METHODS OF ESTIMATION OF URBAN STORM WATER RUNOFF

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Introduction

Storm water hydrology is an area of hydrological practice that is currently the focus of much expenditure aimed at managing both the quantity and quality of runoff from urban environments. The accurately and timely forecasting and warning of likable floods is extremely important for flood protection and mitigation. The reliability of forecasting greatly depends on the understanding of hydrological process, the data collection and processing, as well as telecommunication systems.

Models can be classified as dealing with only water quantities versus also dealing with sediment and/or other water quality constituents. Watershed modeling techniques can be characterized as being, to various degrees, empirical or conceptual. The term empirical implies that a technique is based on observations or gauged data rather than on theoretical considerations. Conceptual or theoretical models are based on general principles or ideas regarding the basic processes of concern. Some of the models consist of conceptual based equations with values for various parameters estimated from empirical information. Others are purely empirical, having been developed from analyses of field observations.
The objective of modeling an urban watershed is to predict its response to a single or a series of storm events. A mathematical urban watershed model is a set of one or more mathematical expressions believed to describe the rainfall-runoff processes that would occur in actual urban drainage systems. Mathematical models can be classified into two categories: distributed and lumped models. Distributed models consider the hydrologic processes occurring at various points within an urban watershed. An extreme example would be a model that considers the runoff processes taking place over every single roof, and in every single street gutter, manhole and storm sewer. Distributed models are generally feasible only

when a computer program is used. In the lumped watershed models, the hydrological characteristics of the entire watershed are lumped into one or more parameters, simple abstract mathematical expressions or graphs. Although the nature of the different elements of the urban watershed can be considered in assigning numerical values to the lumped model parameters, the model does not simulate the hydrologic processes taking place in these elements individually. Spatial variations are not allowed in the model input, and the model predicts the response of the watershed as a whole.

BASIC DEFINITIONS:

Return Period:

It is defined as the average number of years between the occurrences of hydrological event with a certain magnitude or greater. It should be proportional to life of project.

Unit Hydrograph:

The unit hydrograph of a basin is defined as a hydrograph of direct runoff resulting from 1cm of effective rainfall applied uniformly over the basin area at a uniform rate during a specified period of time.

Time of Concentration (T_C)

Defined as the time required for a drop of water to travel from the most hydrologically remote point in the catchment to the outlet point. It is a function of the topography, geology, and land use within the watershed. Time of concentration is useful in predicting flow rates that would result from hypothetical storms, which are based on statistically-derived return periods.

IDF Curve: IDF stands for Intensity-Duration-Frequency. This curve indicates the relationship between the intensity (I) and duration (D) of a rainfall event with a given return period (T). An IDF Curve is a tool that characterizes an area's rainfall pattern.

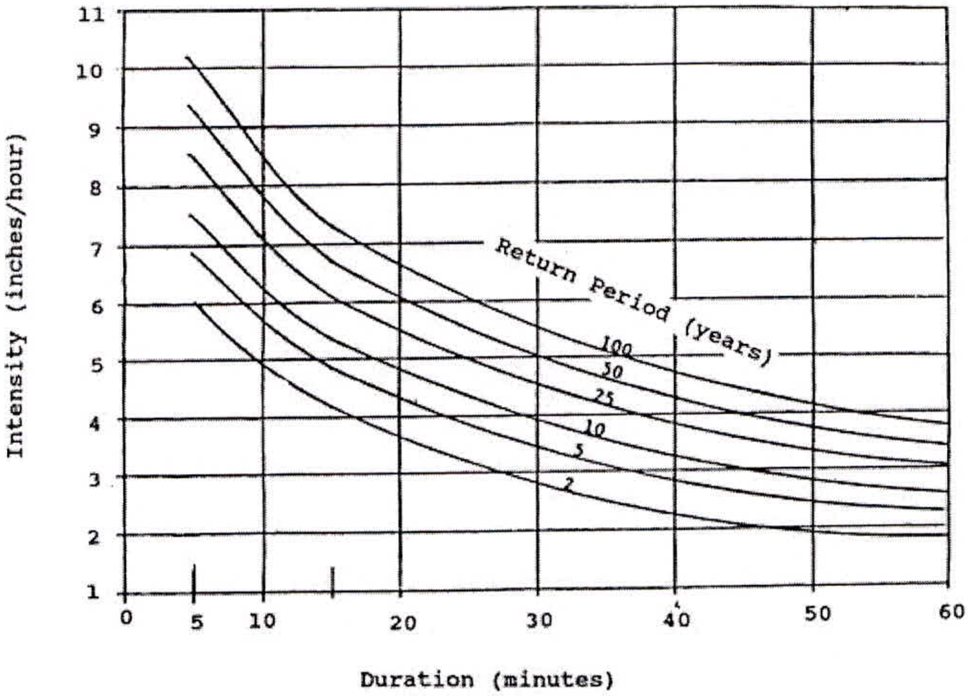

Figure: I-D-F Curve

Modeling Approaches:

