A Comparative Application of the Rational Method and the Illinois Urban Drainage Area Simulator to an Indiana Subdivision

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Introduction

As the twin processes of industrialization and urbanization continue in Indiana, increasing areas of land are converted from natural or agricultural uses to residential developments. Among the important effects of this conversion is a radical modification of the rainfall-runoff relationship. Roofs, parking lots, streets, and sidewalks reduce the area available for infiltration and tend to increase the percentage of precipitation which becomes runoff. Gutters and drainage pipes provide reduced resistance to flow compared to natural drainage paths. Thus urbanization usually results in an increased volume of runoff in a shorter period of time.

Engineers have the primary responsibility for designing economical drainage systems which will minimize the danger, inconvenience, and cost of flooding. Over the past century, many methods have been devised to predict stormwater quantities and thus provide a quantitative basis for sizing storm sewer components. The rational method remains one of the most widely used methods in Indiana and throughout much of the world [5]. This old and frequently criticized technique [4] has retained its popularity because of its simplicity and because it is sanctioned by tradition. In recent years more detailed computer oriented methods such as the Illinois Urban Drainage Area Simulator, ILLUDAS, have become available. These methods embody the fundamental principles of hydraulics and hydrology more completely than does the rational method and so provide the means to design more effective and economical storm sewer systems. In this paper, the rational method and ILLUDAS are each applied to an existing Indiana subdivision. This concrete example illustrates the superiority and practicality of ILLUDAS and suggests the degree to which the state of the art of storm sewer design may be advanced by its adoption.

Methods of Analysis

The rational method allows the determination of the peak discharge from a watershed. The fundamental idea behind the rational method is that the peak rate of surface outflow from a watershed will be proportional to the watershed area and the average rainfall intensity over a period of time just sufficient for all parts of the watershed to contribute to the outflow. The constant of proportionality is supposed to reflect all those characteristics of the watershed, such as imperviousness and antecedent moisture, which affect the rate of runoff. In its simplest form, the rational formula is written as

$$Q = CiA$$

where the symbols and conventional American units are

$Q =$ peak runoff (CFS)

$C =$ ratio of peak runoff rate to average rainfall rate (runoff coefficient)

$i =$ rainfall intensity (inches/hr)

$A =$ area of watershed under consideration (acres)

The value of C depends on the type of land use in the watershed and may be found from suitable handbooks [1]. The rainfall intensity is usually determined for a selected storm return period using a local rainfall intensity-duration-frequency relation. The appropriate duration of rain is the maximum time of concentration considering all upstream subbasins, a parameter which may be estimated by any of several empirical formulas or by rule of thumb [1].

The second method under consideration is ILLUDAS, a non-proprietary computer program developed by the Illinois State Water Survey [7] which can design or evaluate a storm sewer system of up to 999 pipes or channels. ILLUDAS computes the complete runoff hydrograph at any point in the system for an arbitrary rainfall hyetograph. Reference 7 provides a program user's manual and presents evidence for the validity of the program's predictions. ILLUDAS was applied to 21 urban and 2 rural basins ranging from 0.39 to 8.3 square miles. By comparison with measured outflow hydrographs it was concluded that ILLUDAS provided acceptable results for 14 basins, marginal results for 3 basins, and indeterminate results for 3 basins. The data for 3 basins was insufficient to allow a meaningful comparison.

In the application of ILLUDAS, subbasins contributing runoff to each inlet are defined. In each subbasin separate inlet hydrographs for paved and grassed areas are generated from the rainfall hyetograph using the linear time-area method. Grassed area infiltration is calculated according to Horton's equation using parameters which reflect the soil type and initial moisture content. The combined inlet hydrograph is then routed through the pipe to the next inlet. The program computes the size of commercial pipe required to transmit the peak flow when laid on the slope specified. In the evaluation mode the program will check to see whether the specified pipes can transmit the actual flow. A great advantage of ILLUDAS is the ability to compute the necessary volume of desired detention storage or the undesired storage volume (flooding) due to inadequate pipes.

