A SENSITIVITY STUDY ON MODELING HYDROLOGIC EFFECTS DUE TO URBANIZATION

by

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INTRODUCTION

The population in the United States has shifted from principally rural to principally urban during the past half century. This tremendous urban growth has greatly increased the demand for domestic uses of water. The disruptive effects of such things as flooding and power shortages are becoming more intolerable. Without proper foresight, construction in the flood plains can restrict streamflows to the extent that backwaters will flood areas previously safe from flooding. Inadequate culvert designs can cause washed-out roads and bridges. The lack of information regarding projected water supplies and demands can lead to water shortages.

The need for better methods of predicting the hydrologic response of a watershed when subjected to a given precipitation distribution and land use practice led to the development of various watershed models. One of the first models was the Stanford Watershed Model. This model was structured for high speed electronic computers and was first applied primarily to rural watersheds. However, during recent years urbanization has begun to radically alter entire watersheds, by converting forests and grasslands into airports and large shopping center parking lots. To evaluate the effects of urbanization on the hydrology of a watershed, researchers have thus turned to models like the Stanford Watershed Model.

In areas where the rainfall and runoff records are available before and after urbanization, simulation runs have been made with the

Stanford Watershed Model. The differences in the output of such things as total flow, overland flow, interflow, base flow, and peak discharge have been attributed to urbanization. Urbanization does have an effect on water yield, but much urbanization can occur before the input parameters of the Stanford Watershed Model differ sufficiently to reflect a change in water yield.

Since some doubt exists as to the applicability of using the Stanford Watershed Model to detect urbanization changes, a study on the sensitivity of the Model to land use changes was initiated. The Stanford Watershed Model was chosen because it is more readily available and more widely known. It is expected that similar studies could be made with other watershed models.

REVIEW OF LITERATURE

Effects of Urbanization on Watershed Characteristics

Definition

Urbanization is essentially a change in land use, that is, an alteration from rural-like to city-like environment. It is an area that includes a large concentration of people and the things needed to support people. As used in this study, the term will refer to the actions of man which produce changes in the natural hydrology of a watershed. Construction of stores, houses, roads, airports, parking lots, dams, flood walls, etc., are a few specific examples.

Physical Effects

Urbanization can alter the physical appearance of a watershed to the extent that a change in the hydrological characteristics will occur. It normally increases the amount of impervious area (14).* In extreme cases, grading and leveling can reduce the slope and length of overland flow (28). Construction of storm drains results in a greater degree of channelization. The amount of water surface is often increased by the construction of lakes and reservoirs. The vegetative cover is normally changed, with the general trend being from forest to grassland.

Meteorological Effects

Waananen (28) in a brief summary of Landsberg's 1941 publication reported a substantial change in the composition of the atmosphere

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*Numbers in parentheses refer to selected bibliography.

around larger cities. The total atmospheric radiation reaching the earth was reduced as much as 20 percent by air pollution. The mean annual temperature in larger cities was as much as 1.3 degrees Fahrenheit higher than in the surrounding areas. Increased cloudiness, decreased wind speed, and lower humidity were some additional findings. The lower humidity was attributed to the decreased area for evaporation in an urbanized area. A less obvious effect of urbanization is the increased precipitation in and around urbanized areas.

Hydrological Effects

Researchers have used various parts of the hydrological process as measures of the degree of urbanization. With the aid of the Stanford Watershed Model, Ross (21) attributed increased water yield to urbanization and increased flood peaks to extensive channelization.

Wiitala (30) measured the mean annual flood for an urbanized watershed to be three times as large as the mean annual flood from a rural watershed of approximately the same size.

VanSickle (27) used unit hydrographs to compare peak discharges from Brays Bayou watershed in Texas. Brays Bayou discharge records covered 27 years, during which time the watershed changed from farm land to an urbanized area. As shown in Figure 1, VanSickle found that the peak discharge rates for the urbanized condition were approximately three times those for the rural condition.

James (16) studied the effects of urbanization on Morrison Creek in Sacramento County, California. Records were available before and

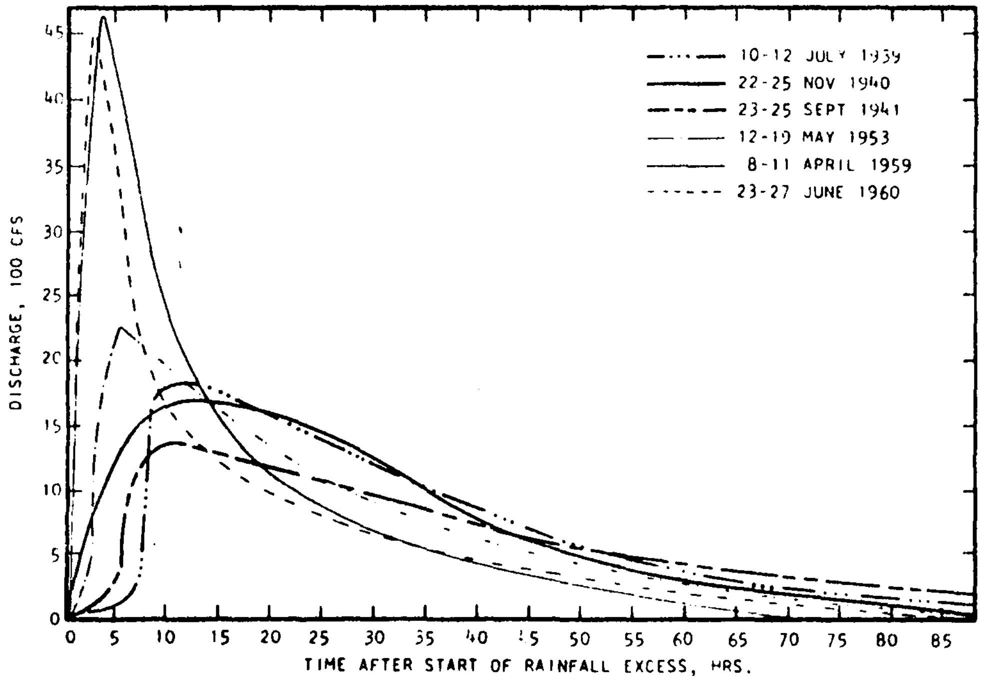

Figure 1. Brays Bayou Unit Hydrograph, adapted from VanSickle (27).

after urbanization so that James was able to develop a long term continuous hydrograph. Some of his conclusions are as follows: Total annual yield was 2.3 times the rural value; base flow was 0.7 times the rural value; surface runoff was greatly increased over the rural value; and the individual flood hydrographs rose and fell more sharply than the rural flood hydrographs.

Sawyer (22) reported that during a 30-year period, base flow in Nassau County, New York, increased 70 percent. He also found a 123 percent increase in direct runoff during a 23-year period.

Increased impervious area can reduce the volume of infiltration and increase the storm peak discharges. Espey, *et al.* (11) reported that peak flows may be as much as tripled and the times to rise reduced by one-third. However, as the magnitude of the flood increases, the effect of urbanization on flood hydrographs decreases (28), because long duration rains saturate soils to the extent that they shed water much like impervious areas. In other words, regardless of the degree of urbanization, the entire watershed behaves as though it were paved.

Variability of Effects

The effects of urbanization are not the same in all cases. Its location within the watershed can greatly influence the timing of peak flows. In fact, there may even be two peak flows--one from the urbanized area and one from the natural area.

The effect is more pronounced on a watershed where the ratio of impervious area to total watershed area is high. This is because the fraction of the precipitation which is discharged directly is the same as the fraction of a watershed area that is impervious.

If water for domestic use is imported from another watershed, there is a tendency toward increased total water yields. The water used for septic systems and watering lawns may increase the volume of infiltration, which can raise water tables and increase base flows (28).

