EFFECTS OF URBAN DEVELOPMENT ON THE FLOOD-FLOW CHARACTERISTICS OF THE WALNUT CREEK BASIN
DES MOINES METROPOLITAN AREA, IOWA

U. S. Geological Survey

Water-Resources Investigations 78-11

Prepared in cooperation with the
Iowa Natural Resources Council

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DES MOINES METROPOLITAN AREA, IOWA

By

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Prepared by the U.S. Geological Survey in cooperation with THE IOWA NATURAL RESOURCES COUNCIL

February 1978

This report deals with the probable impact of urban development on the magnitude and frequency of flooding in the lower reach of the Walnut Creek Basin. Stream-modeling techniques, which include complete definition of unit hydrographs and precipitation loss-rate criteria, were utilized to evaluate the effects of urban development as measured by percentages of impervious area over the basin. A mathematical model, called HEC-1, was calibrated by using concurrent rainfall-runoff data collected at three gaging stations in the basin. The model parameters were regionalized to allow future users to estimate the model parameters for ungauged areas within the basin. Long-term rainfall data recorded at two nearby stations were employed as basic input to the calibrated model to generate annual peak discharges corresponding to selected degrees of urbanization. Results are presented in tables and graphs, which compare the pre-urban and urban flood flow characteristics of the lower reach of the Walnut Creek basin.
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FACTORS FOR CONVERTING ENGLISH UNITS TO INTERNATIONAL SYSTEM (SI) UNITS

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ABSTRACT

This report deals with the probable impact of urban development on the magnitude and frequency of flooding in the lower reach of the Walnut Creek Basin.

Stream-modeling techniques, which include complete definition of unit hydrographs and precipitation loss-rate criteria, were utilized to evaluate the effects of urban development as measured by percentages of impervious area over the basin. A mathematical model, called HEC-1, was calibrated by using concurrent rainfall-runoff data collected at three gaging stations in the basin. The model parameters were regionalized to allow future users to estimate the model parameters for ungauged areas within the basin.

Long-term rainfall data recorded at two nearby stations were employed as basic input to the calibrated model to generate annual peak discharges corresponding to selected degrees of urbanization. Results are presented in tables and graphs, which compare the pre-urban and urban flood flow characteristics of the lower reach of the Walnut Creek basin.
INTRODUCTION

Purpose and Scope

Walnut Creek basin, located within the Des Moines metropolitan area, is one of the more rapidly urbanizing areas in the State of Iowa. A particularly significant aspect of this trend is its effect upon the natural hydrologic system of the basin.

The specific objective of this study was to assess the impact of urban development on the magnitude and frequency of flooding in the lower reaches of the Walnut Creek basin.

Observed flood data of adequate period of record are, obviously, the most reliable source for directly evaluating the consequences of urban development. Lacking these data, as in the Walnut Creek basin, where only 5 years of flood records are available, planners must resort to other sources of usable information and alternate methods of analysis. A surrogate approach often employed in urban planning is known as deterministic modeling or system simulation. According to McGuinness and others (1970), "... deterministic oriented mathematical models of watershed systems appear to offer the most rational approach both for quantitatively describing hydrologic performance of watersheds and for delineating the effects of land use and management practices on stream flow".

Based on the preceding reasoning, a deterministic modeling method was utilized in this study. In general, the steps selected to implement this study can be summarized as follows:

1. Using a rainfall-runoff model, extend the short-term annual flood peaks at the gaging station by utilizing the long-term climatic data recorded at the nearby Des Moines airport and at Perry, Iowa.

2. Using watershed simulation techniques, generate concurrent long-term annual peaks for selected degrees of urbanization.

3. Fit flood-frequency curves to the generated annual peak arrays.

This report describes the simulation technique which was employed and summarizes the results of the investigation.

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The author is grateful to Arlen D. Feldman of the Corps of Engineers Hydrologic Engineering Center, Davis, California, for his advice, assistance, and cooperation in supplying computer programs and documentation.
STUDY AREA

The Walnut Creek basin is in parts of Dallas and Polk Counties, as shown on the location map (fig. 1). Walnut Creek is a left-bank tributary of the Raccoon River and flows in a southeast direction entering the Raccoon River within the city limits of Des Moines. The lower portions of the basin consisting of about 8 to 10 percent of the total area is highly urbanized. Nearly all the remaining area is agricultural with approximately 75 percent in cropland. The predominant soil type is a combination of Clarion and Nicollet (Stevenson and Brown, 1922), which are classified in the hydrologic group B (U.S. Soil Conservation Service, 1972). Soils in this group are characterized by moderate infiltration rates.