Description of the Study Area

Bar Barry Heights subdivision in West Lafayette, Indiana, was selected as the study area because of its history of street flooding due to inadequate storm sewers. Bar Barry Heights is a middle class subdivision with an area of 121.4 acres, about 30 percent of which is impervious. The topography is basically flat and the soil is Soil Conservation Service Type B. A plan drawing of the subdivision is shown in Figure 1. The existing storm sewer layout and drainage subbasins

FIGURE 1. *Plan Drawing of the Bar Barry Heights Subdivision.*

determined by field inspection are indicated in Figure 2. It can be seen all branches converge at the corner of Cumberland Avenue and Barlow Street on the northern edge of the subdivision. The stormwater then travels north through elliptical pipe for about 1400 ft before it discharges into Boes Ditch, part of the Tippecanoe County drainage system.

Input Data Sources

Basin characteristics needed in the analysis were determined primarily by field measurements. These data included gutter slopes, lengths and slopes of individual reaches of pipe, and the areas of subbasins contributing to each inlet. Aerial photographs were used to estimate the percentage of area with impervious cover. Table 1 summarizes this information.

The first column denotes the subbasin which contributes to the pipe designated in columns 2 and 3. Column 4 is the total area of the subbasin while columns 5, 6, and 7 give the areas in each of three categories: DCPA (directly connected paved areas which are streets and driveways); SPA (supplemental paved areas which are impervious areas hydraulically separated from the inlet); and GA (grassed areas which contribute to the runoff). The last four columns give the lengths and slopes of the paths of flow to the inlet. These are used to compute travel times.

