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A HYDROLOGICAL URBAN DRAINAGE MODEL AND ITS APPLICATION – A CASE STUDY

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ABSTRACT

Now a days, water-logging due to excessive rainfall is becoming more serious in urban areas making it necessary to urgently assess and redesign the existing draiage facilities to drain out the storm water more efficiently. In this study, a hydrologic urban drainage model is developed by combining Horton's equation for the estimation of runoff losses and Manning's equation for flow through drains to relate the rainfall-runoff respons. The existing drainage facilities for a typical urban catchment, Ward No. 22 in Khulna City Corporation of Bangladesh are studied, analyzed. To analyze the drainage characteristics efficiently, the study area is sub-divided into 8 sub-catchments. It is found that the existing drainage facilities are not adequate for the study area and the water logging condition will be happend if a rainfall intensity is equalled or exceed 1.2 in/hr irrespective of the rainfall duration, no water logging condition will be occured below this level. It is concluded that the proposed rainfall-runoff model could be used to predict the rainfall-runoff response for other urban catchment also.

Keywords: *Catchment area, Drainage characteristics, Excess rainfall, Infiltration, Rainfall intensity, Runoff.*

1. INTRODUCTION

Heavy rainfall is more likely to occur as a consequence of global warming (Mcbean, 2006; Mailhot et al., 2007). Moreover, innundation due to heavy rainfall is becoming more serious in urban areas, which makes it necessary to urgently appraise and redesign the infrastructure system to drain the storm water more efficiently (Pan et. al., 2011). For most severe urban inundations, the rainfalls often exceed design rainfall values. But for many other minor cases where the rainfalls are below design standard, the urban inundations are caused by failure or improper operation of street inlets, pipe systems, and drainage river system. It is, therefore, necessary to re-design and re-operate infrastructure systems to drain the storm water more efficiently. To facilitate the optimal design and operation of urban drainage system, a sophisticated urban drainage model is required. In fact, the urban storm water flows through considerable complex pathways such as roofs, parking lots, squares, yards, roads, drainage pipelines, flyovers, pump stations, etc. (Hsu et al., 2000), and the flow regime changes substantially as the water moves along the various boundaries, which makes the urban storm water modeling a challenging task.

A lot of research work has been done and a large number of urban storm flow simulation models were proposed. The most widely used approach for designing urban drainage structures, such as roadside swales and gutters, storm drain inlets, open and closed storm sewers, and culverts, is the rational formula or rational method (Pilgrim, 1986; Linsley, 1986), which gives the peak flow rate from a catchment as

$$Q_p = k_u C \bar{i} A \tag{1}$$

where k_u=units conversion factor; C=runoff coefficient that represents the fraction of incident precipitation that appears as surface runoff ($0 \le C \le 1$); $\bar{i}$ =average rainfall intensity for a storm of a particular duration in depth units of rainfall per hour; and A=catchment area. Hsu et al. (2000) used Storm Water Management Model (SWMM) and the two-dimensional diffusive flow model for the coupled simulation of surface inundation in the

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downtown area of Taipei caused by the overflow of the sewer network. Schmitt et al. (2004) built a dual drainage model RisUrSim which incorporated the detailed surface flow simulation and the interaction between surface and sewer flow. Nasello and Tucciarelli (2005) developed a dual model of a double network formed by an upper network of open channels (street gutters) and a lower network of closed conduits (sewer pipes). Fang and Su (2006) proposed a coupled model of the surface and sewer network to simulate the inundation in the city of Beaumont, Texas caused by a tropical storm. In this paper, a hydrologically-enhanced urban drainage model has been proposed by combining Horton's equation for runoff losses and Manning's equation for flow through drains to relate the rainfall-runoff response and several hypothetical rainfall data has been implemented for a typical urban catchment, Ward No. 22 in Khulna City Corporation (KCC) of Bangladesh to show the capacity of the proposed model.