The type of urbanization can be a factor in determining its effects. If the change consists mostly of building stores, streets, and parking lots, then the amount of infiltration and interception storage will be reduced. On the other hand, the amount of infiltration and interception storage can be increased, if barren and open crop land is converted into lawns and parks (3).

It is very difficult to use just one hydrologic process to evaluate the effects of urbanization. When making these evaluations, all water sources, storages, and discharges must be carefully considered. For example, peak flows can be increased or decreased depending on the time to rise for the impervious runoff versus the time to rise for the pervious runoff. Sometimes storm sewers reduce peak flows by temporarily storing backwaters. Discharges from sewage treatment facilities can increase base flows.

Stanford Watershed Model

History of Development

Research with digital computer models of the hydrologic process began at Stanford University in 1959. The first Stanford Watershed

Model was published by Crawford and Linsley (7) in 1962. A snowmelt routine and several other improvements were added later in order to more accurately simulate the hydrologic process. In 1966 Crawford (6) presented Model IV, the most widely publicized version of the Stanford Watershed Model. Although several other models have been developed (2, 8,13,24,25,26), the Stanford Watershed Model remains the best known mathematical model for simulating the hydrologic response of a given watershed area.

The Stanford Watershed Model was originally written in SUBALGOL, a digital computer language used by the Stanford Computing Center and not compatible with most other computing centers. James (18) later translated the original Model into the FORTRAN IV language and called his translated, revised, and expanded version the Kentucky Watershed Model.

Uses

The Stanford Watershed Model has been used to estimate flood peaks, evaluate runoff coefficients, produce continuous hydrographs, study snowmelt processes, and evaluate effects of urbanization. It is especially useful for determining the amount of water available for consumption from a particular area. Through careful use, the model can provide information for designing roads, dams, buildings, and other structures. The effect that structures will have on flooding can be estimated before construction.

Operation of the Stanford Watershed Model

The Stanford Watershed Model keeps a running tabulation of all the moisture entering, stored within, and leaving the watershed [Figure 2]. The Model places watershed moisture into the following categories: Precipitation, interception, groundwater, evapotranspiration or surface runoff. A continuous account is maintained of all water entering the basin until the water either evaporates, reaches groundwater, or enters a channel. The Model then routes the runoff from the point at which it enters a channel to some predetermined downstream location (16).

OPSET

The Stanford Watershed Model is bulky and difficult to understand because it contains a large number of parameters, and many of them must be estimated by a trial and adjustment procedure [see Liou, *et al.* (18) or Shanholtz, *et al.* (23)]. Since this procedure is so time consuming, Liou, *et al.* (18) developed a version of the Kentucky Watershed Model called OPSET to determine the optimum set of values for critical input parameters. The objective of OPSET was to reduce the amount of time required to understand and use the Stanford Watershed Model. OPSET assumes a set of parameter values; and through successive trials, the parameters are adjusted until the difference between simulated and recorded flows is minimized. The group of parameters which yields the most accurate simulation is then called the "set of best fit parameters."

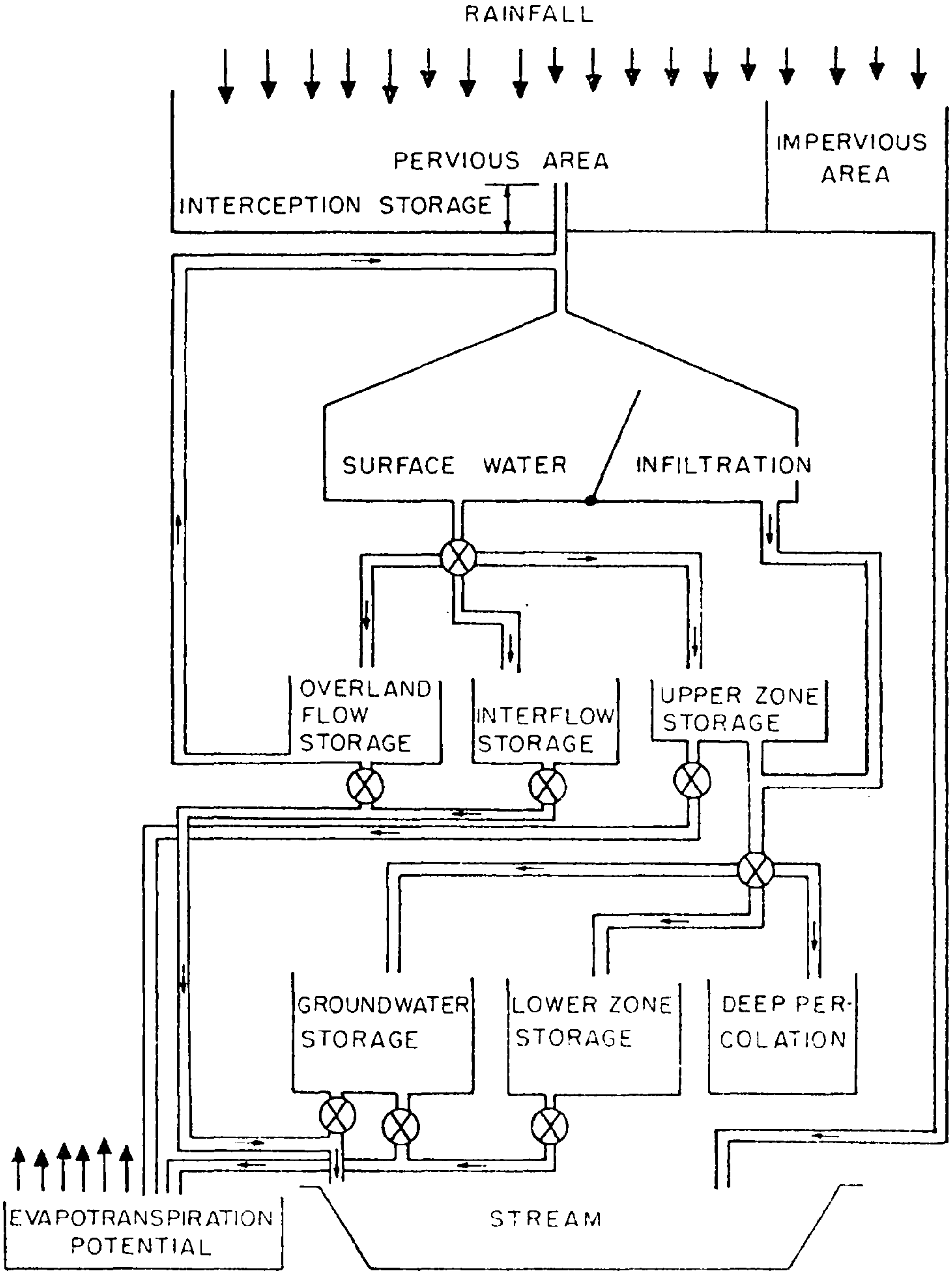

Figure 2. Schematic Diagram of the Stanford Watershed Model, adapted from Coskun, *et al.* (4).

Procedure for Using OPSET with the Stanford Watershed Model

Ross (21) suggests a procedure similar to the following for running OPSET:

1. Select values for watershed shape, area, impervious area, surface slope, roughness, and length.
2. Select the record years to use for calibration. Three years are recommended--one with the largest daily December to May flood, one with the largest daily June to November flood, and one with the least total June to November runoff.
3. Collect the daily streamflows, hourly precipitation, evaporation data, and the hour of occurrence and magnitude of as many as five hydrograph peaks.
4. Estimate the mean daily diversion, subsurface flow, groundwater evapotranspiration, and maximum vegetative interception.
5. Assemble all data in correct format and run OPSET to determine the set of best fit parameters for each year.