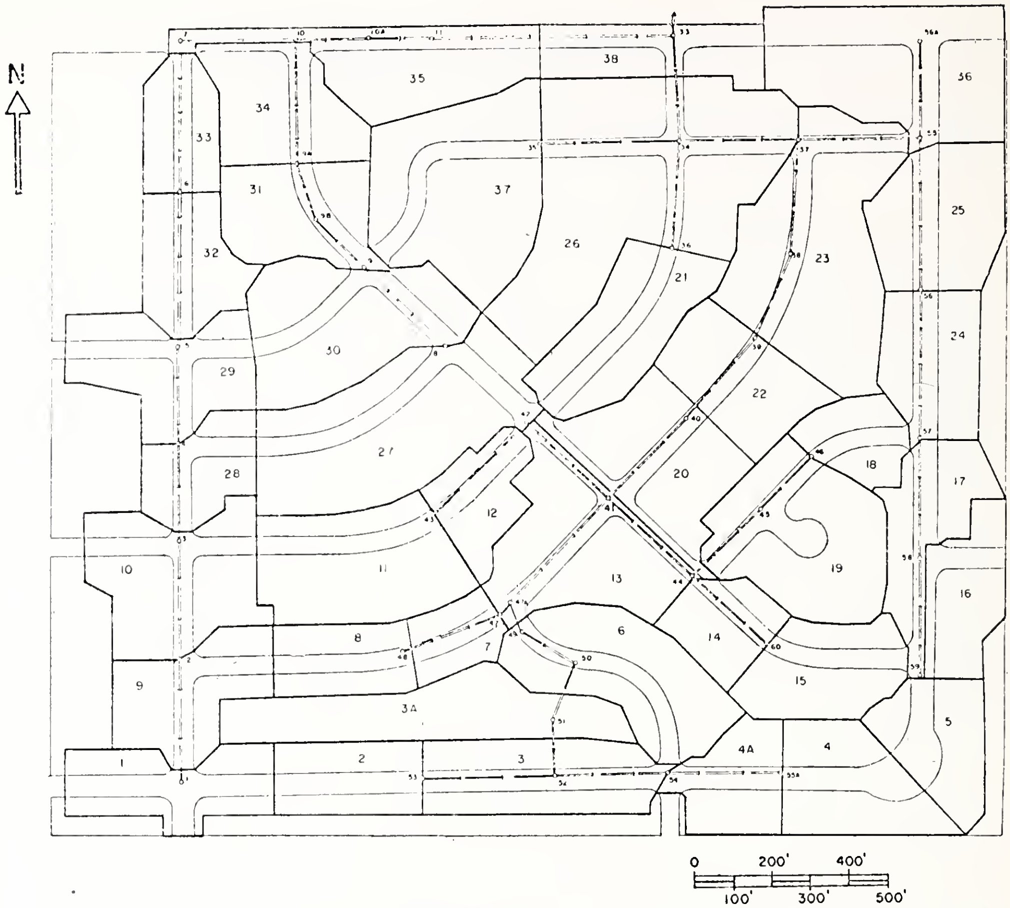

FIGURE 2. *Drainage Subbasins and Storm Sewer Layout of Bar Barry Heights.*

The rainfall data were obtained from an intensity-duration-frequency curve developed for the Lafayette area from U.S. Weather Bureau Technical Paper #40 [3] by using maps of Indiana with lines of equal depths for a 6 hour storm duration and return periods of 2, 5, 10, 25, 50, and 100 years. Depths for other durations were found by recommended conversions, and the intensity was then found by dividing by the appropriate duration. These values were then plotted against the duration on log-log paper to produce the curve shown in Figure 3. An equation suitable for use in computer or calculator programs was fitted to the curves in Figure 3. The final form of this equation is

$$i = \frac{22.5\ T^{0.18}}{(t + 5)^{0.68}}$$

where i = rainfall intensity (inches/hr)

T = return period (years) $2 \leqslant T \leqslant 50$

t = storm duration (minutes) $5 \leqslant t \leqslant 120$

This equation was used to determine the rainfall depths associated with each duration and return period for ILLUDAS as well as the intensities needed in the rational method.

