACT: In the synthesis of hydrograph characteristics of small urban watersheds, the distribution of the water among the various phases of the runoff process is attempted by the concept of "Equivalent Rural Watershed". The criteria for transforming the urban watershed into an equivalent rural watershed requires that, for a given input into both the models (urban and its equivalent rural watershed), the outputs must be identical. The hydrograph of outflow from an urban watershed is obtained by chronologically deducting the losses due to interception, infiltration and depression storage from precipitation on the equivalent rural watershed and then routing it through the surface and channel storages.

This procedure of computing the synthetic outflow hydrograph is accomplished with the analog computer at the Utah Water Research Laboratory, Utah State University at Logan. Testing and verification is done with rainfall and runoff data from the Waller Creek watershed at Austin, Texas. In the verification process, ceofficients representing interception, depression storage, and infiltration are determined by trial and error so that the simulated hydrograph is nearly identical to the measured hydrograph of the prototype. The variation in the values of these coefficients from year to year is assumed to be due to the corresponding variations in the characteristics of urbanization defined by the percentage impervious cover and the characteristic impervious length (ratio of the mean length of travel between the center of the impervious area and the discharge measuring point to the maximum length of travel on the watershed). This study attempted to develop the relation between these coefficients and the urbanization parameters.

SOMMAIRE : Dans la synthèse des caractéristiques de l'hydrogramme des petits bassins versants urbains la distribution des eaux météoriques entre les diverses composantes de l'écoulement est obtenue à l'aide du concept du « bassin rural equivalent ». Le critère employé pour transformer le bassin urbain en un bassin rural équivalent est le suivant: pour la même quantité d'eau fournie aux deux modèles (bassin urbain et son bassin rural équivalent) les hydrogrammes des débits à l'exutoire des bassins doivent être identiques. Pour obtenir l'hydrogramme des débits du bassin urbain la hauteur de pluie excédentaire est calculée en déduisant de la précipitation totale les pertes due à l'interception, à l'infiltration, et au stockage des dépressions superficielles du bassin rural équivalent, ensuite l'hydrogramme de l'écoulement de la pluie excédentaire à travers le réseau hydraulique du bassin est obtenu.

Ce procédé de calcul de l'hydrogramme synthétique des débits est réalisé à l'aide de la calculatrice analogique au « Utah Water Research Laboratory », à Logan. Les tests préliminaires et la vérification sont faits avec des données de précipitation et de débits provenant de « Waller Creek Watershed » à Austin, Texas. Dans la vérification les coefficients représentant l'interception, le stockage dans les dépressions superficielles et l'infiltration sont obtenus par tâtonnements. On adopte ceux pour lesquels l'hydrogramme résultant du modèleest presqu'-identique à l'hydrogramme des débits mesurés à l'exutoir du bassin urbain. Les variations dans les valeurs de ces coefficients pour les diverses années choisies sont dues probablement aux variations dans les caractéristiques d'urbanisation définies par le pourcentage de la couverture imperméable et la longueur caractéristique (rapport de la distance moyenne entre le centre de la surface imperméable et la station hydrométrique à l'exutoire du bassin à la plus grande distance parcourue par une particule d'eau avant d'atteindre la station de jaugeage). Dans cette étude on a essayé de développer une relation entre ces coefficients et les paramètres d'urbanisation.

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INTRODUCTION

Because of the rapid urban development in recent years hydrologic problems associated with urban watersheds have gained great importance. During the past half century, enormous expenditure is being incurred in the United States in the design of urban drainage systems based on empirical approaches. Estimates of expenditures before the year 2000 for storm drainage facilities to serve the growing population exceed 25 billion dollars, (Reed, 1965). When such large amounts are involved in the urban drainage improvement, it is imperative that their design should be based on sound fundamental analysis.

This paper presents briefly a critical review of the literature pertaining to the field of hydrologic modeling, some of the theoretical studies made for relating the various phases of the hydrologic model, testing and verification of the model on the analog computer and the various results.

REVIEW OF LITERATURE

In many hydrologic investigations on small watersheds, data and observations are totally inadequate to provide a basis for the prediction of outflow hydrographs. In order to synthesize a hydrograph, it is necessary to mathematically describe the physical behavior of the dynamic processes involved in the hydrologic system. For a review of some of the methods available for hydrograph synthesis at various stages reference may be made to Narayana (1967).