Elevation in the basin ranges from 850 to 1,050 feet above mean sea level. The topography varies from nearly level to rolling terrain. The average annual precipitation is about 32 inches, most of it falling during freeze-free periods.

RAINFALL-RUNOFF MODEL

A model called HEC-1 which was developed by the Hydrologic Engineering Center, U.S. Army Corps of Engineers, (1973), was selected for use because it satisfies the project requirements, is relatively simple to use, and it requires less data than alternate models.
Basically the model requires complete definition of a unit hydrograph based on the Clark method and precipitation loss-rate criteria for the basin or sub-basins to be modeled. HEC-1 has the capability to determine a set of unit hydrograph and loss-rate parameters which "best" reconstitute observed runoff events, given the average rainfall over the basin, the drainage area, and a few runoff parameter values. The "best" reconstitution is considered to be that which minimizes the weighted square deviations between the observed and the reconstituted hydrographs. For ready reference, following is a list of definitions of the variables and parameters of the model compiled from the Users Manual.

**Runoff Hydrograph Variables**

- **QRCN** - The discharge at which recession flow begins.
- **STRTQ** - Recession flow for antecedent runoff.
- **RTRY** - Recession coefficient that is the ratio of flow at time t to that 10 computational periods (t + 10 t) later during recession.

**Clark Unit Hydrograph Variables**

- **TC** - Clark unit hydrograph time of concentration, in hours.
- **R** - Clark unit hydrograph storage coefficient, in hours.

To reduce the compensating effects of the interdependency between TC and R, the variables are grouped into two new variables for use in the automatic derivation routine.

- **TC+R** - Sum of time of concentration and storage coefficient, variable used in HEC-1 for optimizing unit hydrograph parameters.

- **R/(TC+B)** - Ratio of storage coefficient to sum of time of concentration and storage coefficient; variable used in HEC-1 for optimizing unit hydrograph parameters. For a graphical representation of the Clark unit graph coefficient, see figure 2.

**Loss Rate Parameters**

- **DLTK** - Amount of initial accumulated rainfall loss during which the loss rate coefficient is increased. This parameter is considered to be a function primarily of antecedent soil moisture deficiency and is usually different for different storms.
- **STRK** - Starting value of loss coefficient on exponential recession curve for rainfall losses (snow-free ground). The starting value is considered a function of infiltration capacity and thus depends on such basin characteristics as soil type, land use, and vegetal cover.
- **ETOL** - Ratio of rain loss coefficient on exponential loss curve to that corresponding to 10 inches more of accumulated loss. This variable may be considered a function of the ability of the surface of a basin to absorb precipitation and should be reasonably constant for large rather homogeneous areas.
- **ERAIN** - Exponent of precipitation for rain loss function

\[
ALOSS = (AK + DLTK) \times \text{PRCP}^{ERAIN}
\]

that reflects the influence of precipitation rate on basin-average loss characteristics. It reflects the manner in which storms occur within an area and may be considered a characteristic of a particular region. Varies from 0.0 to 1.0. The terms in the equation are defined as:

- **ALoss** - loss rate for particular time interval in inches per hour.
- **AK** - loss rate coefficient at beginning of time interval.
- **PRCP** - rainfall intensity in inches per hour.
- **DLTK** - incremental increase in loss rate coefficient. DLTK is assumed to be a parabolic function of
the accumulated loss for DLTK amount of accumulated loss. DLTK is a maximum of 0.2 DLTK initially reducing to zero when the accumulated loss equals DLTK. A graphical representation of the loss rate parameters is illustrated in figure 3.

BASIC DATA

During the first year (1975) of this three-year project, a data-collection network was established to obtain concurrent streamflow and rainfall data. The gaging stations in the basin were installed in accordance with the following criteria:

1. Update the instrumentation at the recording station near the mouth of Walnut Creek which has been in operation since 1971.
2. Select a site in the basin to collect data for an essentially rural area.
3. Select a site in the basin to collect data for a partially urbanized area.
4. Select a site in the basin to collect data for a completely urbanized area.
5. Assure that stations in the network represent a significant range of drainage-area sizes.