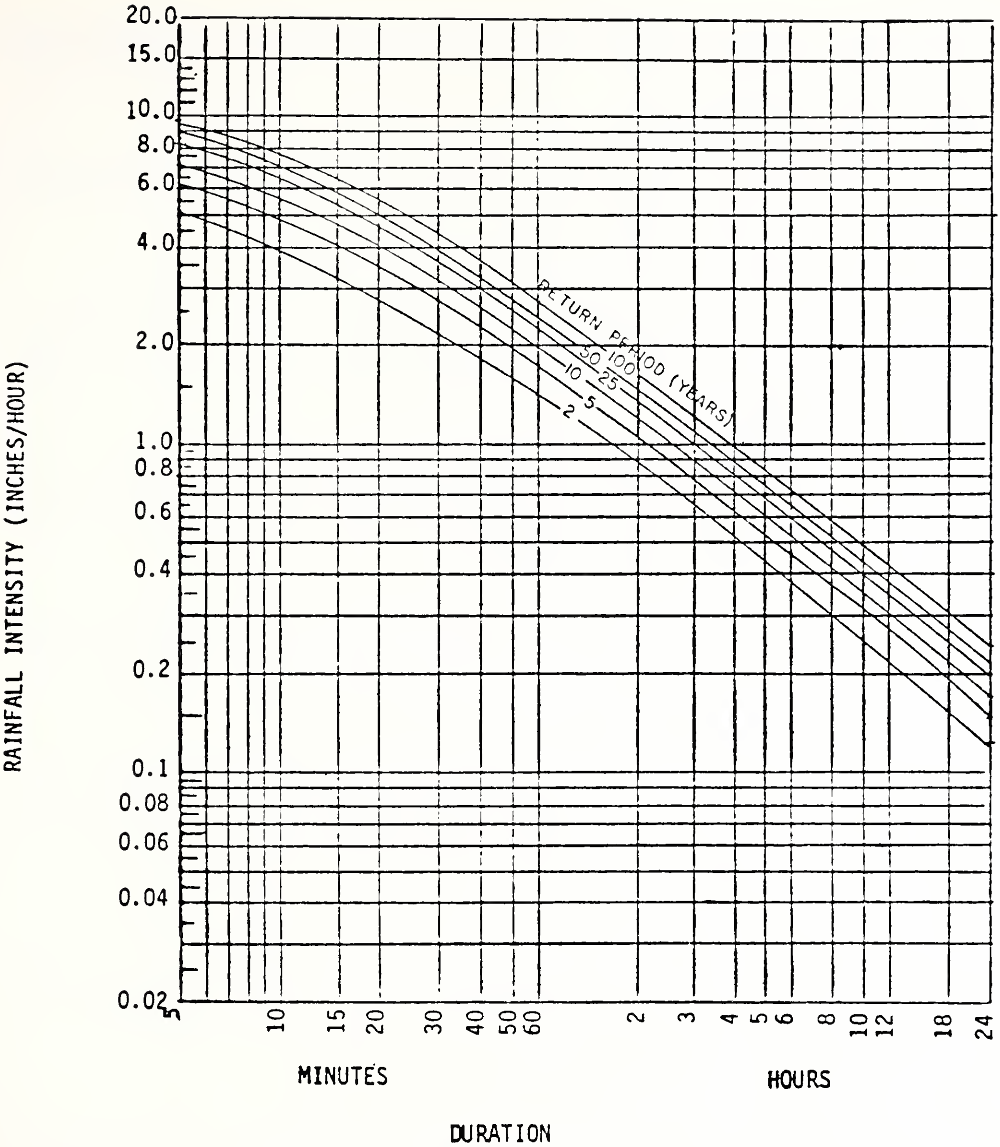

FIGURE 3. *Intensity-Duration-Frequency Curves for West Lafayette, Indiana.*

The rainfall data for the storm of July 4th, 1979, which was simulated with ILLUDAS, was measured at the Purdue gravel pit, 2.5 miles south of Bar Barry Heights.

Results

The rational method was used to design a new storm sewer system for Bar Barry Heights, keeping the locations of all inlets and manholes the same as in the existing system. Computations were carried out for a 5 year storm using individually weighted C values and an assumed 20 minute time of concentration for all subbasins. The system was designed to meet a fixed outfall elevation. Table 2 compares the existing and rational method designed systems. It is interesting to note that 3 existing pipes have a capacity smaller than required ac-

TABLE 1. *Subbasin Characteristics of Bar Barry Heights*

Sub-Basin No.	MH_U-MH_D	Branch-Reach	Basin Area (Acres)	DCPA (Acres)	SPA (Acres)	GA (Acres)	Paved Length (ft)	Paved Slope (%)	Grassed Length (ft)	Grassed Slope (%)
4	55A–54	1–0	2.55	0.64	0.23	1.68	400	0.50	100	2.00
4a	54–52	1–1	1.93	0.45	0.13	1.35	330	0.40	110	2.00
3	52-51	1–2	3.00	0.78	0.19	2.03	320	0.77	70	2.00
3a	51–50	1–3	3.79	0.00	0.46	3.33	0.00	0.00	950	2.00
6	50–49	1–4	3.75	0.94	0.35	2.46	275	1.1	125	1.00
6	49–47A	1–4	—	—	—	—	—	—	—	—
7	47A–41	1–5	1.14	0.40	0.05	0.69	270	0.62	71	2.00
13	41–40	1–6	3.88	0.94	0.35	2.59	410	0.70	70	2.00
20	40–39	1–7	3.05	0.76	0.25	2.04	580	0.78	100	2.00
22	39–38	1–8	2.59	0.38	0.20	2.01	250	0.50	190	2.00
—	38–37	1–9	—	—	—	—	—	—	—	—
23	37–34	6–5	5.99	1.13	0.46	4.4	550	0.40	300	2.00
26	34–33	12–1	8.61	1.43	0.65	6.53	350	0.30	500	1.00
38	33–out	12–2	2.13	0.61	0.16	1.36	350	0.60	65	2.00
1	1–2	9–0	2.55	0.78	0.07	1.76	300	1.00	70	2.0
9	2–3	9–1	2.66	0.73	0.14	1.79	280	0.30	150	2.0
10	3–4	9–2	3.74	1.08	0.30	2.36	290	0.33	169	2.0
28	4–5	9–3	1.84	0.61	0.10	1.13	240	1.00	60	2.0
29	5–6	9–4	3.08	0.90	0.19	1.99	240	0.95	90	2.0