Most of the research work to date involving urban watersheds has dealt with the effect of urbanization on the runoff hydrograph characteristics, such as the lag time and the peak discharge rate. Methods of analysis are statistical in nature.

Viessman (1966) considered the design of urban drainage systems to be two-fold in nature: (1) determination of individual runoff inputs at each inlet or group of inlets and (2) routing and combining these inputs in storm sewers so that outflow hydrographs can be synthesized at any point of interest. His study is limited to the determination of runoff hydrographs for small impervious urban inlet areas. James (1965) using a digital computer program based on the Stanford Watershed Model studied the effects of urban development on flood peaks. Espey *et al.* (1965) made a similar study on the evaluation of urbanization effects on the runoff characteristics of urban watersheds located in the region of Austin, Texas.

METHODS OF ANALYSIS

In order to describe in specific terms the characteristics of an urban watershed, it is necessary to select parameters of urbanization which can be determined easily and with some measure of accuracy. In this study, the percentage of impervious cover, and the characteristic impervious length factor were chosen to be the two such parameters.

The percentage impervious cover (*PIC*) is defined as the ratio of the total impervious area (area covered by houses, roads, parking areas, etc.) to the total watershed area. This factor characterizes the infiltration abstractive process which materially alters the distribution and total volume of the rainfall excess.

The characteristic impervious length factor (PHI) is defined as the ratio of the length of travel (1_I) between the center of a particular impervious area and the discharge measuring point to the maximum length of travel on the watershed. This parameter represents the disposition of the impervious areas within the watershed which controls the travel time of the precipitation excess from the point of its origin to the measuring point.

If the rural watershed is the equivalent of the given urban watershed, the unit hydrograph for each of them should be identical. This assumption, along with the various expressions of Espey *et al.* (1965) lead to the following relations:

$$S_{ER} = \frac{S_U L_U}{L_{ER}} \tag{1}$$

and:

$$L_{ER} = \left[\frac{T_{RU}(S_U L_U)^{.52}}{2.65}\right]^{1/.64} \tag{2}$$

In these expressions:

T_R Rise time of the unit hydrograph;
L Maximum length of travel on the watershed;
S Mean slope of the watershed;
I Percentage impervious cover *PIC*;
Φ Characteristic impervious length factor *PHI*;
U Represents the urban watershed and *ER* the equivalent rural watershed.

Losses that occur on urban watersheds are the same as those which occur on natural or rural watersheds. The analysis for rainfall excess on an urban watershed is therefore the same as that for a rural watershed, and is presented by a mathematical model (fig. 1) and the analog model (fig. 2).