An average of the OPSET results should be used in the Kentucky Watershed Model. Liou, *et al.* (18) suggests taking the arithmetic mean of twelve parameters and the geometric average of the seasonal infiltration adjustment constant [SIAC].*

Using the Stanford Watershed Model to Evaluate Effects of Urbanization

Ross (21) used the fraction of the watershed area that is impervious [FIMP] as a measure of the degree of urbanization. For rural,

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*See Appendix I for Description of Variables.

unurbanized watersheds FIMP was found to be very nearly zero. The parameter includes paved areas, rooftops, and rock out-croppings. However, those scattered impervious areas from which the flow must traverse a pervious area before reaching a flow channel are not included.

The watershed interception volume storage capacity [VINTMR] is another parameter which can be used as a measure of urbanization. VINTMR depends on the type and density of the vegetative cover and has the following suggested range (6):

Watershed Cover	VINTMR
Grassland	0.10
Moderate forest cover	0.15
Heavy forest cover	0.20

OBJECTIVES

This study was initiated with the following two objectives:

(a) Evaluate the ability of OPSET to reflect a change due to urbanization in the best-fit estimates of those watershed parameters which cannot be estimated from historical records or watershed characteristics.

(b) Evaluate the significance of such changes, particularly in the land phase parameters, on water yield predictions from the Kentucky Watershed Model.

INVESTIGATION

Test Procedure

General

In the first part of this study, OPSET was used to compute best-fit parameter sets for various degrees of urbanization. Several of the best-fit parameter sets were then used in the Watershed Model to simulate water yield. The best-fit parameter sets and water yield estimates were then statistically evaluated for significant differences.

The programs used in this study were run at the VPI & SU Computing Center on an IBM 370 Model 155 computer. The OPSET and Stanford Watershed Model versions were essentially those developed by James, *et al.* at the University of Kentucky. They were written in FORTRAN IV and stored on tape.

Watershed Selection

Many watershed characteristics and parameters can be simultaneously altered by urbanization. These changes along with strong interactions make it very difficult to determine which alterations would produce a given change in the areas's hydrologic response. In order to more accurately single out the correct factors, a rural watershed was used, and urbanization was simulated by varying a limited number of parameters while holding all others constant. Little Winns Creek watershed in Halifax County, Virginia, was selected for this study, because the land use has remained essentially unchanged since rainfall and runoff records began on January 1, 1958. The available ten years of records were sufficient for obtaining good estimates of the watershed parameters for a rural or "natural" condition.

The watershed is situated on the Piedmont Plateau and has moderately permeable Cecil and Appling fine sandy loams as the primary soil types. Figure 3 is a map of the watershed, and Table 1 gives the average land use from 1958 to 1968.

OPSET

The following watershed characteristics were assumed constant throughout the entire study:

(a) Area and shape,

(b) Area of water surfaces,

(c) Average slope,

(d) Overland flow length,

(e) Channel capacity,

(f) Manning's roughness coefficients,

(g) Net daily flow diversion,

(h) Groundwater evapotranspiration, and

(i) Subsurface flow.

It was also assumed that the recorded precipitation occurred regardless of the degree of urbanization.

The two parameters selected as indices of urbanization were FIMP and VINTMR. The rural or base values of FIMP and VINTMR were 0.0 and 0.164, respectively.

Table 1. Land Use in Little Winns Creek Watershed.

Land Use	Acres	Percent of Area
Forest	853	58
Pasture	294	20
Rowcrops	206	14
Small grain	59	4
Hay crops	59	4
Impervious	zero	zero
Total	1471	100

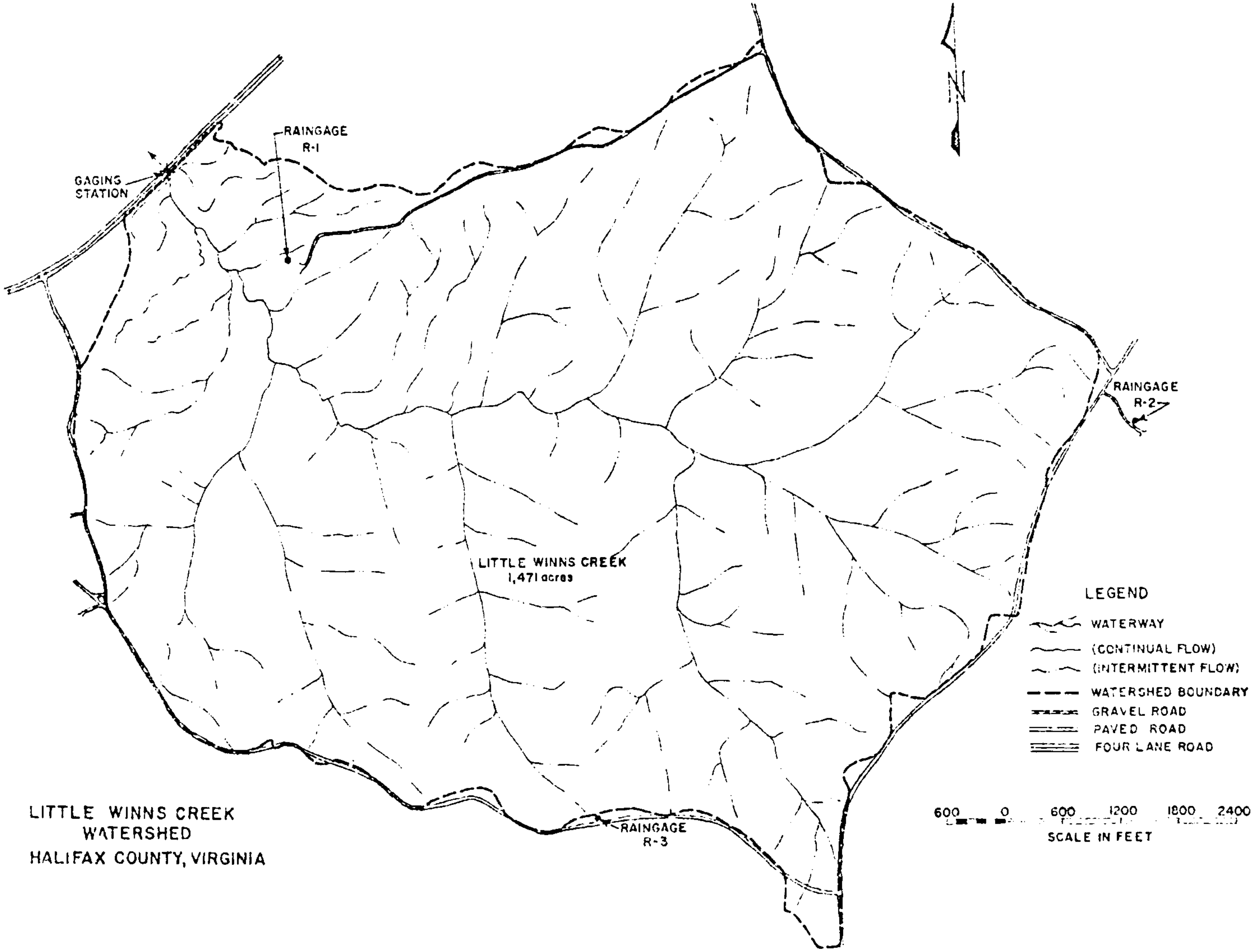

Figure 3. Little Winns Creek Watershed.

The recorded flows were increased to account for the additional runoff from added impervious surfaces. The minimum daily flow from each month was assumed to be the average base flow for the days of that month. The adjusted flow for each day was then computed by the following equation:

$$A = B + (FIMP \times P) + (1.0 - FIMP) \times (F - B), \qquad [1]$$

where A = the adjusted daily flow.

B = the average base flow.

FIMP = the fraction of watershed area that was impervious.

P = the daily recorded precipitation.

F = the unadjusted recorded flow.

Table 2 gives a schedule of the OPSET runs, which were made to check for changes in the optimized parameters as the degree of urbanization was increased.