32	6–7	9–5	2.00	0.67	0.10	1.23	400	0.35	100	2.0
33	7–10	9–6	1.45	0.60	0.10	0.75	380	0.46	80	2.0
34	10–10A	9–7	2.78	0.66	0.23	1.89	300	0.75	200	2.0
35	10A–11	9–8	3.44	0.74	0.18	2.52	550	0.60	100	2.00
—	11–33	9–9	—	—	—	—	—	—	—	—
27	8–9	10–0	5.81	1.25	0.41	4.15	650	0.34	150	2.0
30	9–9B	10–1	4.15	0.75	0.30	3.10	290	0.70	120	2.0
—	9B–9A	10–2	—	—	—	—	—	—	—	—
31	9A–10	10–3	2.59	0.51	0.21	1.87	220	0.75	100	2.0
5	59–58	6–0	1.42	0.52	0.14	0.85	320	0.25	100	2.00
16	58–57	6–1	1.93	0.47	0.16	1.30	350	0.45	150	2.00
17	57–56	6–2	2.23	0.65	0.12	1.46	600	0.65	100	2.00
24	56–55	6–3	2.41	0.65	0.08	1.68	410	0.95	95	2.00
25	55–37	6–4	3.15	0.61	0.18	2.36	400	0.70	150	2.0
18	46–45	4–0	1.35	0.42	0.15	0.78	300	0.30	100	2.00
19	45–44	4–1	4.18	0.84	0.20	3.14	170	1.00	135	2.00
14	44–41	4–2	1.57	0.36	0.10	1.11	260	0.90	144	2.00
15	60–44	5–0	2.46	0.58	0.16	1.72	390	0.65	100	2.00
11	43–42	8–0	3.80	0.78	0.36	2.66	520	0.41	180	2.00
12	42–41	8–1	1.60	0.44	0.12	1.04	330	0.81	175	2.00
37	35–34	11–0	5.39	0.93	0.26	4.20	700	0.50	300	1.00
21	36–34	12–0	3.03	0.88	0.13	2.02	580	0.95	100	2.00
2	53–52	2–0	1.93	0.53	0.08	1.33	410	0.97	70	2.00
36	56A–55	7–0	5.20	1.47	0.31	3.42	260	1.00	190	2.00
8	48–47	3–0	1.77	0.60	0.07	1.10	380	1.10	68	2.00
—	47–47A	3–1	—	—	—	—	—	—	—	—

TABLE 2. *Existing Storm Sewer System and Rational Method Designed System for Bar Barry Heights.*

Branch-Reach	Upstream M.H.-Down-Stream M.H.	Length (ft)	Existing Diameter (inches)	Existing Slope (ft/ft)	Full Pipe Capacity (CFS)	5 Year Rational Diameter (inches)	Rational Slope (ft/ft)	Full Pipe Capacity (CFS)	Computed Flow Rational System (CFS)
1–0	55A–54	314	12	0.0120	3.91	12	0.0095	3.48	3.43
1–1	54–52	316	15	0.0100	6.48	15	0.0126	7.27	5.70
1–2	52–51	160	24	0.0040	14.35	24	0.0030	12.42	11.80
1–3	51–50	167	24	0.0040	14.35	27	0.0021	14.23	14.04
1–4	50–49	175	27	0.0040	19.64	27	0.0035	18.37	18.19
	49–47A	93.5	27	0.0040	19.64	27	0.0035	18.37	18.19
1–5	47A–41	394	30	0.0028	21.76	30	0.0028	21.76	21.41
1–6	41–40	310	42	0.0032	57.07	36	0.0040	42.29	40.88
1–7	40–39	295	42	0.0028	53.38	42	0.0019	43.97	43.54
1–8	39–38	251	42	0.0028	53.38	42	0.0038	62.19	44.86
1–9	38–37	318	42	0.0028	53.38	48	0.00097	44.86	44.86
6–5	37–34	332	48	0.0030	78.89	48	0.002	64.61	64.60
12–1	34–33	295	54	0.0020	88.18	54	0.0016	78.87	78.55
12–2	33-out	1	72 × 44	0.001	49 *	60	0.002	116.79	116.28
9–0	1–2	329	18	0.0036	6.30	15	0.004	4.10	4.04
9–1	2–3	335	24	0.0046	15.38	18	0.0048	7.30	7.28
9–2	3–4	275	24	0.0082	20.54	21	0.0057	11.99	11.98
9–3	4–5	275	27	0.0116	33.44	21	0.009	15.07	14.12
9–4	5–6	423	36	0.0018	28.37	27	0.0033	17.83	17.63