2. METHODOLOGY

Ward. No. 22 of KCC of Bangladesh is selected for this study. Data such as map of KCC and Ward No. 22, and other relevant information are collected from KCC. Field work is also conducted to find out the length, dimensions and flow direction of various drains. Then drainage parameters and properties for the study area are analyzed. A hydrologic lump urban drainage model is developed by combining Horton's equation for the estimation of runoff losses and Manning's equation for flow through drains. Several hypothetical rainfall data are implemented for the selected area to show the capacity of the proposed model. When the storm occurs, the runoff loss is estimated using Horton's equation. The runoff loss is removed from the total rainfall and the net rainfall is obtained, which will cause the overland flow and reaches to the nearby drain of the drainage network. Finally, all the storm water will go into the river network from several outlet of drain networks. The steps in the development of the rainfall-runoff model are as follows:

i) selection of a particular rainfall with intensity (I inch/hr) and rainfall duration (t hr).
ii) sub-divide the rainfall duration into the smallest time interval Δt.
iii) calculation of losses using Horton's Infiltration Model for every time interval Δt by the following equation.

$$f = f_c + (f_0 - f_c)\, e^{-Kt} \tag{2}$$

where,
f = infiltration after time "***t***" (in/hr)
f_c = final infiltration capacity (in/hr)
f_0 = initial infiltration capacity (in/hr)
K = constant depending upon the soil characteristics
t = duration of rainfall (hr)

The value of f_c, f_0 and K can be calculated from Table 1.

iv) calculation of excess rainfall by subtracting the losses from actual rainfall for every time interval Δt.

Table 1 Horton's Infiltration Parameters (Source: Akan, 1993)

Soil Type	f_0 (in/hr)
Dry sandy soil with little to no vegetation	5
Dry loam soil with little to no vegetation	4
Dry clay soil with little to no vegetation	1
Dry sandy soil with dense vegetation	10
Dry loam soil with dense vegetation	6
Dry clay soil with dense vegetation	2
Moist sandy soil with little to no vegetation	1.7
Moist loam soil with little to no vegetation	1
Moist clay soil with little to no vegetation	0.3
Moist sandy soil with dense vegetation	3.3
Moist loam soil with dense vegetation	2
Moist clay soil with dense vegetation	0.07

Soil Type	f_c (in/hr)	K (hr^{-1})
Clay loam, Silty clay loam	0-0.05	4.14
Sandy clay loams	0.05-0.15	4.14
Silt loam, loam	0.15-0.30	4.14
Sand, loamy sand, sandy loams	0.30-0.45	4.14

v) determination of outlet discharge capacity using Manning's equation for every time interval Δt.

$$\text{Outlet discharge capacity (inches)} = \frac{Q}{A_c} \times \Delta t \qquad (3)$$

$$\text{Runoff depth } (t+\Delta t) = \text{Runoff depth } (t) + \text{Excess Rainfall } (\Delta t) \text{ if any} - \text{Outlet Discharge } (\Delta t) \qquad (4)$$

Where, Q = outlet discharge capacity by Manning's equation (ft^3/s) $= \frac{\varphi}{n} A R^{\frac{2}{3}} S^{\frac{1}{2}}$ (5)

A_c = catchment area (ft^2)
φ = 1.486 (1 for SI unit)
n = Manning's roughness coefficient
A = cross-sectional area of drain (ft^2)
R = hydraulic radius of drain (ft)
S = slope of drain (ft/ft)

vi) calculation of runoff depth in the catchment at any time interval ($t+\Delta t$) by subtracting the runoff depth at Δt time earlier plus excess rainfall increment if any and minus the outlet discharge increment.

vii) the runoff depth in the catchment will be treated as water logging depth for the catchment.

The model is then applied to the catchments for different rainfall duration and intensity to relate the rainfall-runoff response. Finally, a graphical representation for every identical rainfall has been developed.