Budget constraints limited the number of gaging stations to four including the existing gaging station. Each gaging site was equipped with a Stevens A-35 water-stage recorder with a rainfall recording attachment. Figure 1 shows their locations.
Data-collection expectations were not fully realized because the study area, experienced severe drought conditions with very little storm activity. This situation persisted throughout the time of the project limiting the collection of data to no more than two or three significant storms at each gaging station. Furthermore, the location of the gage installed to collect data for a fully urbanized area proved to be unsatisfactory and had to be moved. Hence, data from only three stations were available at the time of this study (1977).

Other data used in this study were long-term records of hourly rainfalls at the Des Moines airport and concurrent 24-hour total rainfall amounts recorded at Perry, Iowa. The locations of these rainfall stations are shown in figure 1.

**MODEL CALIBRATION**

**Regional Analysis of Model Parameters**

The usefulness of a calibrated model, such as the one described above, is considerably expanded by providing future investigators with the ability to estimate the model parameters for ungaged areas within the basin. This was accomplished by regionalization techniques in which model parameters were related to physiographic, land-use, and climatic characteristics of the basin. Regionalization of model parameters is not one of the primary objectives of the present study. However, efforts have been made at this time to develop a set of criteria for
estimating model parameters for ungaged watersheds within the Walnut Creek basin.

The modeling sequence and the results of the regionalization studies are summarized below.

**Modeling Sequence**

The calibration of the model and definition of regional relations were accomplished generally in the following sequence.

1. Compile precipitation and runoff data for all of the storms at the gage.
2. Determine STRTQ for each storm at the gage.
3. Determine QHCSN for the recorded flood by plotting the flow recession on semilogarithmic paper and selecting the discharge above which the recession significantly departs from a linear relation.
4. Determine RTIOR. This value is equal to the slope of the linear function discussed in Step 3.
5. Compute TC, R, STRKR, DLTKR, RTIOL, and ERAIN for all storms at the gage using the optimizing routine of the model.
6. Repeat steps 1 through 5 for all gages in the basin. Based on the results, select an average regional value for ERAIN.
7. Repeat Step 5 for all gages and selected storms with ERAIN fixed to equal the regional value. Select a regional value for RTIOL based on previous computations.
8. Compute TC, R, STRKR, DLTKR, using the optimizing routine of the model for all storms at all gages with the regional values of ERAIN and RTIOL fixed.
9. From the results of Step 8, select a representative value of STRKR for each gage, and recompute TC, R, and DLTKR for all gages and storms with ERAIN, RTIOL, and STRKR fixed.
10. Select an appropriate value for DLTKR and an average value for R/TC+R for each subbasin and optimize TC and R, with R/TC+R, STRKR, ERAIN, DLTKR, and RTIOL fixed for the selected storms at each gage.
11. Select an average representative value of TC and R for each stream, check the goodness of fit of selected storms. Adjust TC+R and rerun if needed.
12. Regionalize the model parameters.
13. To judge the quality of the regional approach compute the model parameters by using the regional relations and reconstitute known runoff events at each site and compare. Examples of such comparisons are shown in figures 4, 5, and 6. In addition, the final rainfall-runoff values were compared to the relations developed by the Soil Conservation Service (1972) where less rates
Figure 4. Observed and computed hydrographs for Walnut Creek at Des Moines, Iowa (drainage area, 78.4 mi²) for flood of June 18, 1975.

Figure 5. Observed and computed hydrographs for Walnut Creek near Grimes, Iowa (drainage area, 30.0 mi²) for flood of June 18, 1975.
are characterized by a curve number (CN) which is a function of the land cover (land use) and soil characteristics (hydrologic soil group). The results of this comparison were quite satisfactory and well within acceptable limits of departure from the curves that apply to the Walnut Creek basin.

The results of the regional study are summarized below.

Results of Regional Analysis

Runoff-Hydrograph Variables

\[ Q_{RCSN} = 35 \ \text{A}^{0.5} \]  
\[ R_{TDB} = 2.10/\text{A}^{0.10} \]  
\[ SRTQ = 0.5\text{A} \]  

Clark Unit Hydrograph Variables

\[ TC + R = 1.65 \ \text{A}^{0.5} \]  

and

\[ B/(TC + R) = 0.50 \]  

Substituting between 4 and 5

\[ B = 0.83 \ \text{A}^{0.5} \]  

A = Drainage area in square miles.