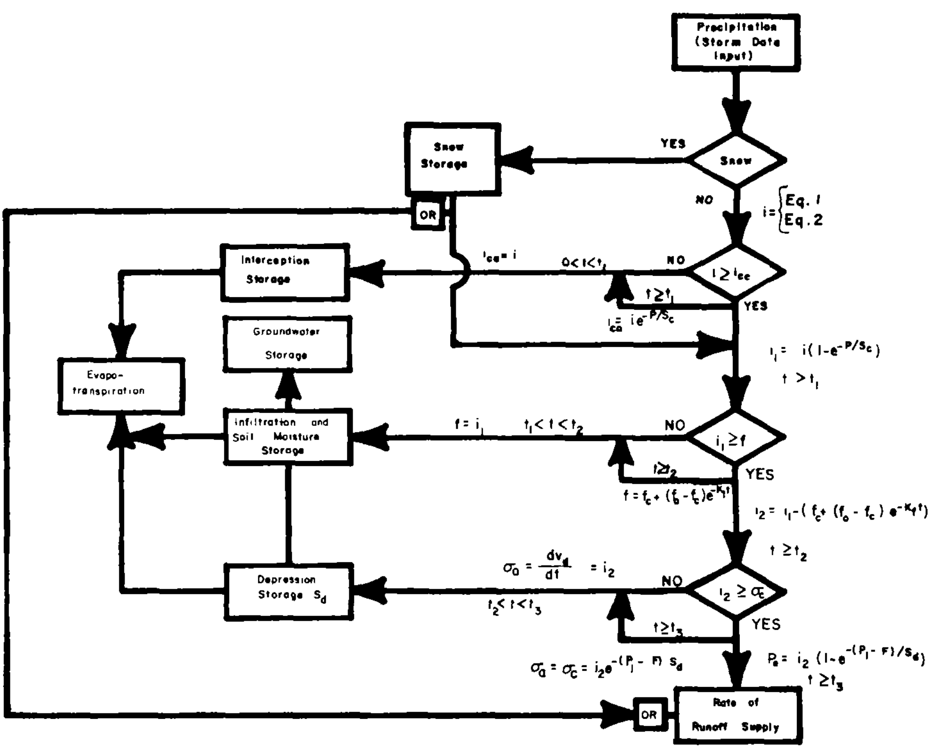

FIGURE 1. *Schematic flow chart for obtaining hydrograph of rainfall excess*

The routing procedure is based on the general continuity equation (3) for any linear storage system defined by equation 4.

$$p_e - q = \frac{ds}{dt} \tag{3}$$

where:

p_e rainfall excess rate;
q runoff rate;
s storage in the reservoir.

$$s = T_R q \tag{4}$$

Equation 3 and 4 yields the following:

$$p_e - q = T_R \frac{dq}{dt} \tag{5}$$

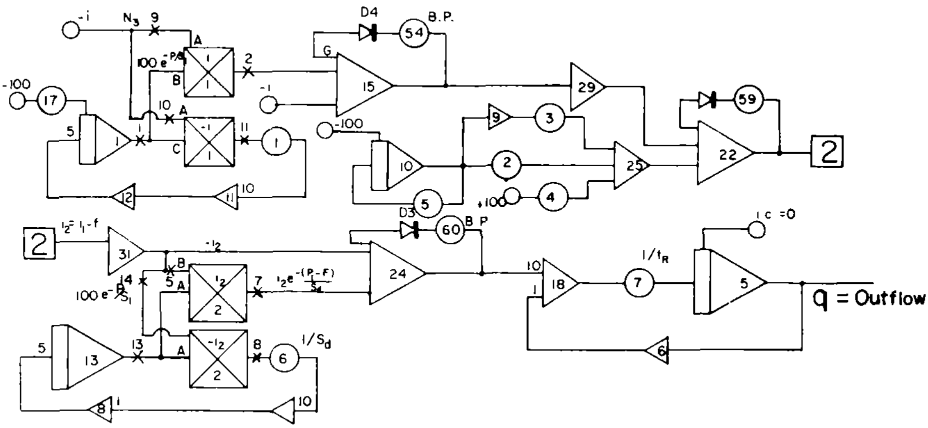

FIGURE 2. *Analog computer program for outflow hydrograph from equivalent rural watershed*

EXPERIMENTAL AREA

Testing and verification of these relationships were done by simulating runoff events on the Waller Creek Watershed, Austin, Texas with the data of rainfall and runoff from 1956-1965 obtained from U.S. Geological Survey at Austin. The drainage area above the 23rd street is 4.13 sq. miles, and above the 38th street is 2.31 sq. miles.

An exclusive study of the watershed has been made using the aerial photographs made in 1951, 1958, and 1964. Typical chronological urban development in the watershed for three various subunits is shown by figure 3. This figure indicates that the maximum urban growth took place between 1958 and 1964. Table 1 summarizes the chronological development of the urban parameters of the 23rd and 38th streets of the watersheds in the Waller Creek basin.