- Watershed time of concentration and lag time estimation methods
- Peak discharge from the intensity-duration-frequency(IDF) relationship : Rational method
- Runoff volumes for given rainfall depths: the National Resource Conservation Services (NRCS) Curve Number (CN), Green and Ampt, and Horton methods.
- Unit hydrograph approach for transforming runoff volumes to stream flow hydrographs.

  -unit hydrograph from gauged flows

  -NRCS, snyder, and Clark synthetic unit hydrographs

Rational Method

Rational Method is widely used to estimate the peak surface runoff rate for design of a variety of drainage structures, such as a length of storm sewer, a storm water inlet, or a storm water detention pond. The Rational Method is most suitable for small urban watersheds that don't have storage such as ponds or swamps. It is best for areas less than 100 acres.

The Formula is Q = C I A

where Q is the peak surface runoff rate in cfs,
A is Drainage area in acres,
I is Design Intensity of Rainfall in inch/hour
C is Runoff coefficient

The runoff coefficient is the fraction of rainfall striking the drainage area that becomes runoff from that drainage area. It is an empirically determined constant, dependent on the nature of the drainage area surface.

Type of Area	Runoff Coefficient Values
Concrete Pavement	0.70-0.95
Parks	0.10-0.25
Downtown Business	0.70-0.95
Residential Area	0.30-0.50

The design rainfall intensity is the intensity of a constant intensity design storm with the specified design return period and duration equal to the time of concentration of the drainage area. Once the design return period and duration are determined, the design rainfall intensity can be determined from an appropriate intensity-duration-frequency graph or equation for the location of the drainage area.

SCS CURVE METHOD:

The runoff curve number (also called a Curve Number or simply CN) is an empirical parameter used in hydrology for predicting direct runoff or infiltration from rainfall excess. The curve number method was developed by the USDA Natural Resources Conservation Service, which was formerly called the Soil Conservation Service or SCS, the number is still popularly known as a "SCS runoff curve number" in the literature. The runoff curve number was developed from an empirical analysis of runoff from small catchments and hill slope plots monitored by the USDA. It is widely used and efficient method for determining the approximate amount of direct runoff from a rainfall event in a particular area.

The runoff curve number is based on the area's hydrologic soil group, land use, treatment and hydrologic condition. References, such as from USDA indicate the runoff curve numbers for characteristic land cover descriptions and a hydrologic soil group.

The basic assumption of the SCS curve number method is that, for a single storm, the ratio of actual soil retention after runoff begins to potential maximum retention is equal to the ratio of direct runoff to available rainfall. This relationship, after algebraic manipulation and inclusion of simplifying assumptions, results in the following equation, where curve number (CN) represents a convenient representation of the potential maximum soil retention, S
The runoff equation is

$$Q = \frac{(P - I_a)^2}{P - I_a + S}$$

Where Q is runoff (inches)
P is rainfall (inches)
S is the potential maximum soil moisture retention after runoff begins (inches)
Ia is the initial abstraction (inches), or the amount of water before runoff, such as infiltration, or rainfall interception by vegetation; and Ia = 0.2 S

The runoff curve number, CN, is then related

$$S = \frac{1000}{CN} - 10$$

CN has a range from 30 to 100; lower numbers indicate low runoff potential while larger numbers are for increasing runoff potential. Depending on the hydrologic soil group and the land use practices, a runoff curve number, CN is assigned to a catchment.

Table: Hydrologic Soil Group Definitions

Group	Meaning	Saturated Hydraulic Conductivity (in/hr)
A	Low runoff potential. Soils having high infiltration rates even when thoroughly wetted and consisting chiefly of deep, well to excessively drained sands or gravels E.g., sand, loamy sand and sandy loam	≥ 0.45
B	Soils having moderate infiltration rates when thoroughly wetted and consisting chiefly of moderately deep to deep, moderately well to well-drained soils with moderately fine to moderately coarse textures. E.g., shallow loess, sandy loam.	0.30 – 0.15
C	Soils having slow infiltration rates when thoroughly wetted and consisting chiefly of soils with a layer that impedes downward movement of water, or soils with moderately fine to fine textures. E.g., clay loams, shallow sandy loam.	0.15 – 0.05
D	High runoff potential. Soils having very slow infiltration rates when thoroughly wetted and consisting chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a clay-pan or clay layer at or near the surface, and shallow soils over nearly impervious material.	0.05 – 0.00