3. STUDY AREA AND DATA COLLECTION

Khulna City Corporation (KCC) is third biggest city corporation in Bangladesh. It is declared as City Corporation in 1990. It is situated at the western bank of the river Rupsha and between 21.38^0 and 23.1^0 north latitude and 88.58^0 east latitude. The main urban area has developed along a high ridge of land bordering the river. The entire urban area is low lying with maximum elevations of 4 – 4.5 meters on the embankment decreasing to 2 meters and less by the Mayur River and its extensions to the north (Kudi Khal) and south (Hatia Nadi river). Over time the city has extended westward and southward to lower lying, and hence more flood prone areas to the west. The area of this City Corporation is 45.65 km^2 and population is over 1.4 million. Figure 2 shows the drainage network of the KCC area. The network is extensive consisting of just under 420 km of which 45 km are main (carrier) drains, 290 km are concrete secondary and tertiary drains, 34 km are of semi-pucca (concrete plus earthen) and 45 km are kutcha (earthen). Drains along the major roads are now generally covered. There are 31 wards in KCC. The study area is Ward No. 22, which starts from Circuit House More and ends at Rupsha Ferri Ghat. It has boundary with Ward No. 21, Ward No. 23 and Ward No. 29. The eastern part of the ward is in touch with river Rupsha. There are three big outlets situated in this ward carrying all the water coming from the main Khulna City. The water comes from rainfall and human being discharge into the nearby river Rupsha. The total length of drain in this ward is 13.2 km and area covered is 1.73 km^2. The study ward is also shown in Figure 1.

Data such as map of the city and the ward have been collected from the office of the KCC. Field work has been carried out to collect all relevant information of all drains in the ward. Photographs of drains and outlets at different locations are also taken. The length of various types of drains is also obtained. The area occupied by the study area is also obtained from the map. Drainage parameters and drainage properties such as stream order, drainage density (length of stream per unit area) and stream density (number of streams to the area drained) for the catchments are calculated. The dimensions of different types of drains are given in Table 2. There are 3 outlets through which whole runoff from the study area discharge in to the river Rupsha. The pictorial view of various important locations has been collected during the study. Some of those pictures are shown in Figure 2.

4. ANALYSIS AND RESULTS

In this study the existing drainage facilities of Ward No. 22 of KCC is studied and analyzed. To analyze the drainage characteristics efficiently, the total catchment area is sub-divided into 8 sub-catchments (Figure 3). The areas occupied by each sub-catchments areas are calculated. The Drainage network including different stream orders of the catchments are also shown in Figure 3. Drainage parameters and drainage properties for the catchments are given in Table 3.

