Example of Storm Sewer Design for a 20-ac Area Along Goodwin Avenue In Urbana, Illinois

EXAMPLE 11.1.1

The computational procedure in the rational method is illustrated through an example design of sewers to drain a 20-ac area along Goodwin Avenue in Urbana, Illinois, as shown in Figure 11.1.1. The physical characteristics of the drainage basin are given in Table 11.1.3. (The catchments are identified by the manholes they drain directly into. The sewer pipes are identified by the number of the upstream manhole of each pipe. The Manning's roughness factor n is 0.014 for all the sewers in the example (adapted from Yen (1978)).

SOLUTION

Table 11.1.4 shows the computations for the design of 12 sewer pipes, namely, all the pipes upstream of sewer 6.1. The rainfall intensity-duration relationship is developed using National Weather Service report HYDRO-35 (see Chapter 7 or Frederick et al. (1977)) and plotted in Figure 11.1.2 for the design return period of two years. The entries in Table 11.1.4 are explained as follows:

Columns (1), (2), and (3): The sewer number and its length and slope are predetermined quantities.

Column 4: Total area drained by a sewer is equal to the sum of the areas of the subcatchments drained by the sewer, e.g., for sewer 3.1, the area 8.45 ac is equal to the area drained by sewer 2.1 (7.30 ac in column 4) plus the area drained by sewer 2.2 (0.45 ac) plus the incremental area given in column (6) (0.70 ac for subcatchment 3.1).

Column (5) The identification number of the incremental subcatchments that drain directly through manhole or junction into the sewer being considered.

Column (6) Size of the incremental subcatchment identified in column 5 (Table 11.1.4).

Column (7) Value of runoff coefficient for each subcatchment (Table 11.1.4).

Column (8) Product of C and the corresponding subcatchment area.

Column (9) Summation of CA for all the areas drained by the sewer, which is equal to the sum of contributing values in column (9) and the values in column (8) for that sewer, e. g., for sewer 3.1, $5.97 = 5.12 + 0.36 + (0.49)$.

Column (10) Values of inlet time (Table 11.1.4) for the subcatchment drained (computed using methods in Table 11.1.2), i.e., the overland flow inlet time if the upstream subcatchment is no more than one sewer away from the sewer being designed (e.g., in designing sewer 3.1, 5.2 min for subcatchment 2.2 and 8.7 min for subcatchment 3.1); otherwise it is the total flow time to the entrance of the immediate upstream sewer (e.g., in designing sewer 3.1, 13.7 min for sewer 2.1).

Column (11) The sewer flow time of the immediate upstream sewer as given in column (19).

Column (12) The time of concentration t_c for each of the possible critical flow paths; t_c = inlet time (column (10)) + sewer flow time (column (11)) for each flow path.

Column (13) The rainfall duration t_d is assumed equal to the longest of the different times of concentration of different flow paths to arrive at the entrance of the sewer being considered; e.g., for sewer 3.1, t_d is equal to 14.1 min for sewer 2.1, which is longer than from sewer 2.2 (6.2 min) or directly from subcatchment 3.1 (8.7 min).

Column (14) The rainfall intensity i for the duration given in column (13) is based on HYDRO-35 for the two-year design return period (see Figure 11.1.2).

Column (15) Design discharge is computed by using Equation (11.1.2), i.e., the product of columns (9) and (14).

Column (16) Required sewer diameter in ft, as computed using Manning's formula, Equation (11.1.7), with $n = 0.014$, Q is given in column (15) and S_0 in column (3).

Column (17) The nearest commercial nominal pipe size that is not smaller than the computed size is adopted.

Column (18) Flow velocity computed by using $V = 4Q_p/(\pi D^2)$, i.e., column (15) multiplied by $4/\pi$ and divided by the square of column (17).

Column (19) Sewer flow time is computed as equal to L/V, i.e., column (2) divided by column (18) and converted into min.

This example demonstrates that in the rational method each sewer is designed individually and independently (except for the computation of sewer flow time) and the corresponding rainfall intensity i is computed repeatedly for the area drained by the sewer. For a given sewer, all the different areas drained by this sewer have the same i. Thus, as the design progresses towards downstream sewers, the drainage area increases and usually the time of concentration increases accordingly. This increasing t_c in turn gives a decreasing i, which should be applied to the entire area drained by the sewer. Failure to realize this variation of i is the most common mistake made in using the rational method for sewer design.