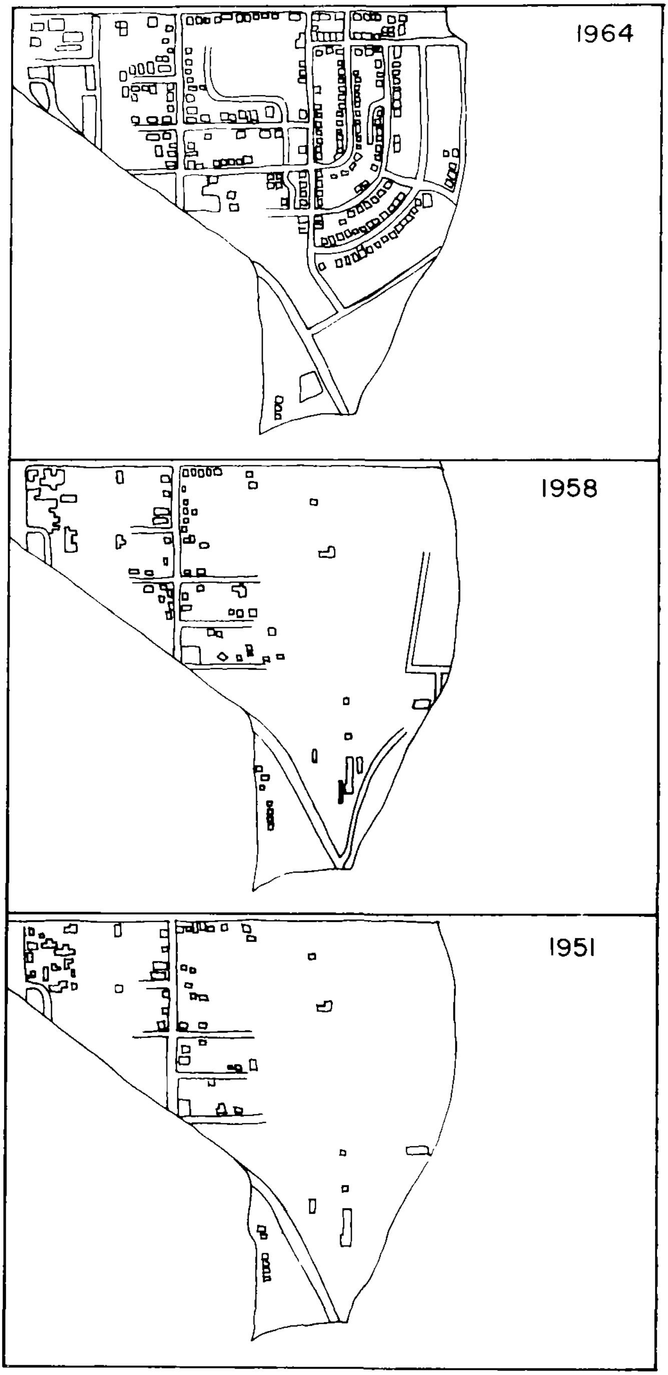

FIGURE 3. *Urbanization in subunit 29 during years 51, 58, 64*

TABLE 1. Chronological development of urbanization

	Total		(PIC)			(l_I)	
	Square miles	1951	1958	1964	ft 1951	ft 1958	ft 1964
23rd Street	4.13	.272	.332	.378	10,727	11,753	12,409
38th Street	2.31	.236	.313	.364	10,031	11,120	11,406

PROCEDURE OF VERIFICATION

Using appropriate values of PIC and l_I and the transformation equations 2 and 3 a digital computer program was written to obtain the characteristics of the unit hydrographs and the length, area and slope of the equivalent rural watershed at various stages of urban development.

Based on the logic in figure 1 and equation 5, an analog computer program was developed (fig. 2).

The input into the analog computer is precipitation during any storm applied in the form of a staircase step function. Each step of this function represents the voltage equivalent of the value of precipitation occurring in the corresponding 30 minute interval of the storm. Check for the simulated output is the actually recorded outflow hydrograph for the storm under study. The potentiometers representing the interception capacity (S_I), maximum (f_0) and minimum (f_c) infiltration capacity rates and the exponential decay factor (k_f) in the Horton's infiltration equation, the depression storage capacity (S_D), and the routing coefficient (t_R) are so manipulated that the simulated output is nearly identical with the actual output. The verification of the model is accomplished by achieving the identity between the characteristics of both the hydrographs in the following order of priority.

(1) Peak rate of outflow;
(2) Rise time;
(3) Total volume of outflow;
(4) Total duration of outflow.

RESULTS AND DISCUSSIONS

Geometric characteristics of the equivalent rural watershed. The following changes in the watershed geometry resulted from changes in the urbanization.