9–5	6–7	423	36	0.0018	28.37	30	0.0031	22.89	19.55
9–6	7–10	324	36	0.0006	16.38*	30	0.0047	28.19	20.92
9–7	10–10A	200	42	0.0039	62.99	36	0.0029	36.06	36.06
9–8	10A–11	168	42	0.0039	62.99	48	0.00073	38.91	38.89
9–9	11–33	669	48	0.0017	59.38	48	0.00073	38.91	38.89
10–0	8–9	318	15	0.0060	5.02*	18	0.005	7.45	7.25
10–1	9–9B	183	18	0.0060	8.16*	21	0.0077	13.94	11.73
10–2	9B–9A	167	18	0.0060	8.16*	21	0.0055	11.78	11.73
10–3	9A–10	351	21	0.0060	12.30*	30	0.0012	14.25	14.03
6–0	59–58	323	15	0.0040	4.09	12	0.006	2.77	2.39
6–1	58–57	333	18	0.0075	9.25	15	0.0065	5.22	4.75
6–2	57–56	419	21	0.0125	17.76	18	0.010	10.53	7.45
6–3	56–55	415	24	0.0100	22.68	21	0.008	14.21	10.04
6–4	55–37	339	33	0.0040	33.43*	36	0.009	20.06	19.18
4–0	46–45	199	12	0.0040	2.66*	12	0.0045	2.40	2.39
4–1	45–44	260	15	0.0100	6.48*	21	0.002	7.10	6.98
4–2	44–41	320	18	0.0100	10.53*	21	0.0054	11.67	11.66
5–0	60–44	271	12	0.0100	3.57	12	0.0095	3.48	3.13
8–0	43–42	353	12	0.0100	3.57*	15	0.0065	5.22	4.85
8–1	42–41	313	12	0.0100	3.57*	18	0.0073	8.99	6.82
11–0	35–34	380	21	0.0048	11.00	21	0.0014	6.00	6.00
12–0	36–34	298	15	0.0100	6.48	18	0.0029	5.67	4.28
2–0	53–52	368	12	0.0093	3.44	12	0.0125	3.83	2.53
7–0	56A–55	269	27	0.0016	11.79	30	0.0006	10.07	7.01
3–0	48–47	270	12	0.0140	4.23	12	0.007	2.99	2.56
3–1	47-47A	41	30	0.0028	21.76	12	0.014	4.22	4.11

* Existing pipes do not have sufficient capacity.