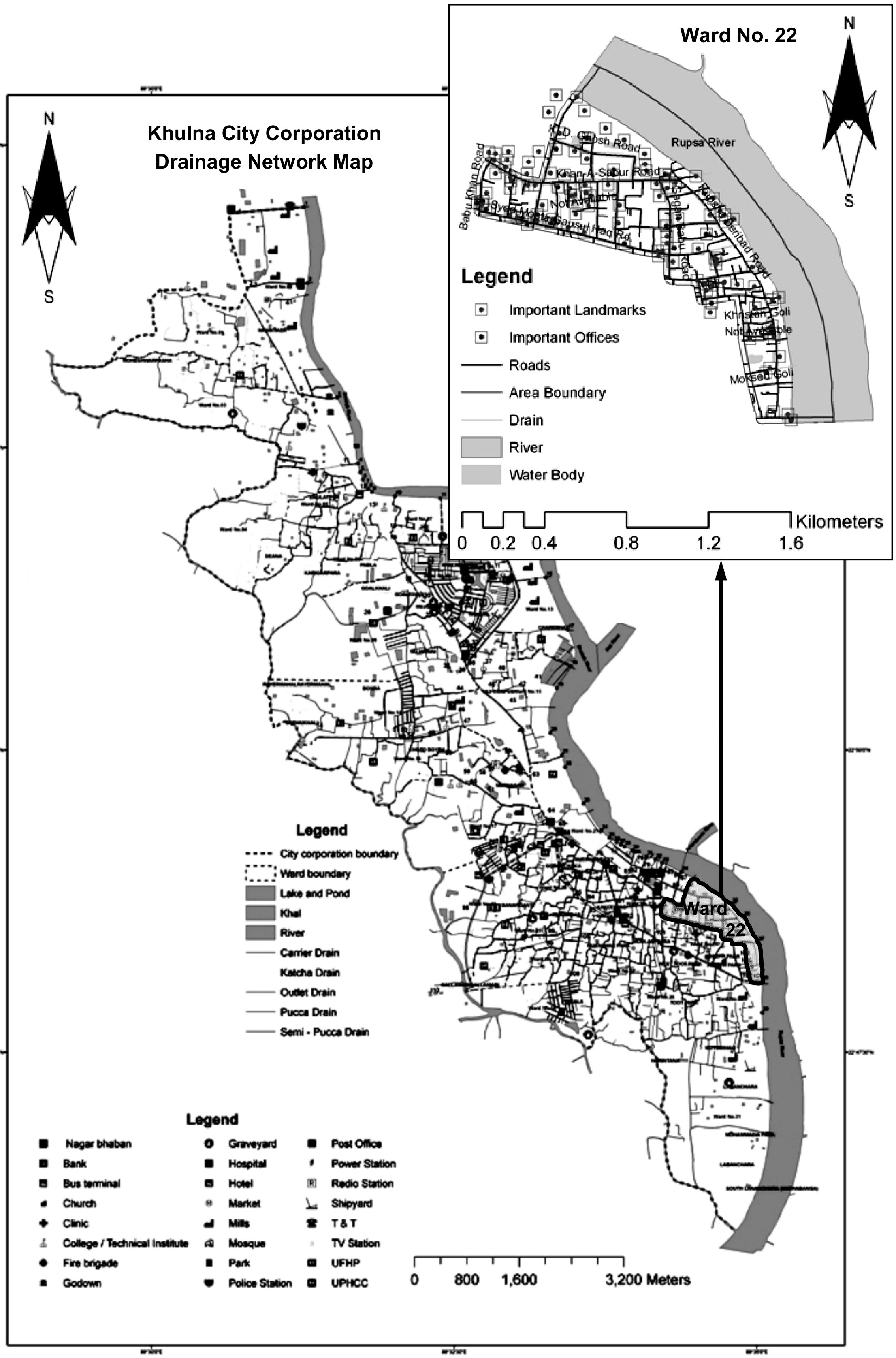


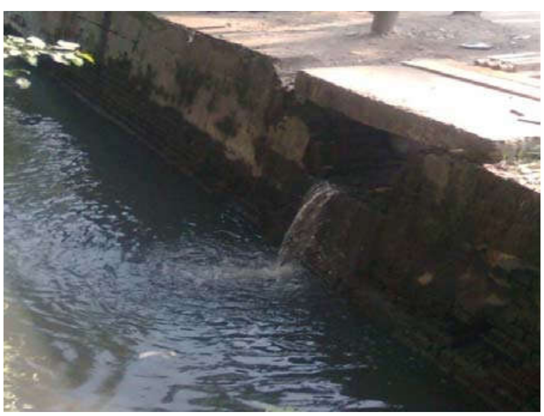
Figure 1 Drainage network map of KCC and the study area

Table 2 Dimensions of Different Types of Drains in the study ward

Serial No.	Width (ft)	Depth (ft)	Length (km)
1	6	6	0.5
2	4	6	4.8
3	5	6	2.7
4	4	4	8.3
5	3	4	3.5
6	4	2	2.7
7	2	2	4.5