Figure 7 shows the relation between TC + R and drainage area. Each point represents the average optimized value at the gage.
Loss Rate Parameters

RAIN = 0.54
RTIOI = 2.94
STRIK = 0.32

DLTK (function of antecedent conditions).

It should be noted that the results obtained from the regional relations are applicable only to the Walnut Creek basin.

SYNTHESIS OF FLOOD PEAKS

Processing of rainfall data

The rainfall-runoff model, calibrated as explained previously, was used to synthesize flood peaks using long-term rainfall records for Walnut Creek at Des Moines (drainage area 78.4 mi²). Rainfall storms were selected from data recorded at the Des Moines airport and at Perry, Iowa.

The Des Moines rainfall-recording station has been in operation since 1879. However, the time response of the basin is such that the model requires hourly rainfall distribution data. Therefore, only the 36-year record for 1941-76 water years is usable.

HEC-1 performs "lumped" parameter modeling. This means that the computed parameters and the input data, such as rainfall, are considered to be average values and, in the case of rainfall, uniformly distributed over the watershed. In order to meet this

Figure 7. Relation between Clark unit hydrograph parameters and the drainage area for Walnut Creek basin.
data requirement, it was necessary to take into consideration the additional rainfall record at Perry, Iowa (fig. 1). However, the concurrent data at Perry consists of 24-hour totals only. Of the various rainfall distribution schemes tried the best results were obtained by using the hourly rainfall distribution pattern recorded at the Des Moines station and adjusting each hourly total by the ratio between the 24-hour total recorded at both stations. The results of this procedure compared satisfactorily to the rainfall distribution indicated by the short-term rainfall data recorded at the stations in the network during the three years of operation. In addition, long-term station rainfall data prepared according to this procedure were used to reproduce the peaks from 1972 to 1976 recorded at the existing gaging station on Walnut Creek at Des Moines. Results were essentially the same as those obtained using short-term rainfall data. Thus the long-term rainfall distribution can be used to synthesize annual peaks with acceptable accuracy.

The antecedent conditions before a given storm event were determined by examining the rainfall activity for the 10 days preceding the storm.

All of the storm events in the long-term record which appeared likely to produce a high peak were simulated with the model. From these runs, the storm event which resulted in the highest peak discharge within a water year was selected and included in an array of 36 annual storms. These data constitute the basic input to simulate the basin response to selected levels of urban development stages.

Simulation of Peaks

Leopold (1968) describes four interrelated but separable effects of land use changes on the hydrology of a watershed: changes in total runoff, changes in peak flow characteristics, changes in quality of water, and changes in the hydrologic amenities.

The scope of this study is limited to the changes in peak flow characteristics.

The principal factors governing the peak flow characteristics are the portion of area made impervious by the urbanization processes and the rate at which the flow is conveyed across the land to the stream channels.

The volume of storm runoff is governed primarily by the infiltration characteristics, which are related to land slope, soil types, and vegetative cover. Thus the infiltration characteristics of the basin are directly related to the percent of area made impervious by urbanization.

The rate at which water is conveyed across the basin is related to the density, size, and hydraulic characteristic of the tributary channels. Therefore it is also related to the provision of storm sewerage systems, which alter the natural conditions of the basin. Observed data to develop relations
describing the effect of channel modification on the unit hydrograph parameters are not available at this time. For the purpose of this study, factors for adjusting these parameters have been obtained from experimental data compiled by the Soil Conservation Service (1975).

Results

To compare the effects of urbanization on the flood flow characteristics of Walnut Creek, five simulation runs were made. The first run was for the basin in its present stage of urbanization (about 5 percent of the area impervious). The remaining runs were made by changing the pertinent model parameters to reflect 20, 30, 50, and 100 percent of the basin impervious. Taking into account the size of the drainage area and the type of urban development expected to take place, the upper limit is likely to be less than 50 percent impervious.

The synthetic annual peaks for each year of rainfall record are listed in Table 1. Frequency curves for each of the annual peak series listed in Table 1, were computed by fitting the Pearson Type III distribution function to the logarithms of the annual peaks. The computed log-Pearson distribution parameters are listed at the bottom of Table 1. The resulting frequency curves are shown in figure 8.

The variation of the log-Pearson type III distribution parameters with percent of impervious area is shown in figure 9. If desired, this figure could be used to calculate frequency curves between those shown in figure 8.