(1) The area of the equivalent rural watershed (AER) is not materially altered.
(2) The maximum length of travel (L_{ER}) has been shortened by more than 60% in the equivalent rural watershed.
(3) The slope of the equivalent rural watershed (S_{ER}) has become steeper.
(4) With increase in urbanization, the risetime, base of the unit hydrograph, and other time parameters (W_{50U}, W_{75}) have been shortened, while the peak discharge increased nearly by 27%.

Model verification. Nearly 48 storm events were simulated on the analog computer and verified. Figure 4 represents some of these verified events which compare the simulated and actual hydrographs. Some values of the various characteristics verified are reported

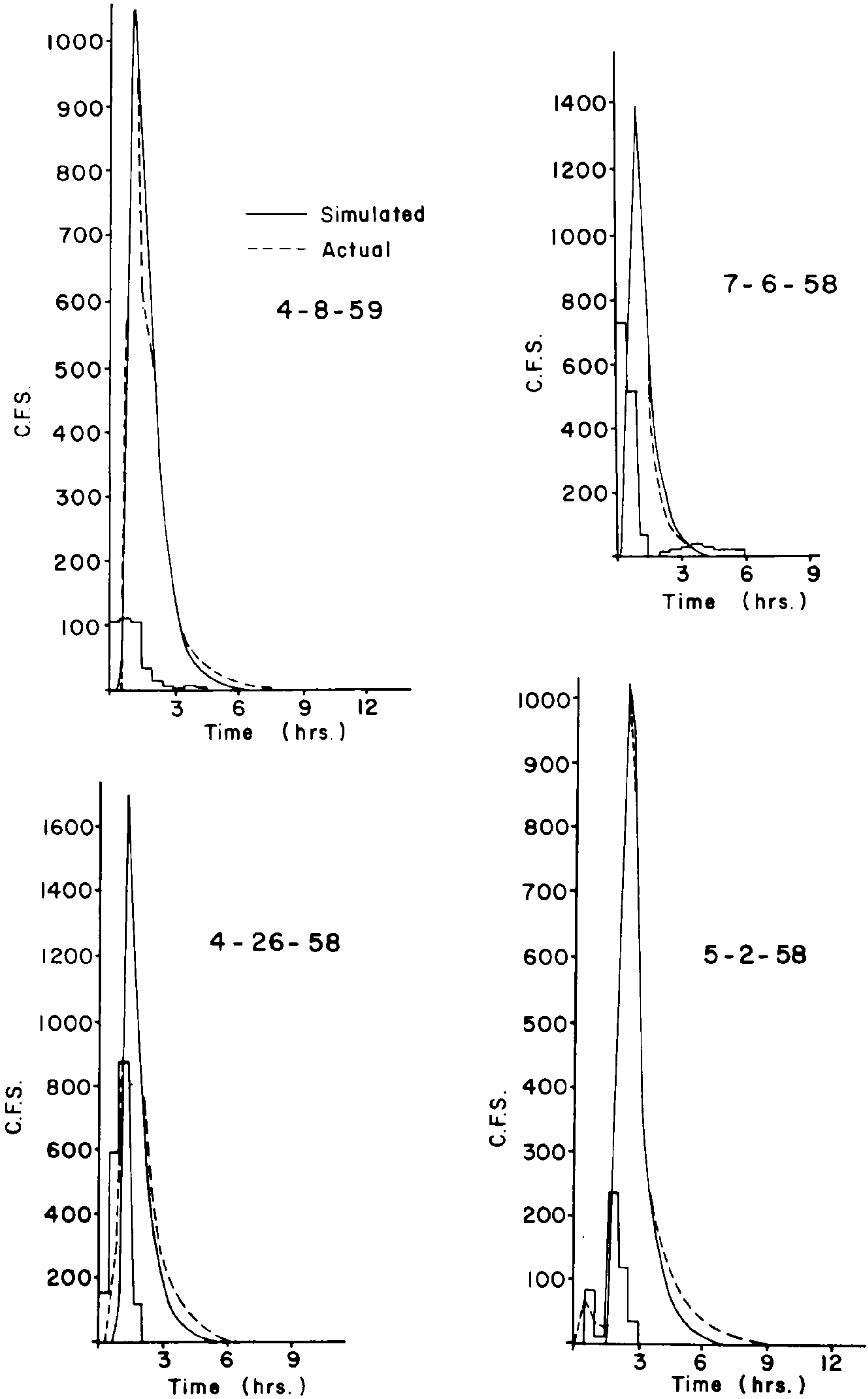

FIGURE 4. *Comparison between the simulated and actual hydrographs*

in table 2. Further comparison between these various values is presented in figure 5. Coefficients of regression between the simulated and actual values of the various parameters of verification range from 0.95 to 0.99.