Watershed Model

Two sets of simulation runs were made with the Kentucky Watershed Model. The first was with the best-fit parameters and corresponding values of FIMP. In order to eliminate FIMP as a source of variation in the water yield estimates, a second set of runs were made with the same best-fit parameters but with FIMP equal to zero. Table 3 shows the schedule of Watershed Model runs.

Statistical Tests

Analysis of variance tests were used to test for significant

Table 2. Schedule of OPSET Runs.

Run No.	FIMP	VINTMR
1	0.0	0.050
2	0.0	0.100
3	0.0	0.164
4	0.0	0.200
5	0.0	0.250
6	0.0	0.300
7	0.1	0.164
8	0.2	0.164
9	0.3	0.050
10	0.3	0.100
11	0.3	0.164
12	0.3	0.200
13	0.3	0.250
14	0.3	0.300
15	0.5	0.050
16	0.5	0.100
17	0.5	0.164
18	0.5	0.200
19	0.5	0.250
20	0.5	0.300

Table 3. Schedule of Kentucky Watershed Model Runs.

Run No.	FIMP	VINTMR	Input Parameters from OPSET Run No.*
1	0.0	0.164	3
2	0.1	0.164	7
3	0.2	0.164	8
4	0.3	0.164	11
5	0.5	0.164	17
6	0.0	0.164	3
7	0.0	0.164	7
8	0.0	0.164	8
9	0.0	0.164	11
10	0.0	0.164	17

*These run numbers are the OPSET run numbers given in Table 2.

changes in both the best-fit parameter estimates and the water yield estimates from the Watershed Model simulations. The mean squares used in a F test for significance were computed by BMDO2V [Bio-medical computer program for factorial analysis].

In analyzing the best-fit parameters, the Two Mixed-Model Three-Factor Factorial model was used. Figure 4 shows the level of each factor involved. FIMP and VINTMR were included to reflect land use changes; date was included to check for possible year to year variations in the optimizing procedure. The F factors were computed as follows:

$$F_{(DATE)} = MS_D/MS_{DV} \qquad [2]$$

$$F_{(FIMP)} = MS_F/MS_{FV} \qquad [3]$$

$$F_{(VINTMR)} = MS_V/MS_R \qquad [4]$$

where MS_D = Mean square for date factor.

MS_F = Mean square for FIMP factor.

MS_V = Mean square for VINTMR factor.

MS_{DV} = Mean square for date-VINTMR interaction.

MS_{FV} = Mean square for FIMP-VINTMR interaction.

MS_R = Residual mean square.

The predicted flows of the two sets of simulation runs were analyzed separately. A two-variable analysis of variance test with two-way classification was used. In both cases the variables were date and

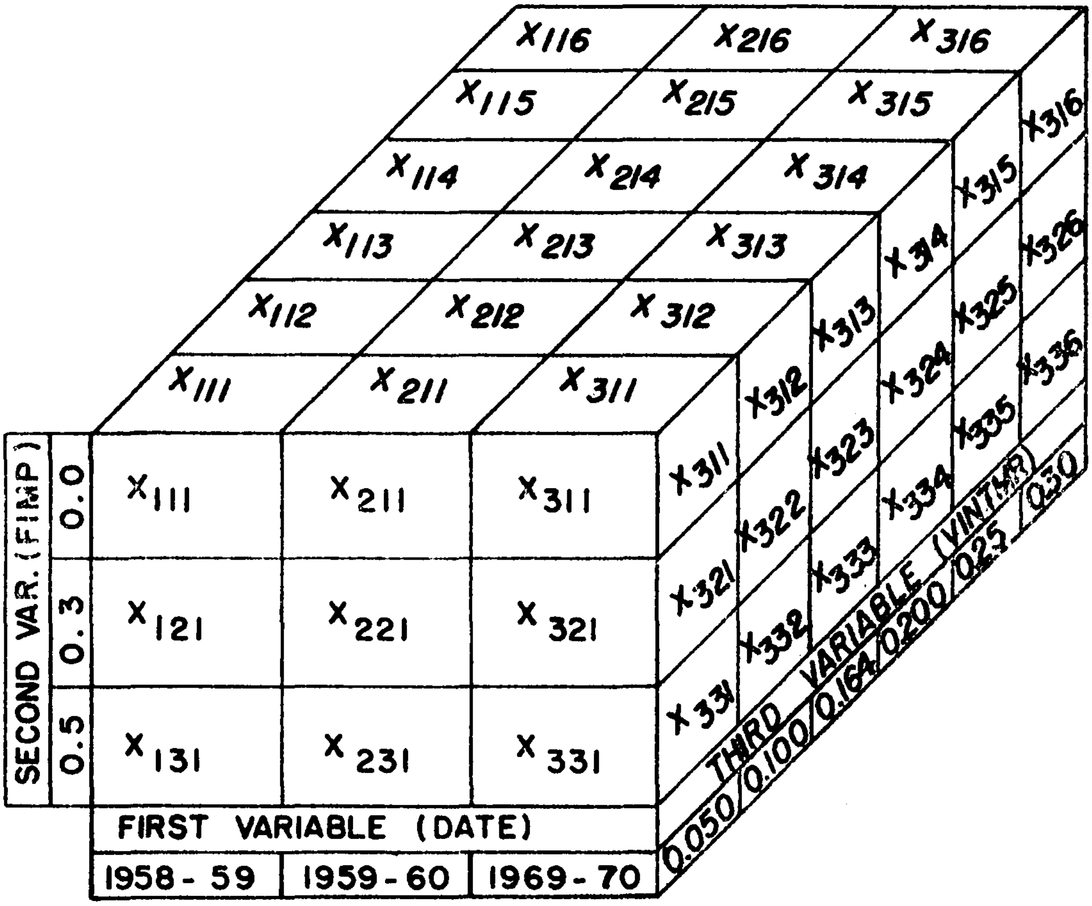

Figure 4. Design of Analysis of Variance Test for Best-Fit Parameters as Determined by OPSET.

parameter set. Equations 5 and 6 were used to compute F values.

$$F_{(DATE)} = MS_D/MS_R \tag{5}$$

$$F_{(Set)} = MS_S/MS_R \tag{6}$$

where MS_S = Mean square for parameter set factor.

Using OPSET to Derive the Best-Fit Model Parameters

Optimization Process

OPSET is a re-arranged trial and adjustment version of the Kentucky Watershed Model. It attempts to match simulated flows with recorded flows by systematic and objective parameter adjustment. The set of parameters yielding the best match is called the best-fit set of parameters. A total of 13 parameters are optimized with the major emphasis being on the land phase parameters.

Input Information

The input data for the OPSET Model can be divided into five main categories:

1. Program option and output controls.

   This information specifies the frequency of the evaporation data, the routing interval, rain gage location, number of cycles and trips to be made in optimizing, and the amount of output to be printed.

2. Climatological information.

   This includes the hourly rainfall data from base and/or auxillary gages; evaporation data on a daily, ten-day, or annual basis; and any necessary evaporation or rainfall adjustment factors.

3. The time-area histogram.

   The number of base time routing increments and their values are given.

4. Watershed characteristics.

   These are physical watershed characteristics such as area, overland slope, etc.

5. Streamflow records.

   These are daily flow records and are included for comparison with synthetic flows during the optimization procedure.

Values of the input information were determined from maps and watershed records for Little Winns Creek watershed. Table 4 summarizes the input data to OPSET.

Output

There are essentially three passes made through the OPSET Model with the output consisting of a step-by-step report of the optimization progress in each pass. During the first pass, the streamflow routing is bypassed while the land phase parameters are estimated. Using the best-fit land phase parameters, a second pass is made to estimate the channel routing parameters. Finally, a third pass is made with the final set of estimated parameters to simulate the streamflows for an entire year.