TABLE 3. *ILLUDAS Results for Existing Storm Sewer System for Bar Barry Heights*

	10-Year Return Period				5-Year Return Period				2-Year Return Period			
Duration (minutes)	Rainfall Depth (inches)	Peak Runoff (CFS)	Time to Peak (min)	No. of Pipes Passing	Rainfall Depth (inches)	Peak Runoff (CFS)	Time to Peak (min)	No. of Pipes Passing	Rainfall Depth (inches)	Peak Runoff (CFS)	Time to Peak (min)	No. of Pipes Passing
						AMC 1						
60	1.97	135.5	16	31	1.76	120.1	16	36	1.49	100.0	17	41
50	1.86	143.7	15	21	1.64	124.9	15	32	1.39	105.0	16	40
45	1.79	151.7	14	18	1.58	128.0	15	32	1.34	107.1	15	39
40	1.71	154.9	14	17	1.51	129.6	14	30	1.28	107.9	15	37
35	1.62	157.0	13	16	1.43	130.7	14	24	1.21	108.7	14	37
30	1.52	164.3	13	13	1.34	132.1	13	21	1.14	109.5	13	36
25	1.40	164.6	12	11	1.24	137.4	12	18	1.05	109.6	13	36
20	1.27	164.1	12	13	1.12	127.6	12	18	0.95	105.3	12	35
						AMC 2						
60	1.97	137.9	16	29	1.76	120.1	16	36	1.49	100.0	17	41
50	1.86	159.4	15	18	1.64	124.9	15	32	1.39	105.0	16	40
45	1.79	167.6	15	16	1.58	129.2	15	31	1.34	107.1	15	39
40	1.71	179.9	14	12	1.51	133.3	14	27	1.28	107.9	15	37
35	1.62	186.3	13	12	1.43	144.8	14	19	1.21	108.7	14	37
30	1.52	193.4	13	7	1.34	150.3	13	18	1.14	109.5	13	36
25	1.40	196.2	12	7	1.24	153.4	13	16	1.05	109.6	13	34
20	1.27	195.9	12	7	1.12	152.6	12	15	0.95	107.9	12	33
						AMC 3						
60	1.97	201.1	17	15	1.76	166.6	18	21	1.49	125.0	18	36
50	1.86	219.3	16	11	1.64	178.5	16	16	1.39	133.0	17	31
45	1.79	225.6	15	8	1.58	183.8	16	16	1.34	137.5	16	27
40	1.71	230.4	15	7	1.51	192.1	15	13	1.28	140.4	15	23
35	1.62	234.8	14	7	1.43	195.8	14	12	1.21	142.0	15	21
30	1.52	237.1	13	7	1.34	197.6	13	10	1.14	143.9	14	20
25	1.40	235.6	13	6	1.24	198.7	13	8	1.05	142.8	13	20
20	1.27	232.9	12	6	1.12	193.9	12	9	0.95	138.5	12	19
						AMC 4						
60	1.97	240.4	18	10	1.76	206.7	18	15	1.49	163.1	19	23
50	1.86	253.5	16	8	1.64	215.2	16	11	1.39	167.8	17	20
45	1.79	258.1	16	7	1.58	220.0	16	11	1.34	173.5	16	17
40	1.71	261.6	15	7	1.51	223.2	15	9	1.28	175.3	16	17
35	1.62	263.2	14	6	1.43	224.2	14	8	1.21	175.9	15	16
30	1.52	263.3	14	5	1.34	224.4	14	7	1.14	176.7	14	15
25	1.40	260.5	13	5	1.24	223.6	13	7	1.05	173.2	13	15
20	1.27	254.8	12	5	1.12	216.3	12	7	0.95	167.9	13	15