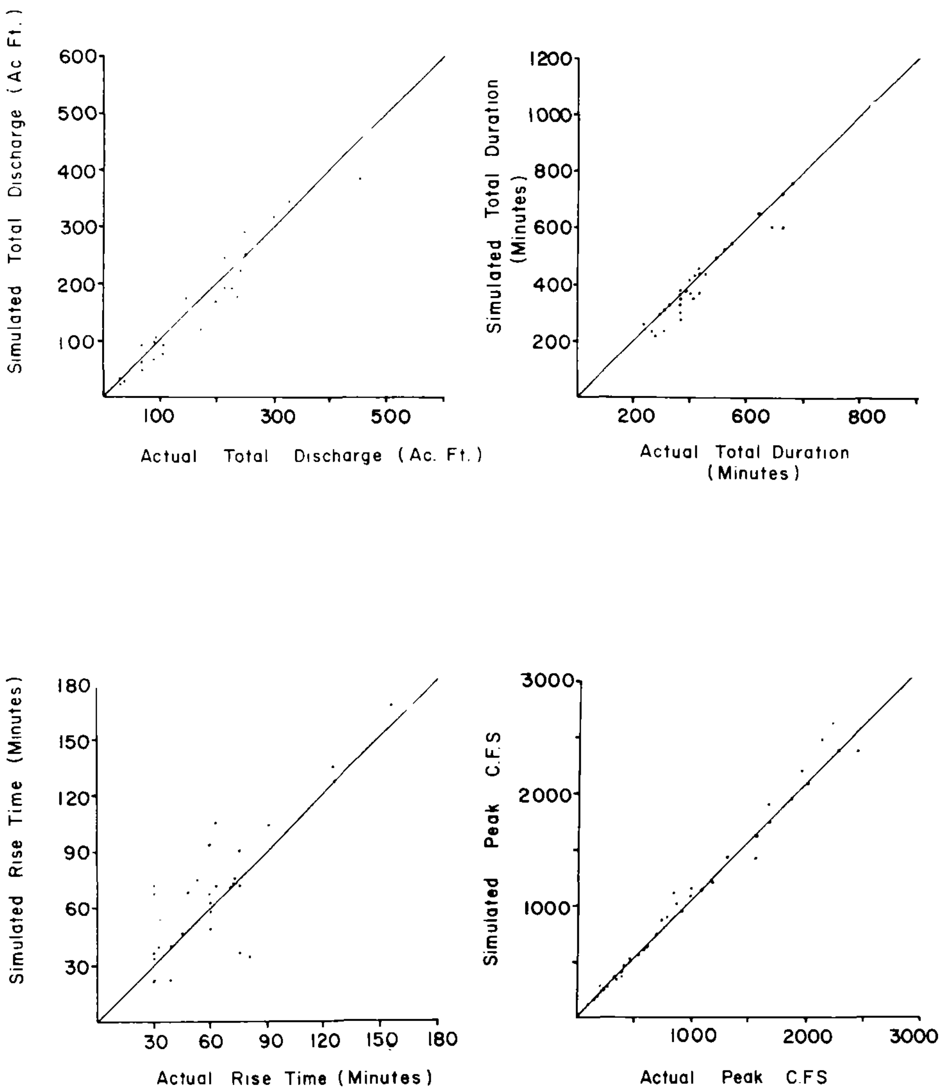

FIGURE 5. *Comparison between the simulated and actual characteristics of hydrographs*

These values indicate that the model verification was accomplished with a reasonable degree of accuracy and therefore could be utilized for evaluating the watershed coefficients.