Table 4. Input Data for OPSET (see Appendix I for description of variables).

Variable	Input Value
NSYT	3
MNRC	15
NFTR	1
NLTR	3
NBTRI	15
BTRI (15 values)	0.0160, 0.0270, 0.0390, 0.0620, 0.0500, 0.0550, 0.0610, 0.0680, 0.1300, 0.1270, 0.0830, 0.0400, 0.1010, 0.0750, 0.0660
RMPF	318.0 cfs (4 ft channel depth)
CHCAP	202.0 cfs (3 ft channel depth)
RGPMB	1.0
AREA	1471.0 acres
FIMP	(Varied with each run)
FWTR	0.007468
VINTMR	(Varied with each run)
SUBWF	0.0
GWETF	0.0
OFSS	0.1068 ft/ft
OFMN	0.358
OFMNIS	0.02
OFSL	400.0 ft
DIV	0.0
EPAET	40.5 in.
MNRD (one for each record year)	87 for 1958-59; 109 for 1959-60; 91 for 1969-70.
NRHP	5
NHPT	1.00
RHPD	5 recorded storm sequences for each water year [see Liou (18) for input format].
RHPH	
RHPF	
NSGRD	0
WSG	0.0
SGRT	0
IWBG	hourly rainfall. [see Liou (18) for input format].
YEAR	
MONTH	
DATE	

Results

In an effort to obtain the best possible set of parameters, three years were run on OPSET, and the results were averaged. The three years were selected on a basis of "extreme flows"* (see Table 5). The largest winter flood occurred in 1958-59; the highest summer flood in 1959-60; and the least total summer runoff in 1969-70. In averaging the results, the arithmetic average was used for all parameters except SIAC,* which was averaged geometrically. The averaged best-fit land phase parameters are given in Table 6, while the averaged best-fit recession and routing parameters are presented in Table 7.

Since changes in streamflow routing were not included in the scope of this study, only the seven best-fit land phase parameters, current lower zone storage [LZS), and groundwater storage [GWS] were analyzed for significant changes. Appendix II lists the parameters which were analyzed. A summary of the analysis of variance tests for LZC is given in Table 8, while the remaining 8 parameters are summarized in Table 1 of Appendix III.

Streamflow Simulation

Input-Output

Using a series of mathematical relationships, the Watershed Model attempts to represent the hydrologic cycle from precipitation to streamflow. Input data for the Watershed Model consists of the input

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*Liou (18) found this to give best results.

Table 5. "Extreme Flows" Table.

Year	Largest Winter Flood (Date)	Largest Summer Flood (Date)	Smallest Total Summer Runoff
	(in)	(in)	(in)
1958-59	1.0833 (12,28)	0.3720 (6,4)	3.3930
1959-60	0.6167 (4,5)	1.4973 (10,10)	6.0592
1960-61	0.4069 (2,8)	0.3331 (6,24)	4.4264
1961-62	0.8244 (1,6)	0.1484 (6,20)	2.9540
1962-63	0.8518 (3,6)	0.2782 (11,9)	2.9269
1963-64	0.1986 (2,6)	0.2124 (7,12)	2.7613
1964-65	0.3062 (3,17)	0.5903 (10,4)	4.0394
1965-66	0.4561 (2,28)	0.1571 (9,21)	1.9821
1966-67	0.1204 (2,20)	0.1029 (8,9)	2.0206
1967-68	0.3625 (3,12)	0.1300 (6,3)	1.5568
1968-69	0.2207 (3,7)	0.3393 (6,15)	1.7859
1969-70	0.2410 (2,17)	0.1377 (8,10)	1.4098

Table 6. Averaged Best-Fit Land Phase Parameters from OPSET.

Run No.	LZC	BMIR	SUZC	ETLF	BUZC	SIAC	BIVF
1	8.0711	4.0562	0.4333	0.1138	0.8145	0.4733	1.1816
2	8.0185	4.3819	0.4333	0.1121	0.8106	0.4712	1.2224
3	7.9428	4.4818	0.4333	0.1110	0.8059	0.4688	1.2225
4	8.2802	5.1592	0.4731	0.1009	0.5365	0.6062	1.2088
5	8.3496	5.2308	0.4732	0.0998	0.5329	0.6034	1.2072
6	8.2197	5.1806	0.4708	0.0998	0.5302	0.5969	1.2697
7	6.0449	4.1496	0.5675	0.1049	0.9342	0.3287	0.6755
8	6.3983	5.2703	0.6487	0.1865	1.1905	0.3463	0.8524
9	9.1983	3.3212	0.8664	0.2690	1.1733	0.4468	0.8794
10	9.1570	3.3186	0.8592	0.2763	1.0475	0.5186	0.8502
11	9.0162	3.0420	0.8486	0.2581	1.0037	0.4833	0.8303
12	8.1855	2.9312	0.7537	0.2409	0.9000	0.4432	0.7529
13	8.7884	2.9313	0.7712	0.2582	0.8205	0.5206	0.8221
14	8.4928	2.7848	0.7721	0.2433	0.8262	0.4809	0.7361
15	12.2375	3.9127	1.2134	0.3556	1.7201	0.6855	1.7690
16	10.5721	5.3857	1.0289	0.3422	1.3197	0.5576	1.1833
17	10.0965	4.2727	0.9620	0.4745	1.0082	0.4649	0.9454
18	9.8315	3.8693	0.9674	0.4134	0.9669	0.4938	0.8542
19	9.4375	3.4563	0.9710	0.3937	0.9248	0.4415	0.8012
20	9.3930	3.2192	0.9604	0.3638	0.8896	0.3979	0.7450

Table 7. Averaged Best-Fit Recession and Routing Paramters from OPSET.

Run No.	BFRC	IFRC	CSRX	FSRX	NBTRI	CHCAP
1	0.9719	0.2029	0.5515	0.5515	5.0000	202.00
2	0.9719	0.2029	0.5633	0.5633	5.0000	202.00
3	0.9719	0.2029	0.5633	0.5633	5.0000	202.00
4	0.9719	0.2029	0.5633	0.5633	5.0000	202.00
5	0.9719	0.2029	0.5633	0.5633	5.0000	202.00
6	0.9719	0.2029	0.5633	0.5633	5.0000	202.00
7	0.9571	0.2873	0.6013	0.6013	5.0000	202.00
8	0.9623	0.2513	0.8307	0.8307	7.0000	202.00
9	0.9602	0.2321	0.8523	0.8523	7.0000	202.00
10	0.9602	0.2321	0.8523	0.8523	7.0000	202.00
11	0.9602	0.2321	0.8523	0.8523	7.0000	202.00
12	0.9602	0.2321	0.8523	0.8523	7.0000	202.00
13	0.9602	0.2321	0.8523	0.8523	7.0000	202.00
14	0.9602	0.2321	0.8526	0.8526	7.0000	202.00
15	0.9680	0.2745	0.8345	0.8345	8.3333	202.00
16	0.9680	0.2745	0.8345	0.8345	8.3333	202.00
17	0.9680	0.2745	0.8367	0.8367	8.3333	202.00
18	0.9680	0.2745	0.8367	0.8367	8.3333	202.00
19	0.9680	0.2745	0.8367	0.8367	8.3333	202.00
20	0.9680	0.2745	0.8367	0.8367	8.3333	202.00

Table 8. Analysis of Variance for LZC

	Sum of Squares	Degrees of Freedom	Mean Square	F
Date	129.342	2	64.671	178.67*
FIMP	42.133	2	21.066	18.02*
VINTMR	8.044	5	1.609	2.16
Date-FIMP Interaction	13.470	4	3.368	
Date-VINTMR Interaction	3.619	10	0.362	
FIMP-VINTMR Interaction	11.693	10	1.169	
Residual	14.922	20	0.746	
Total	223.223	53		

*Significant difference at the 5 percent level.

to OPSET plus the averaged set of best-fit parameters determined by OPSET (18). The predicted flows of interest in this study were total flow, overland flow, interflow, and base flow.