(a) Flow reduced due to garbage at Munsi Para

(b) Outlet point at 2 no. custom Ghat



(c) Drain at 1 no. Custom Ghat

(d) Drain at 1 no. Custom Ghat

Figure 2 Some pictorial views of drains at the study area

Figure 4 shows the graphical representation of the model out put for four different rainfalls. In field observation, the soil characteristics of the study area was found as silty clay with vegetation for which initial infiltration capacity, $f_0 = 2$ (in/hr), final infiltration capacity, $f_c = 0.05$ (in/hr) and the constant, $K = 4.14$ (hr^{-1}) were used for calculating the losses by Horton equation (Table 1). For estimating the drain flow/capacity by Manning's equation, the slope of drains is assumed as 1 in 400 (ft/ft) and the Manning's n is taken as 0.015 (Chow, 1956). The model is run for the incremental time interval of 'Δt' of 1 min. The model is run for several hypothetical rainfal data and it is found that water logging condition will be happened if the rainfall intensity is equal or exceeded 1.2 in/hr irrespective of the rainfall duration, no water logging condition will be occured below this level. Table 4 shows the rainfall-runoff response produce from the model for 8 set of hypothetical rainfall data of intensity 2 in/hr and duration varies from 1 to 8 hr. In the analyses, the rainfall duration is divided into minutes and rainfall intensity is converted into in/min. The infiltration capacities f_0 and f_c and the constant K are converted to in/min and min^{-1}, respectively. Horton's infiltration losses is calculated in in/min also. The model shows water logging depth in the catchment after initiation of any identical rainfall in inches. Table 5 shows the water logging depth and time requirement for draining out stagnant water for different rainfall intensities and duration varies from 2 to 6 in/hr and 1 to 6 hr, respectively. The analysis also shows how long it takes to remove stagnant water after initiation of rainfall (Figure 4, Table 4 and 5). Moreover, the analysis also shows that for which rainfall water logging condition will happen or not.

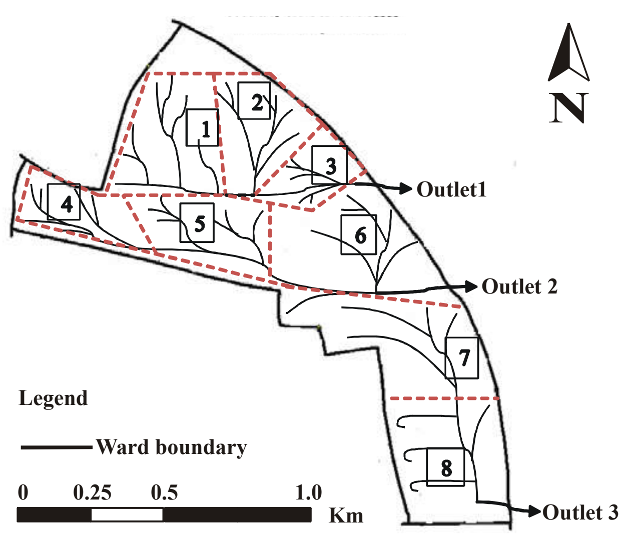


Figure 3 Drainage network for the Ward No. 22

Table 3 Drainage properties for the Ward No. 22 of KCC

Outlet	Sub-catchment area	Mean stream length (km) and number of streams in parenthesis			Occupied area (km^2)	Drainage density D_d (km/km^2)	Stream density D_s (1/km^2)
		Order 1	Order 2	Order 3			
1	1	0.215 (7)	0.175 (4)	0.124 (2)	0.148	16.5	87.7
	2	0.146 (6)	0.105 (3)	0.120 (1)	0.168	7.8	59.7
	3	0.317 (6)	0.215 (4)	0.110 (1)	0.058	49.8	190.8
2	4	0.175 (6)	0.100 (2)	0.120 (3)	0.255	6.3	43.1
	5	0.228 (4)	0.145 (3)	--	0.266	5.1	26.3
	6	0.165 (3)	0.095 (2)	--	0.335	2.0	14.9
3	7	0.195 (5)	0.090 (4)	--	0.198	6.8	45.5
	8	0.220 (5)	0.125 (4)	--	0.302	5.3	29.8