Watershed coefficients. Some values of the watershed coefficients (S_I, f_0, f_c, S_D and t_R) derived from the analog computer verification for various storms are presented in table 3. Figure 6 indicates the variation of these coefficients in relation to the urban parameters. K_f is maintained at a constant value of .8 for the entire period of study.

TABLE 2. Characteristics of simulated and actual outflow hydrograph for the Waller Creek Watershed

23rd Street	Q_P cfs		T_R min		Q_T acre feet		TD min		TL min	
Date	sim.*	act.*	sim.	act.	sim.	act.	sim.	act.	sim.	act.
010556	620	615	84	72	123	121	480	480	72	126
220957	310	340	30	25	32	25	324	324	22	45
060758	1360	1330	54	60	107	120	288	306	9	9
230959	1920	1915	45	45	171	143	288	360	36	28
281060	1685	1600	52	45	175	207	270	270	234	234
090761	2275	2163	148	135	299	299	360	396	270	240
030662	2580	2270	72	72	247	213	713	720	54	45
160964	160	140	27	30	10	16	216	195	180	190
160565	1980	2000	57	75	222	240	288	324	90	72

TABLE 3. Urban parameters and physical characteristics of the equivalent rural watersheds of Waller Creek urban catchments

23rd Street	PIC	PHI	S_I inches	f_o in/hr	f_c in/hr	S_D inches	T_R min.
010556	.3145	.4159	0.075	.225	.175	0.079	39.7
080458	.3310	.4258	0.104	.155	.115	0.117	38.3
020558	.3310	.4258	0.125	.185	.16	0.167	38.9
230959	.3392	.4301	0.132	.17	.14	0.126	38.3
281060	.3475	.4399	0.156	.16	.14	0.179	37.9
100662	.3640	.4428	0.179	.1	.05	0.250	35.6
160964	.3805	.4496	0.136	.1	.05	0.145	36.4
160565	.3387	.4500	0.136	.1100	.075	0.145	37.2

From figure 6, the values of f_0 and f_c for $PIC = 0$ and 1 are given below:

	f_e	f_c
$PIC = 0$	$1.1''/hr$	$.7''/hr$
$PIC = 1$	0	0

The values for $PIC = 0$ represent the average for an ideal rural watershed which seems reasonable for clay soils of varying thickness.

The values of S_D and S_I seem to increase relatively between the years 1958 to 1962 (fig. 6), which incidentally is the period of the high urbanization activity. The increase in the interception and depression storage capacities during 1958 to 1962 may be justified by the increased urbanization which would reflect in the construction activity, increased area under lawns, ornamental shrubs, avenue trees, etc. This may also be due to the fact that this watershed is located in a semi arid region where the vegetative growth in a natural watershed may not be so profuse as under urban conditions. Further, by 1956, the rural characteristics of this watershed would have been completely altered due to partial urbanization in the form of leveling, removal of unwanted vegetation in the proposed