Results

Table 9 gives the Watershed Model output for the runs in which the best-fit parameter sets were run with their corresponding values of FIMP. Table 10 gives the Watershed Model output for the same sets of best-fit parameters but with FIMP constant at 0.0 for all runs.

Changing the parameter set did not significantly change overland flow in the simulation runs made with FIMP constant at zero. All other simulated flows changed significantly with changes in parameter sets. Different water years produced significant difference in all flows for all runs. The analysis of variance results are summarized in Tables 2 and 3 of Appendix III.

Table 9. Simulated Flows from Watershed Model with FIMP Varying from 0.0 to 0.5.

Year	FIMP	Parameter Set No.*	Total Flow	Overland Flow	Interflow	Base Flow
1958-59	0.0	3	8.865	0.485	3.139	5.241
	0.1	7	12.090	4.944	1.393	5.753
	0.2	8	13.532	7.296	1.291	4.945
	0.3	11	15.591	11.087	1.138	3.366
	0.5	17	22.336	17.447	1.020	3.869
1959-60	0.0	3	17.515	2.602	6.967	7.946
	0.1	7	21.338	9.719	3.245	8.374
	0.2	8	22.939	11.418	3.775	7.746
	0.3	11	25.064	17.251	2.758	5.055
	0.5	17	32.252	24.324	2.558	5.370
1969-70	0.0	3	5.505	0.291	1.475	3.739
	0.1	7	8.288	3.181	0.770	4.337
	0.2	8	9.556	5.326	0.652	3.578
	0.3	11	11.194	8.020	0.629	2.545
	0.5	17	16.494	12.874	0.526	3.094

*These set numbers refer to the OPSET run numbers given in Table 2.

Table 10. Simulated Flows from Watershed Model with FIMP Equal to Zero.

Year	Parameter Set No.*	Total Flow	Overland Flow	Interflow	Base flow
1958-59	3	8.865	0.485	3.139	5.241
	7	9.274	1.634	1.479	6.161
	8	7.545	0.500	1.445	5.600
	11	6.255	0.955	1.350	3.950
	17	6.677	0.424	1.348	4.905
1959-60	3	17.515	2.602	6.967	7.946
	7	18.227	5.636	3.524	9.067
	8	16.319	2.748	4.461	9.110
	11	14.704	4.744	3.621	6.339
	17	14.726	2.602	4.278	7.846
1969-70	3	5.505	0.291	1.475	3.739
	7	6.118	0.694	0.818	4.606
	8	4.995	0.285	0.735	3.975
	11	4.104	0.477	0.734	2.893
	17	4.585	0.265	0.659	3.661

*These set numbers refer to the OPSET run numbers given in Table 2.

DISCUSSION OF RESULTS

Optimization

Analysis of variance tests for the best-fit parameters indicated that changing the level of VINTMR would not produce significant changes in the estimates with two exceptions--BUZC and BIVF. Changing the type of vegetation can produce changes in the depression and interception storages, which should be reflected by BUZC, since it is an index to the average upper zone storage capacity. BIVF controls the quantity and distribution of interflow, which can also be affected by changes in upper zone storage.

Changes in FIMP seem to produce pronounced changes in all the parameters except SIAC. LZS and GWS are current storage estimates during simulation and could vary with different levels of FIMP. However, the changes in LZC, BMIR, SUZC, ETLF, BUZC, and BIVF are hard to rationalize since these parameters only apply to the pervious portion of the watershed. The parameters could be changed by urbanization, but not by changes in FIMP alone.

Changes in date produced highly significant changes in all parameters except BIVF. Year-to-year variations in LZS and GWS certainly seem likely; but the land phase parameters would not change from year to year, if the model were exact. Because of the way OPSET optimizes the parameters, a late September storm, for example, produces high storages at the beginning of the water year, which leads to parameter estimate errors. This is the reason for averaging the results from the three "extreme flow" years before using them in the Watershed Model.

Simulation

As expected, changes in date produced significant differences in the water yield estimates. The estimates seemed to be more sensitive to changes in FIMP than changes in best-fit parameter estimates. However, since the best-fit parameter estimates partially depend on the value of FIMP, the changes in water yield could be caused by changes in FIMP and/or parameter estimates. The interaction between various best-fit parameters was not evaluated in this study. In some cases two different parameter sets produce the same flow estimates. In other words, the watershed characteristics could change, and there would be no change indicated in the water yield estimates.

In general, urbanization tends to increase total flow and overland flow, while decreasing interflow. These trends are reflected in the flow simulations shown in Table 9. A comparison of the simulated flows with the corrected recorded flows is given in Table 11.

Table 11. Total Recorded* vs. Simulated Flows.

	1958-59		1959-60		1969-70	
FIMP	Recorded	Simulated	Recorded	Simulated	Recorded	Simulated
0.0	8.000	8.865	16.248	17.515	4.883	5.505
0.1	11.536	12.090	20.363	21.338	7.672	8.288
0.2	15.071	13.532	24.478	22.939	10.461	9.556
0.3	18.606	15.591	28.593	25.064	13.251	11.194
0.5	25.676	22.336	36.822	32.252	18.829	16.494

*Recorded flows were corrected for increased impervious area.

CONCLUSIONS

(1) Changing the vegetative cover (VINTMR) on a watershed does not significantly affect the estimates made by OPSET of lower zone storage capacity (LZC), basic maximum infiltration rate (BMIR), seasonal upper zone storage capacity (SUZC), evapotranspiration loss factor (ETLF), seasonal infiltration adjustment constant (SIAC), current lower zone storage (LZS), or current groundwater storage (GWS). Changes in vegetative cover significantly change the basic upper zone storage capacity factor (BUZC) and the basic interflow volume parameter (BIVF).

(2) Varying the amount of impervious area (FIMP) produces significant changes in the estimates of lower zone storage capacity (LZC), basic maximum infiltration rate (BMIR), seasonal upper zone storage capacity (SUZC), evapotranspiration loss factor (ETLF), basic upper zone storage capacity factor (BUZC), basic interflow volume parameter (BIVF), current lower zone storage (LZS), and current groundwater storage (GWS). The seasonal infiltration adjustment constant (SIAC) was not significantly changed by the percent impervious area.

(3) Different record years produce highly significant changes in the estimates of lower zone storage capacity (LZC), basic maximum infiltration rate (BMIR), seasonal upper zone storage capacity (SUZC), evapotranspiration loss factor (ETLF), basic upper zone storage capacity factor (BUZC), seasonal infiltration adjustment constant

(SIAC), current lower zone storage (LZS), current groundwater storage (GWS), and water yield. The basic interflow volume parameter (BIVF) is the only parameter not significantly changed by changes in record years.

(4) OPSET seemed to produce best-fit parameters with which the Watershed Model could simulate flows compatible with those one might expect from increased urbanization.

RECOMMENDATIONS

The author recognizes that only one watershed was used in this study, and that the conclusions may only apply to that watershed. Therefore, similar studies must be made on additional watersheds before these results can be accepted as general. Future studies might include the routing parameters and the effects of urbanization on timing and magnitude of peak flows.

Since this study strongly indicates that the non-measurable watershed parameters in the Stanford Watershed Model change with the percent of impervious area (FIMP), future studies should also include a search for a parameter(s) that would be independent of the remaining model parameters and reflect hydrologic changes due to urbanization.

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APPENDIX I

DESCRIPTION OF VARIABLES

Table 1. Definition of Variables.