The size of a particular pipe is based upon computing the smallest available commercial pipe that can handle the peak flow rate determined using the rational formula (11.1.2). Manning's equation has been popular in the United States for sizing pipes:

$$Q = \frac{m}{n} S_f^{1/2} A R^{2/3} \tag{11.1.5}$$

where m is 1.486 for U.S. customary units (1 for SI units), S_f is the friction slope, A is the inside cross-sectional area of the pipe $\pi D^2/4$ in ft^2 (m^2), R is the hydraulic radius, $R = A/P = D/4$ in ft (m), P is the wetted perimeter (πD) in ft (m), and K is the inside pipe diameter in ft (m). By substituting in the bed slope S_0 for the friction slope (assuming uniform flow) and $A = \pi D^2/4$ and $R = D/4$ (assuming that the pipe is flowing full under gravity, not pressurized), Manning's equation becomes

$$Q = \frac{m}{n} S_0 \left(\frac{\pi D^2}{4}\right)\left(\frac{D}{4}\right)^{2/3} = m\left(\frac{0.311}{n}\right) S_0^{1/2} D^{8/3} \tag{11.1.6}$$

Equation (11.1.6) can be solved for the diameter

$$D = \left(\frac{m_D Q n}{\sqrt{S_0}}\right)^{3/8} \tag{11.1.7}$$

where m_D is 2.16 for U.S. customary units (3.21 for SI units). Q is determined using the rational formula, and D is rounded up to the next commercial size pipe. The Darcy–Weisbach equation can also be used to size pipes,

$$Q = A\left(\frac{8g}{f} R S_f\right)^{1/2} \tag{11.1.8a}$$

Equation (11.1.8a) can be solved for D using $S_f = S_0$ as

$$D = \left(\frac{0.811 f Q^2}{g S_0}\right)^{1/5} \tag{11.1.8b}$$

which is valid for any dimensionally consistent set of units. ■

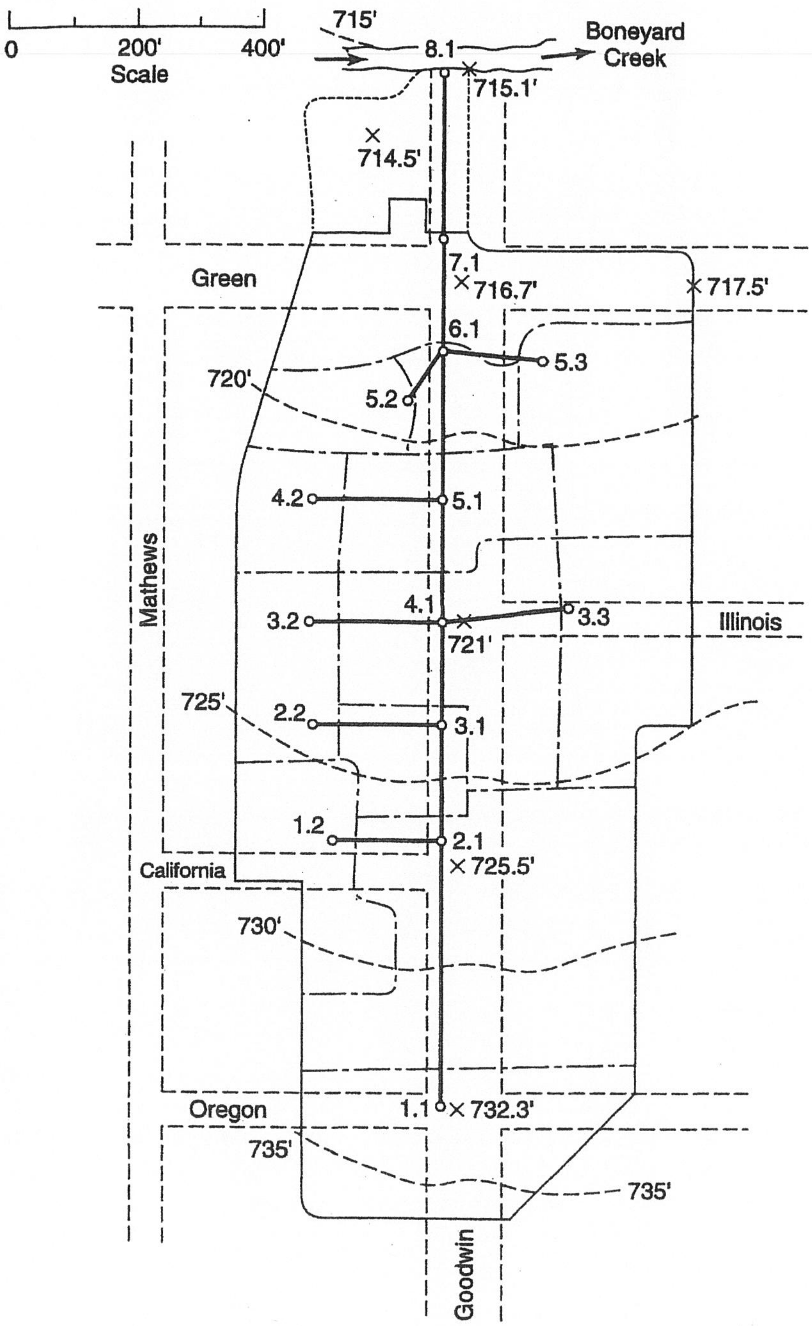

Figure 11.1.1 Goodwin Avenue drainage basin at Urbana, Illinois (from Yen 1978).