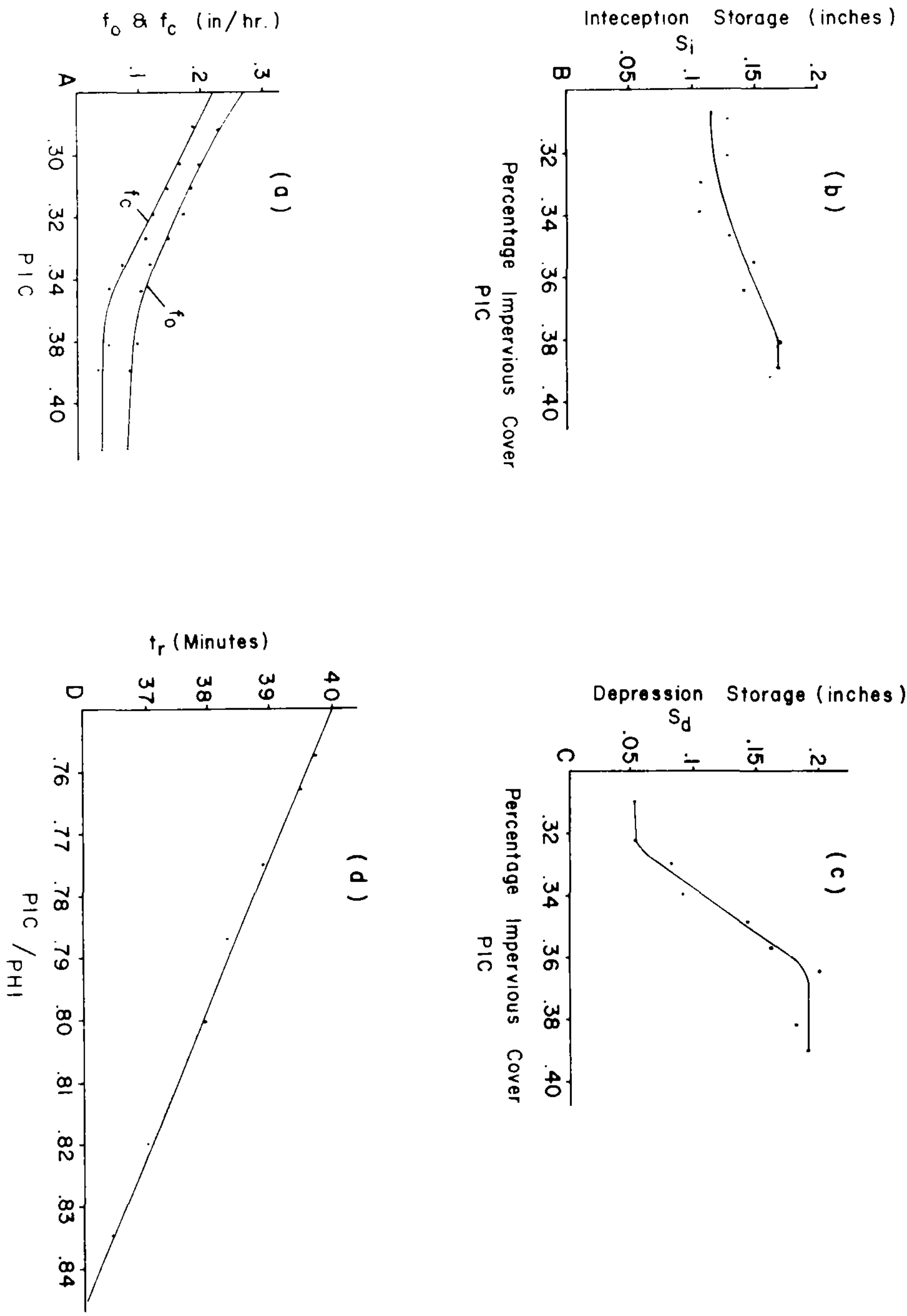

FIGURE 6. *Relations between the average physical characteristics and urban paremeters of Waller Creek Water Shed, Austin, Texas*

dwelling areas etc. However, the values in 1964, 65 indicate that S_D and S_I may remain constant under the prevailing trend of growth. The fact that, whether this phenomena is unique to this watershed or universal, needs to be studied in greater detail on other watersheds for which data may be available.

CONCLUSIONS

Some of the important conclusions resulting from this study are listed as follows:

(1) The various mathematical expressions adopted or derived in describing the continuous and dynamic runoff process seem to be adequate.
(2) It is possible to transform any given urban watershed into a hypothetical equivalent rural watershed with the type of equations developed by Espey Jr. *et al.* (1965) and then conveniently model it to develop the relations between the urban parameters and the characteristics of the equivalent rural watershed.
(3) The analog computer yields the output very quickly in graphical form. Easy manipulation of the various computer components facilitates varying the different parameters within the model. It is thus possible to rapidly determine the optimum combination of parameters that identifies the simulated output with the actually measured one.
(4) Some of the relations developed in this study between the urban parameters and the watershed characteristics seem to be unique for this watershed alone. Additional studies will be needed to develop general regional relations on the basis of the present work.

SUMMARY

This paper presents briefly a method of transforming a given urban watershed as an equivalent rural watershed. This equivalent rural watershed is modeled on an analog computer for simulating several runoff events on the watershed. The procedure of testing and verifying this model (simulated) output with the actually recorded outflow and determining the representative physical characteristics of the watershed for each year of study are reported. These physical coefficients thus determined are related to the urban parameters measured from aerial photographs during the period of study.

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