Variable	Description
AREA	Watershed area.
BFRC	Base flow recession constant.
BIVF	Basic interflow volume parameter.
BMIR	Basic maximum infiltration rate within watershed.
BTRI	Elements of the time-area histogram.
BUZC	Basic upper zone storage capacity factor.
CHCAP	Channel capacity.
CSRX	Channel storage routing index.
DATE	Day.
DIV	Mean daily flow diversion into the basin.
EPAET	Mean annual lake evaporation.
ETLF	Evapotranspiration loss factor.
FIMP	Fraction of the Watershed being impervious.
FSRX	Flood plain storage routing index.
FWTR	Fraction of the Watershed being water.
GWETF	Groundwater evapotranspiration factor.
GWS	Current groundwater storage.
IFRC	Interflow recession constant.
IWBG	Index number for precipitation gage.
LZC	Lower zone storage capacity.
LZS	Current lower zone storage.
MNRC	Minimum number of rough cycles to be made.
MNRD	Mean annual number of rainy days.
MONTH	Month.
NBTRI	Number of elements in the time-area histogram.
NFTR	Number of first trip to be run for a given station year.
NHPT	Number of hours between hydrograph printing points.
NLTR	Number of last trip to be run for a given station year.
NRHP	Number of recorded flood hydrograph peaks.
NSGRD	Number of storage gage rainfall days.
NSYT	Total number of station years included in a given job.
OFMN	Mannings n for pervious surface overland flow.
OFMNIS	Mannings n for impervious surface overland flow.
OFSL	Overland flow surface length.
OFSS	Overland flow surface slope.
RGPMB	Recording gage precipitation multiplier--basic.
RHPD	Recorded hydrograph peak day of the year.
RHPF	Recorded hydrograph peak flow.
RHPH	Recorded hydrograph peak hour.
RMPF	Requested minimum daily peak flow to be printed.
SGRT	Storage gage reading time.
SIAC	Seasonal infiltration adjustment constant.
SUBWF	Subsurface water flow out of the basin.
SUZC	Seasonal upper zone storage capacity factor.
VINTMR	Vegetative interception--maximum rate.
WSG	Weighting factor for storage raingage.

APPENDIX II

OPSET PARAMETER VALUES WHICH WERE ANALYZED

TABLE 1. 1958-59 BEST-FIT PARAMETERS THAT WERE ANALYZED

FIMP	VINTMR	LZC	BMIR	SUZC	FTLF	BUZC	SIAC	BIVF	LZS	GWS
0.0	0.050	9.9161	2.3112	0.6500	0.1651	1.0112	0.5418	1.0167	4.3749	1.7581
0.0	0.100	9.9331	2.3296	0.6500	0.1639	1.0064	0.5369	1.0208	4.3596	1.7581
0.0	0.164	9.9811	2.3512	0.6500	0.1627	1.0020	0.5334	1.0189	4.3482	1.7581
0.0	0.200	11.0839	4.2794	0.7694	0.1332	0.2000	1.1560	0.9802	7.7658	1.7581
0.0	0.250	11.3066	4.2711	0.7696	0.1314	0.2000	1.1431	0.9721	8.0027	1.7581
0.0	0.300	10.9739	4.2629	0.7623	0.1319	0.2000	1.1162	0.9726	7.6877	1.7581
0.3	0.050	12.0000	1.2000	1.3000	0.2500	1.5000	0.9000	0.7899	6.0000	2.8701
0.3	0.100	12.0000	1.2000	1.3000	0.2500	1.5000	0.9000	0.7919	6.0000	2.8701
0.3	0.164	12.0000	1.2000	1.3000	0.2500	1.5000	0.9000	0.7917	6.0000	2.8701
0.3	0.200	10.3395	1.1891	1.0393	0.1986	1.3348	0.7768	0.7915	6.0234	2.8701
0.3	0.250	10.0948	1.1788	1.0216	0.1924	1.3167	0.7497	0.7874	5.9534	2.8701
0.3	0.300	9.9165	1.1726	0.9993	0.1875	1.2985	0.7288	0.7823	5.8872	2.8701
0.5	0.050	12.0000	1.2000	1.3000	0.2500	1.5000	0.9000	1.1116	6.0000	4.8344
0.5	0.100	12.0000	1.2000	1.3000	0.2500	1.5000	0.9000	1.1000	6.0000	4.8344
0.5	0.164	12.0000	1.2000	1.3000	0.2500	1.5000	0.9000	1.0907	6.0000	4.8344
0.5	0.200	12.0000	1.2000	1.3000	0.2500	1.5000	0.9000	1.0908	6.0000	4.8344
0.5	0.250	12.0000	1.2000	1.3000	0.2500	1.5000	0.9000	1.0917	6.0000	4.8344
0.5	0.300	12.0000	1.2000	1.3000	0.2500	1.5000	0.9000	0.9826	6.0000	4.8344

TABLE 2. 1959-60 BEST-FIT PARAMETERS THAT WERE ANALYZED

FIMP	VINTMR	LZC	BMIR	SUZC	FTLF	BUZC	SIAC	BIVF	LZS	GWS
0.0	0.050	7.0556	4.2139	0.3250	0.0841	0.6740	0.2250	1.0606	6.6067	0.2271
0.0	0.100	6.8119	4.3867	0.3250	0.0831	0.6719	0.2250	1.1449	6.3869	0.2271
0.0	0.164	6.5826	4.4897	0.3250	0.0824	0.6673	0.2250	1.1460	6.1820	0.2271
0.0	0.200	6.5097	4.5380	0.3250	0.0822	0.6623	0.2250	1.1473	6.1220	0.2271
0.0	0.250	6.4793	4.5834	0.3250	0.0819	0.6520	0.2250	1.1473	6.0944	0.2271
0.0	0.300	6.4699	4.6113	0.3250	0.0817	0.6466	0.2250	1.3616	6.0789	0.2271
0.3	0.050	8.9721	4.8051	0.9266	0.3121	1.7533	0.0943	1.1894	7.6699	0.1562
0.3	0.100	8.6957	5.0508	0.8825	0.3633	1.2266	0.1779	1.1352	7.3369	0.1562
0.3	0.164	7.9340	4.6752	0.8763	0.3039	1.1422	0.1507	0.9698	6.7457	0.1562
0.3	0.200	7.3639	4.5059	0.8742	0.2892	1.0913	0.1376	0.8894	6.2939	0.1562
0.3	0.250	8.5371	4.9330	0.9384	0.3462	0.9670	0.2728	0.9076	8.8007	0.1562
0.3	0.300	8.2756	4.7657	0.9376	0.3321	0.9332	0.2648	0.8715	8.6120	0.1562
0.5	0.050	12.7124	9.3380	1.0403	0.5667	2.1602	0.3977	2.2822	12.3078	0.1703
0.5	0.100	11.4830	7.7893	1.0482	0.5264	1.7702	0.2227	1.7479	11.2612	0.1703
0.5	0.164	10.4672	6.7211	1.0637	0.9352	0.9719	0.1330	1.1453	10.0086	0.1703
0.5	0.200	10.0494	6.3167	1.0815	0.7621	0.7559	0.1669	0.8970	9.7753	0.1703
0.5	0.250	9.3219	5.6655	1.0954	0.7172	0.6841	0.1282	0.7568	9.1616	0.1703
0.5	0.300	8.5846	5.2739	1.0673	0.6407	0.5994	0.1019	0.6992	8.5242	0.1703