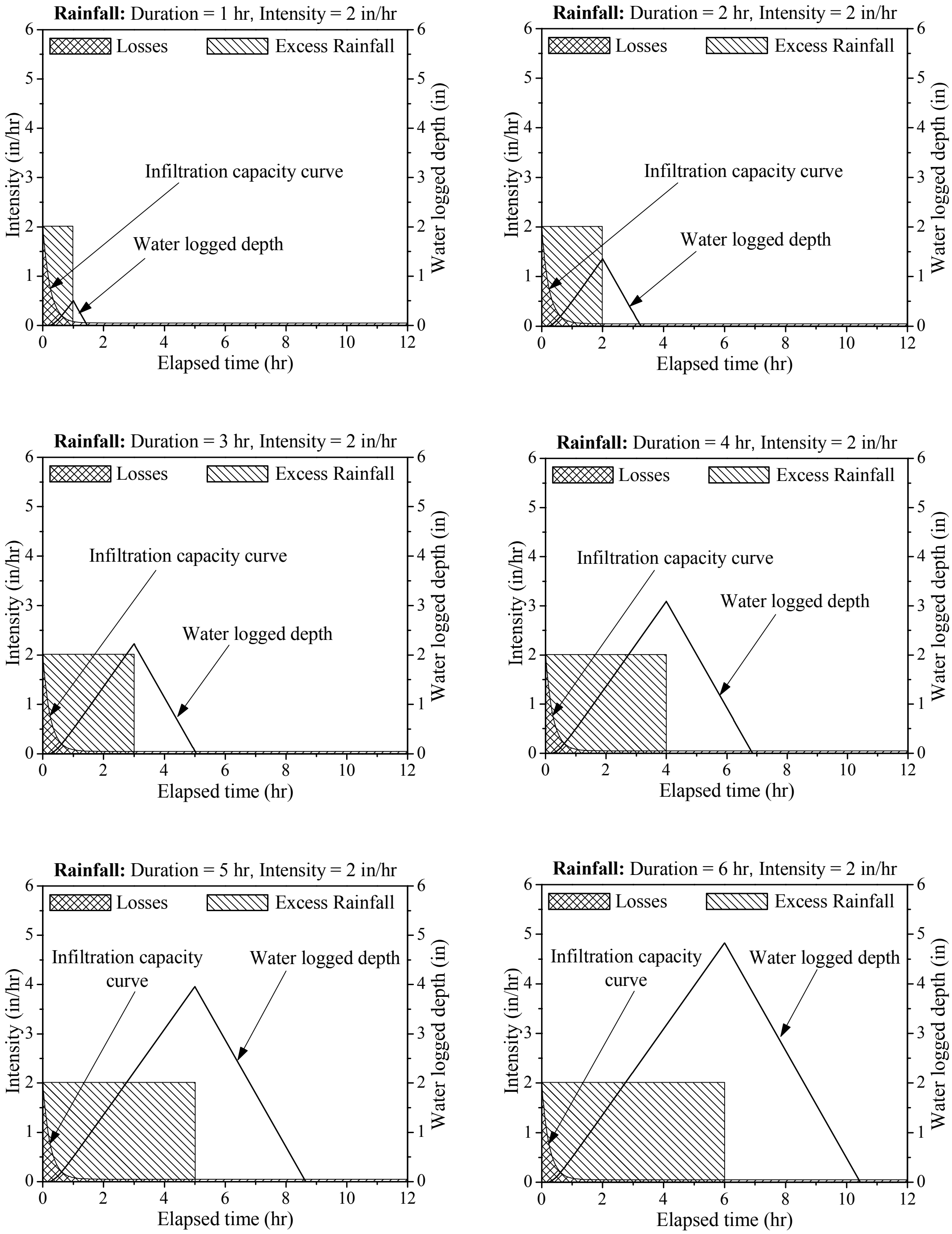


Figure 4 Results from the developed rainfall-runoff model for typical indicated rainfalls.

Table 4 Rainfall-Runoff response from the model for a typical rainfall intensity of 2 in/hr for different indicated rainfall duration