Table 11.1.2 Summary of Time of Concentration Formulas

Method and date	Formula for t_c (min)	Remarks
Kirpich (1940)	$t_c = 0.0078L^{0.77}S^{-0.385}\cancel{-0.385}$ L = length of channel/ditch from headwater to outlet, ft S = average watershed slope, ft/ft	Developed from SCS data for seven rural basins in Tennessee with well-defined channel and steep slopes (3% to 10%); for overland flow on concrete or asphalt surfaces multiply t_c by 0.4; for concrete channels multiply by 0.2; no adjustments for overland flow on bare soil or flow in roadside ditches.
California Culverts Practice (1942)	$t_c = 60\left(11.9L^3/H\right)^{0.385}$ L = length of longest watercourse, mi H = elevation difference between divide and outlet, ft	Essentially the Kirpich formula; developed from small mountainous basins in California (U.S. Bureau of Reclamation, 1973 and 1987).
Izzard (1946)	$t_c = \dfrac{41.025(0.0007i + c)L^{0.33}}{S^{0.333}i^{0.667}}$ i = rainfall intensity, in/h c = retardance coefficient L = length of flow path, ft S = slope of flow path, ft/ft	Developed in laboratory experiments by Bureau of Public Roads for overland flow on roadway and turf surfaces; values of the retardance coefficient range from 0.0070 for very smooth pavement to 0.012 for concrete pavement to 0.06 for dense turf; solution requires iteration; product i times L should be < 500.
Federal Aviation Administration (1970)	$t_c = 1.8(1.1 - C)L^{0.50}/S^{0.333}$ C = rational method runoff coefficient L = length of overland flow, ft S = surface slope, %	Developed from airfield drainage data assembled by the Corps of Engineers; method is intended for use on airfield drainage problems, but has been used frequently for overland flow in urban basins.
Kinematic wave formulas (Morgali and Linsley, 1965; Aron and Erborge, 1973)	$t_c = \dfrac{0.94L^{0.6}n^{0.6}}{\left(i^{0.4}S^{0.3}\right)}$ L = length of overland flow, ft n = Manning roughness coefficient i = rainfall intensity, in/h S = average overland slope, ft/ft	Overland flow equation developed from kinematic wave analysis of surface runoff from developed surfaces; method requires iteration since both i (rainfall intensity) and t_c are unknown; superposition of intensity-duration-frequency curve gives direct graphical solution for t_c.
SCS lag equation (U.S. Soil Conservation Service, 1975)	$t_c = \dfrac{100L^{0.8}[(1000/\mathrm{CN}) - 9]^{0.7}}{1900S^{0.5}}$ L = hydraulic length of watershed (longest flow path), ft CN = SCS runoff curve number S = average watershed slope, %	Equation developed by SCS from agricultural watershed data; it has been adapted to small urban basins under 2000 ac; found generally good where area is completely paved; for mixed areas it tends to overestimate; adjustment factors are applied to correct for channel improvement and impervious area; the equation assumes that $t_c = 1.67 \times$ basin lag.
SCS average velocity charts (U.S. Soil Conservation Service, 1975 and 1986)	$t_c = \dfrac{1}{60}\sum \dfrac{L}{V}$ L = length of flow path, ft V = average velocity in ft/s for various surfaces found using Figure 8.8.2	Overland flow charts in U.S. Soil Conservation Service (1986) show average velocity as function of watercourse slope and surface cover.

Source: Kibler (1982).

Table 11.1.3 Characteristics of Catchments of Goodwin Avenue Drainage Basin

(1) Catchment	(2) Ground elevation at manhole (ft)	(3) Area A (ac)	(4) Runoff coefficient C	(5) Inlet time t_o (min)
1.1	731.08	2.20	0.65	11.0
1.2	725.48	1.20	0.80	9.2
2.1	724.27	3.90	0.70	13.7
2.2	723.10	0.45	0.80	5.2
3.1	722.48	0.70	0.70	8.7
3.2	723.45	0.60	0.85	5.9
3.3	721.89	1.70	0.65	11.8
4.1	720.86	2.00	0.75	9.5
4.2	719.85	0.65	0.85	6.2
5.1	721.19	1.25	0.70	10.3
5.2	719.10	0.70	0.65	11.8
5.3	722.00	1.70	0.55	17.6
6.1	718.14	0.60	0.75	7.3
7.1	715.39	2.30	0.70	14.5

Source: Yen (1978).