TABLE 3. 1969-70 BEST-FIT PARAMETERS THAT WERE ANALYZED

FIMP	VINTMR	LZC	BMIR	SUZC	ETLF	BUZC	SIAC	BIVF	LZS	GWS
0.0	0.050	7.2417	5.6436	0.3250	0.0922	0.7593	0.8700	1.4675	4.1498	0.1704
0.0	0.100	7.3105	6.4295	0.3250	0.0892	0.7536	0.8663	1.5016	4.2844	0.1704
0.0	0.164	7.2648	6.6044	0.3250	0.0878	0.7484	0.8587	1.5025	4.2748	0.1704
0.0	0.200	7.2469	6.6602	0.3250	0.0872	0.7472	0.8565	1.4990	4.2709	0.1704
0.0	0.250	7.2630	6.8379	0.3250	0.0861	0.7457	0.8541	1.5023	4.3039	0.1704
0.0	0.300	7.2153	6.6675	0.3250	0.0857	0.7440	0.8469	1.4754	4.2693	0.1704
0.3	0.050	6.6228	3.9586	0.3726	0.2450	0.2667	1.0507	0.6590	3.1581	0.1377
0.3	0.100	6.7752	3.7050	0.3951	0.2157	0.4159	0.8712	0.6234	3.6953	0.1377
0.3	0.164	7.1147	3.2509	0.3696	0.2205	0.2689	0.8321	0.7305	3.9130	0.1377
0.3	0.200	6.8530	3.0987	0.3475	0.2350	0.2738	0.8145	0.5777	3.5025	0.1377
0.3	0.250	7.7333	2.6820	0.3535	0.2359	0.1777	0.6897	0.7713	4.1968	0.1377
0.3	0.300	7.2862	2.4160	0.3795	0.2104	0.2469	0.5763	0.5544	4.1455	0.1377
0.5	0.050	12.0000	1.2000	1.3000	0.2500	1.5000	0.9000	1.9131	6.0000	0.1798
0.5	0.100	8.2333	7.1677	0.7384	0.2503	0.6889	0.8650	0.7021	5.4963	0.1798
0.5	0.164	7.8222	4.8970	0.5224	0.2383	0.4227	0.8394	0.6002	5.4626	0.1798
0.5	0.200	7.4451	4.0911	0.5208	0.2280	0.6047	0.8018	0.5749	5.2924	0.1798
0.5	0.250	6.9907	3.5033	0.5177	0.2138	0.5902	0.7457	0.5550	5.1205	0.1798
0.5	0.300	7.5943	3.1837	0.5138	0.2008	0.5695	0.6871	0.5531	5.8427	0.1798

APPENDIX III

ANALYSIS OF VARIANCE RESULTS FOR OPSET OUTPUT AND SIMULATED FLOWS

Table 1. Analysis of Variance Results for OPSET Output.

Parameter	Source of Variation	Degrees of Freedom	Mean Squares	F
LZC	Date	2	64.671	178.67*
	FIMP	2	21.066	18.02*
	VINTMR	5	1.609	2.16
	Date-FIMP	4	3.368	
	Date-VINTMR	10	0.362	
	FIMP-VINTMR	10	1.169	
	Residual	20	0.746	
BMIR	Date	2	59.382	53.34*
	FIMP	2	12.990	11.84*
	VINTMR	5	0.470	0.63
	Date-FIMP	4	11.736	
	Date-VINTMR	10	1.113	
	FIMP-VINTMR	10	1.097	
	Residual	20	0.750	
SUZC	Date	2	1.600	143.85*
	FIMP	2	1.469	122.18*
	VINTMR	5	0.015	0.90
	Date-FIMP	4	0.124	
	Date-VINTMR	10	0.011	
	FIMP-VINTMR	10	0.012	
	Residual	20	0.017	
ETLF	Date	2	0.180	74.80*
	FIMP	2	0.364	129.64*
	VINTMR	5	0.002	0.73
	Date-FIMP	4	0.128	
	Date-VINTMR	10	0.002	
	FIMP-VINTMR	10	0.003	
	Residual	20	0.003	
BUZC	Date	2	1.536	30.98*
	FIMP	2	0.998	19.57*
	VINTMR	5	0.340	4.31*
	Date-FIMP	4	0.704	
	Date-VINTMR	10	0.050	
	FIMP-VINTMR	10	0.051	
	Residual	20	0.079	
SIAC	Date	2	2.456	128.24*
	FIMP	2	0.006	0.23
	VINTMR	5	0.005	0.27
	Date-FIMP	4	0.006	
	Date-VINTMR	10	0.019	
	FIMP-VINTMR	10	0.025	
	Residual	20	0.018	

*Significant at 5% level.

Table 1. Analysis of Variance Results for OPSET Output (Continued)

Parameter	Source of Variation	Degrees of Freedom	Mean Squares	F
BIVF	Date	2	0.174	3.65
	FIMP	2	0.752	5.24*
	VINTMR	5	0.168	3.76*
	Date-FIMP	4	0.336	
	Date-VINTMR	10	0.048	
	FIMP-VINTMR	10	0.144	
	Residual	20	0.045	
LZS	Date	2	54.745	62.84*
	FIMP	2	15.313	15.18*
	VINTMR	5	0.326	0.47
	Date-FIMP	4	6.824	
	Date-VINTMR	10	0.871	
	FIMP-VINTMR	10	1.009	
	Residual	20	0.690	
GWS	Date	2	53.307	999.+*
	FIMP	2	4.758	999.+*
	VINTMR	5	0.000	0.00
	Date-FIMP	4	4.906	
	Date-VINTMR	10	0.00001	
	FIMP-VINTMR	10	0.00001	
	Residual	20	-0.00002	

*Significant at 5% level.

Table 2. Analysis of Variance Results for Simulation Runs with Varying FIMP.

Flow Tested	Source of Variation	Degrees of Freedom	Mean Squares	F
Total flow	Date	2	240.755	504.62*
	Parameter set	4	71.788	150.47*
	Residual	8	0.477	
Overland flow	Date	2	66.045	21.97*
	Parameter set	4	125.174	41.64*
	Residual	8	3.006	
Interflow	Date	2	12.541	23.57*
	Parameter set	4	3.083	5.79*
	Residual	8	0.532	
Base flow	Date	2	15.281	64.29*
	Parameter set	4	3.392	14.27*
	Residual	8	0.238	

*Significant at the 5% level.

Table 3. Analysis of Variance Results for Simulation Runs with FIMP Constant at 0.0.

Flow Tested	Source of Variation	Degrees of Freedom	Mean Squares	F
Total flow	Date	2	171.149	774.43*
	Parameter set	4	4.270	19.32*
	Residual	8	0.221	
Overland flow	Date	2	15.858	37.23*
	Parameter set	4	1.482	3.48
	Residual	8	0.426	
Interflow	Date	2	18.568	58.39*
	Parameter set	4	2.040	6.41*
	Residual	8	0.318	
Base flow	Date	2	23.900	241.66*
	Parameter set	4	2.150	21.74*
	Residual	8	0.099	

*Significant at the 5% level.

A SENSITIVITY STUDY ON MODELING HYDROLOGIC EFFECTS DUE TO URBANIZATION

by

George Franklin Grandle

(ABSTRACT)

During recent years the Standford Watershed Model has become a popular means of predicting the hydrologic response of land use changes. A special trial and adjustment model of the Kentucky version is available for determining best-fit values for the input parameters to the Watershed Model. This study was initiated to evaluate the ability of OPSET to reflect changes due to urbanization in the best-fit estimates of those watershed parameters which cannot be estimated from historical records or watershed characteristics. This study also included an evaluation of the significance of these changes, particularly in the land phase parameters on water yield predictions from the Kentucky Watershed Model.

Changes in the vegetative cover (VINTMR) produced significant changes in the basic upper zone storage capacity factor (BUZC) and the basic interflow volume parameter (BIVF). No significant changes in the remaining land phase parameters were found.

Varying the amount of impervious area (FIMP) produced significant changes in all land phase parameters except the seasonal infiltration adjustment constant (SIAC).

There were significant year-to-year variations in all the land phase parameter estimates except the basic interflow volume parameter

(BIVF). Water yield also changed from year to year.

OPSET seemed to produce best-fit parameters with which the Watershed Model could simulate flows compatible with those which might be expected from increased urbanization. Different sets of parameter estimates produced significantly different water yields.