Rainfall Duration (hr)	1	2	3	4	5	6	7	8
Duration (hr)	Water logging depth in the catchment after initiation of rainfall (in)							
0	0	0	0	0	0	0	0	0
0.25	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
0.50	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
0.75	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
1.00	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
1.25	0.23	0.71	0.71	0.71	0.71	0.71	0.71	0.71
1.50	0	0.93	0.93	0.93	0.93	0.93	0.93	0.93
1.75		1.14	1.14	1.14	1.14	1.14	1.14	1.14
2.00		1.36	1.36	1.36	1.36	1.36	1.36	1.36
2.25		1.09	1.58	1.58	1.58	1.58	1.58	1.58
2.50		0.82	1.79	1.79	1.79	1.79	1.79	1.79
2.75		0.55	2.01	2.01	2.01	2.01	2.01	2.01
3.00		0.28	2.23	2.23	2.23	2.23	2.23	2.23
3.25		0	1.95	2.44	2.44	2.44	2.44	2.44
3.50			1.68	2.66	2.66	2.66	2.66	2.66
3.75			1.41	2.88	2.88	2.88	2.88	2.88
4.00			1.14	3.09	3.09	3.09	3.09	3.09
4.25			0.87	2.82	3.31	3.31	3.31	3.31
4.50			0.60	2.55	3.52	3.52	3.52	3.52
4.75			0.33	2.28	3.74	3.74	3.74	3.74
5.00			0.06	2.01	3.96	3.96	3.96	3.96
5.25			0	1.74	3.69	4.17	4.17	4.17
5.50				1.47	3.42	4.39	4.39	4.39
5.75				1.19	3.14	4.61	4.61	4.61
6.00				0.92	2.87	4.82	4.82	4.82
6.25				0.65	2.60	4.55	5.04	5.04
6.50				0.38	2.33	4.28	5.26	5.26
6.75				0.11	2.06	4.01	5.47	5.47
7.00				0	1.79	3.74	5.69	5.69
7.25					1.52	3.47	5.42	5.91
7.50					1.25	3.20	5.15	6.12
7.75					0.98	2.93	4.88	6.34
8.00					0.71	2.66	4.61	6.56
8.25					0.43	2.38	4.33	6.28
8.50					0.16	2.11	4.06	6.01
8.75					0	1.84	3.79	5.74
9.00						1.57	3.52	5.47
9.25						1.30	3.25	5.20
9.50						1.03	2.98	4.93
9.75						0.76	2.71	4.66
10.00						0.49	2.44	4.39
10.25						0.22	2.17	4.12
10.50						0	1.89	3.84
10.75							1.62	3.57
11.00							1.35	3.30
11.25							1.08	3.03
11.50							0.81	2.76
11.75							0.54	2.49
12.00							0.27	2.22
12.25							0	1.95
12.50								1.68
12.75								1.41
13.00								1.13
13.25								0.86
13.50								0.59
13.75								0.32
14.00								0.05
14.25								0

5. Conclusions

In this study, a rainfall-runoff model is proposed to investigate the rainfall-runoff response of the study area. Horton's infiltration model and Manning's formula are used to calculate the losses and outlet capacity of the drain, respectively in the model. It is concluded that the existing drainage facility is not adequate for the study area, Ward No. 22 and that water logging condition will be happened if the rainfall intensity is equal or exceeded 1.2 in/hr irrespective of the rainfall duration, no water logging condition will be occured below this level. The analysis also shows how long it takes to remove stagnant water after initiation of rainfall. The developed rainfall-runoff model could be used to predict the rainfall-runoff response for the other urban catchment also.

Table 5 Maximum water loggin depth in inches and time required to drain out storm water completely in hours after the initiation of raifall in parenthesis

Rainfall duration (hr)	Maximum water logging depth (in) and water logging duration (hr) in parenthesis for indicated rainfall intensity (in/hr)				
	2	**3**	**4**	**5**	**6**
1	0.50 (1.50)	1.42 (2.50)	2.42 (3.25)	2.33 (4.25)	4.42 (5.25)
2	1.36 (3.50)	3.28 (5.25)	5.28 (7.00)	7.28 (8.75)	9.28 (10.75)
3	2.23 (5.25)	5.14 (7.75)	8.14 (10.75)	11.14 (13.50)	14.14 (16.25)
4	3.09 (7.00)	7.01 (10.50)	11.01 (14.25)	15.01 (18.00)	19.01 (21.75)
5	3.96 (8.75)	8.87 (13.25)	13.87 (18.00)	18.87 (22.50)	23.87 (27.25)
6	4.82 (10.50)	10.74 (16.00)	16.74 (21.50)	22.74 (27.00)	28.74 (32.75)

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