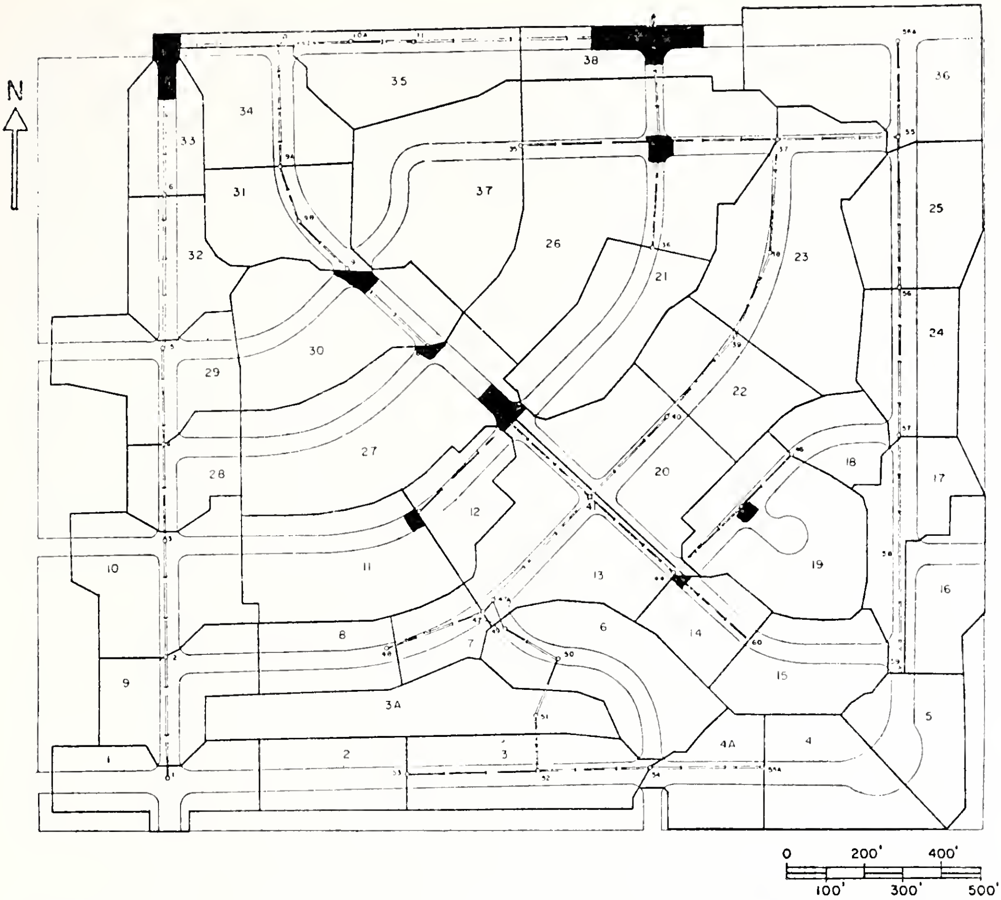

FIGURE 4. *Areas in Bar Barry Heights which Undergo Flooding as Predicted by ILLUDAS for the Storm of July 4, 1979.*

cording to the rational method. These pipes are the outfall, MH #42 - MH #41, and MH #7 - MH #10. The outfall pipe has less than half the required capacity.

ILLUDAS was applied to the existing system in the "evaluation in the design mode" for first quartile storms with return periods of 2, 5, and 10 years, durations of 20, 25, 30, 35, 40, 45, 50, and 60 minutes, and antecedent moisture conditions 1, 2, 3, and 4. The May 1979 program version with modifications made after an August 15, 1979, discussion with Michael Terstriep was used. A one minute time increment and routing option 1 were specified. Each simulation required about one minute of computer time. The peak flow, time to peak, and number of existing pipes passing the predicted flows are shown in Table 3. It can be seen that the peak flows occur with the higher return periods, higher antecedent conditions (AMC's), and lower durations, with the peak value occurring for a ten year 30 minute storm with AMC 4.

The peak flows for a two year return period and AMC 1 and 2 are identical. This indicates that only the impervious areas are contributing to the flow. The peak flows for AMC 3 and 4 clearly show that pervious areas are now being considered. For a five year return period, the peak flows for AMC 1 and 2 are identical for the longer durations, but the shorter durations provide an intensity which is sufficient to exceed the allowable infiltration capacity of the pervious areas. The peak flows for AMC 3 and 4 are seen to change in the same manner as for the two year return period storms. The peak flows for a ten year return period clearly illustrate the effect of grassed area runoff contributing to the flow. In all cases the maximum peak flow occurs for durations of 25 or 30 minutes. Analysis of the pipes which fail for the various cases shows that once again the outfall pipe and the pipes between MH #42 - MH #41 and MH #7 - MH #10 fail for every condition. ILLUDAS automatically specifies the pipe sizes which would be needed to pass the peak flow from each case.

The July 4th storm, which caused severe flooding, was simulated to get a gross check on the accuracy of ILLUDAS by comparing the predicted flooding areas to those actually flooded. The predicted flooding areas, shown in Figure 4, were found to be in relatively close agreement with those reported by residents [6]. It is seen that the most severe flooding occurs in the areas which feed into the previously determined undersized pipes.

Simulation of the new rational method designed system by ILLUDAS revealed that 14 pipes failed for a 5 year, 60 minute, AMC 1 storm [2]. Thus the rational method design did not provide the degree of protection specified in the design criteria. Additional simulations indicated that although a system designed according to the rational method for an N-year storm might be adequate for long duration N-year storms, it would fail for shorter durations. This appears to be a particularly undesirable characteristic of the rational method.

Conclusions

It is obvious that ILLUDAS provides a more comprehensive basis for design than does the rational method. Where the rational method provides only a peak flowrate for each pipe, ILLUDAS predicts complete hydrographs. This enables the engineer to specify detention storage requirements as well as pipe sizes. The lengthy hand calculations required by the rational method effectively preclude the investigation of alternative pipe layouts or design storms. With ILLUDAS the investigation of alternatives is relatively easy. ILLUDAS provides a straight forward procedure to investigate the response of the storm sewer system to any storm for which a hyetograph is known. This is impossible with the rational method. Most importantly, the rational method often fails to provide the degree of protection specified in the design criteria. Hence, it lacks reliability. Since the data needs and computer requirements of ILLUDAS are not excessive, ILLUDAS offers a practical alternative to the rational method which offers the promise of significantly improved storm sewer design for Indiana's urbanizing areas.

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