Included in figure 8 and for the purpose of comparison, is a "regional frequency curve" which was estimated by using an entirely different approach from the one discussed in this report. Methods for estimating regional flood-frequency curves for the state of Iowa are explained by Lara (1973, 1974). Theoretically, the regional curve describes the flood-frequency characteristics of Walnut Creek in its natural condition. The impact of urbanization on the flood-frequency characteristics of Walnut Creek, as measured by increasing percentages of impervious area over the basin, can be evaluated from the data summarized in Table 1 and figure 8.
Table 1. Synthetic annual peak discharges, in cubic feet per second, compiled from model responses to present conditions and to selected degrees of urbanization.

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Mean 3.617 3.555 3.609 3.694 3.819
S.D. 0.307 0.251 0.235 0.215 0.180
Skew -0.450 -0.380 -0.380 -0.150 -0.03

* The skew for this array was adjusted according to U.S. Water Resources Council Guidelines Bulletin 17 (1976). It was assumed that these peaks represents closely the natural conditions of the basin. No other adjustments were made.

Figure 8. Flood frequency curves showing the effect of urbanization as measured by increased percentage of impervious area for Walnut Creek at Des Moines.
For example, the flood discharge which has a 1 percent chance of occurring within any given year (100-year flood) for the basin in its present stage of urbanization (about 5 percent impervious) is 10,600 cubic feet per second (cfs). It could increase to 14,700 cfs when the impervious area in the basin reaches a 50 percent level. In terms of the probability of occurrence, the present 1 percent flood could have a future probability of 6 percent (17-year flood). Likewise, the 50 percent flood (2-year flood) could increase from the present 2,760 cfs to 5,000 cfs, or the present 2-year flood could have a future probability of 90 percent. Note that, in the preceding example the magnitude of the 100-year flood increases by 39 percent, while that of the 2-year flood increases by 81 percent. These trends are consistent with those reported by other investigators who have conducted similar studies elsewhere, such as Anderson (1968), Leopold (1968), Bantz (1971), and Waananen and Crippen (1977).

CONCLUSIONS

It could be anticipated that an appreciation of the results of this modeling project will vary with the level from which it is viewed. To the user basing his conclusions on the tabulated results, and the appearance of the computed and observed hydrographs, it may suggest that the complexities of the rainfall-runoff relations in the Walnut Creek basin have been
satisfactorily explained. To the modeler who has had to struggle with data which may be inadequate and assumptions which may not be entirely satisfactory, it may appear that the results are tentative and in need of further refinement. Because this report has been prepared for the benefit of the user as well as the modeler, it is appropriate to point out briefly its strong points, identify its weaknesses, and suggest possible future studies.

Among its strengths are the conclusions derived from this study, which appear to be consistent and in close agreement with the results reported by investigators who have conducted similar studies elsewhere in the nation.

The reader also is referred to figure 8 to observe the close agreement between the synthetic frequency curve corresponding to the basin in its present state and the regional frequency curve, which theoretically represents the flood flow characteristic of the basin in its natural state. Considering that the basin is presently about 5 percent impervious, the agreement is indeed remarkable. Hence, another element of strength is the fact that the results from a simulation approach have been verified by the results of a widely used and accepted technique, which uses a statistical approach.

The obvious shortcoming and most probable source of criticism are the limited runoff data available to conduct this study. In addition there is a lack of recorded data concerning the effect of severed or improved channels on the time of concentration and storage characteristics of the watershed and subbasins.

The above remarks are not intended in any way to demean the information presented in this report. By describing the strengths and deficiencies, the intention is to underline the confidence with which the information may be placed to practical use.

In reference to further studies in this basin, there is a need to develop a set of flood-routing criteria, similar to the unit hydrograph and loss-rate criteria developed in this study. A set of routing criteria would give the users of this model the capacity, for example, to evaluate the impact of a project in a distant tributary of the basin on the flood-flow characteristics at a downstream location, or to conduct comprehensive flood-plain management studies, such as the one outlined by Davis (1976) for the Oconee River basin in Georgia and Farnham (1977) for the Crow Creek basin in Iowa.
REFERENCES


Stevenson, W. H., Brown, P. E., 1922, Soil Survey of Iowa, report No. 24, Polk County Soils, Iowa Agriculture Experiment Station.