Table 11.1.4 Design of Sewers by the Rational Method

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)
				Increment														
Sewer	Length L	Slope S (ft)	Total area drained (ac)	Catchment	Area (ac)	C	CA	ΣCA	Inlet time (min)	Upstream sewer flow time (min)	t_c (min)	t_d (min)	i (in/hr)	Design discharge Q_p (cfs)	Computed diameter D_r (ft)	Pipe size used D_n (ft)	Flow velocity (fps)	Sewer flow time (min)
1.1	390	0.0200	2.20	1.1	2.20	0.65	1.43	1.43	11.0	–	11.0	11.0	4.00	5.72	1.08	1.25	4.6	1.42
1.2	183	0.0041	1.20	1.2	1.20	0.80	0.96	0.96	9.2	–	9.2	9.2	4.30	4.13	1.28	1.50	2.3	1.31
2.1	177	0.0245		2.1	3.90	0.70	2.73		13.7	–	13.7							
				1.1					11.0	1.4	12.4							
				1.2					9.2	1.3	10.5							
			7.30					5.12				13.7	3.68	18.8	1.62	1.75	7.8	0.38
2.2	200	0.0180	0.45	2.2	0.45	0.80	0.36	0.36	5.2	–	5.2	5.2	5.30	1.91	0.73	0.83	3.5	0.95
3.1	156	0.0104		3.1	0.70	0.70	0.49		8.7	–	8.7							
									13.7	0.4	14.1							
				2.2					5.2	1.0	6.2							
			8.45					5.97				14.1	3.63	21.6	2.00	2.00	6.9	0.39
3.2	210	0.0175	0.60	3.2	0.60	0.85	0.51	0.51	5.9	–	5.9	5.9	5.07	2.59	0.82	0.83	4.7	0.74
3.3	130	0.0300	1.70	3.3	1.70	0.65	1.11	1.11	11.8	–	11.8	11.8	3.90	4.32	0.90	1.00	5.5	0.39
4.1	181	0.0041		4.1	2.00	0.75	1.50		9.5	–	9.5							
									14.1	0.4	14.5							
				3.3					11.8	0.4	12.2							
			12.75					9.09				14.5	3.60	32.7	2.79	3.00	4.6	0.65
4.2	200	0.0026	0.65	4.2	0.65	0.85	0.55	0.55	6.2	–	6.2	6.2	4.98	2.75	1.20	1.25	2.2	1.49
5.1	230	0.0028		5.1	1.25	0.70	0.88		10.3	–	10.3							
									14.5	0.7	15.2							
			14.65					10.52				15.2	3.50	36.8	3.13	3.50	3.8	1.00
5.2	70	0.0250	0.70	5.2	0.70	0.65	0.46	0.46	11.8	–	11.8	11.8	3.90	1.79	0.67	0.67	5.1	0.23
5.3	130	0.0060	1.70	5.3	1.70	0.55	0.94	0.94	17.6	–	17.6	17.6	3.30	3.10	1.07	1.25	2.5	0.86

Source: Yen (1978).

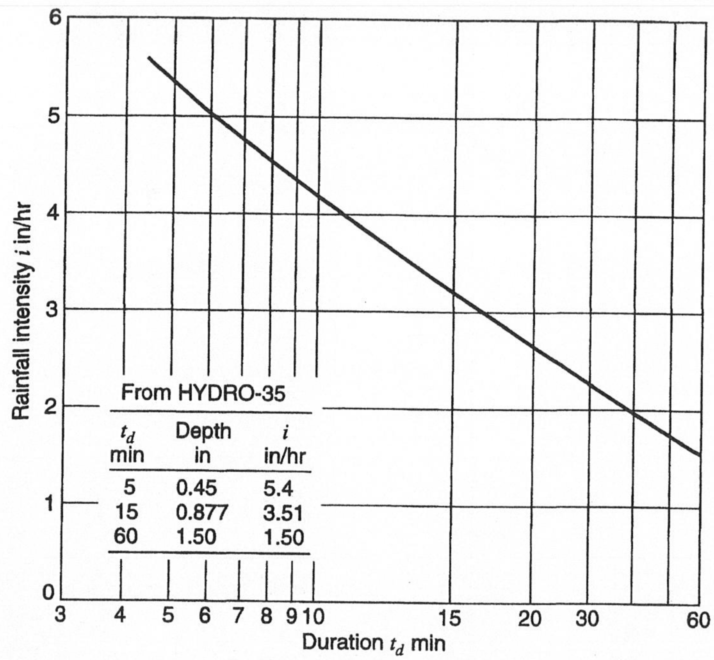

Figure 11.1.2 Variation of rainfall intensity with duration at Urbana, Illinois (from Yen (1978)).

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