Table: Runoff Curve Numbers for urban areas (SCS, 1986)

Description of Land Use	**Hydrologic Soil Group**			
	A	**B**	**C**	**D**
Paved parking lots, roofs, driveways	98	98	98	98
Streets and Roads:				
Paved with curbs and storm sewers	98	98	98	98
Gravel	76	85	89	91
Dirt	72	82	87	89
Cultivated (Agricultural Crop) Land :				
Without conservation treatment (no terraces)	72	81	88	91
With conservation treatment (terraces, contours)	62	71	78	81
Pasture or Range Land:				
Poor (<50% ground cover or heavily grazed)	68	79	86	89
Good (50-75% ground cover; not heavily grazed)	39	61	74	80
Meadow (grass, no grazing, mowed for hay)	30	58	71	78
Brush (good, >75% ground cover)	30	48	65	73
Woods and Forests:				
Poor (small trees/brush destroyed by over-grazing or burning)	45	66	77	83
Fair (grazing but not burned; some brush)	36	60	73	79
Good (no grazing; brush covers ground)	30	55	70	77

Open Spaces (lawns, parks, golf courses, cemeteries, etc.):				
Fair (grass covers 50-75% of area)	49	69	79	84
Good (grass covers >75% of area)	39	61	74	80
Commercial and Business Districts (85% impervious)	89	92	94	95
Industrial Districts (72% impervious)	81	88	91	93
Residential Areas:				
1/8 Acre lots, about 65% impervious	77	85	90	92
1/4 Acre lots, about 38% impervious	61	75	83	87
1/2 Acre lots, about 25% impervious	54	70	80	85
1 Acre lots, about 20% impervious	51	68	79	84

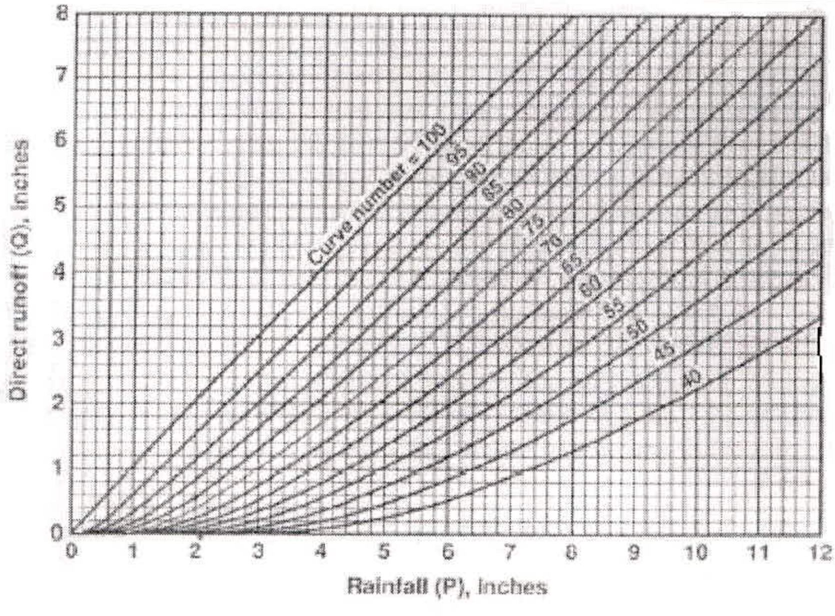

Figure: Graphical solution of SCS curve number

Tabular Hydrograph Method

This method can develop partial composite flood hydrographs at any point in a watershed by dividing the watershed into homogeneous sub areas. For each sub area, the following need to know the size of the drainage area, time of concentration, runoff curve and number and travel time from the sub area outlet to the watershed outlet.

The contribution of an individual sub area to discharge at the watershed outlet at any time is calculated from

$$q = q_r * A_m * Q$$

Where q = discharge coming from a sub area at time t (cfs)

q_r = unit discharge at time t (cfs/mi^2/in)

A_m = drainage area of sub area (mi^2)

Q = depth of rainfall excess or runoff (in)

To find the total discharge at the watershed outlet at any time, the contributions from different sub area are summed.

The Santa Barbara Urban Hydrograph Method

The Santa Barbara urban hydrograph (SBUH) method was first developed for the water conservation district. It was originally meant for desktop computer. However, due to the ease of application, the method can be used manually. In SBUH method the impervious portion of the urban watershed is assumed to be directly connected to the drainage system, and the losses from rain falling on impervious areas are neglected. To determine the losses from rainfall over pervious areas, the SCS curve number technique or any other method of preference can be employed. The SBUH method combines the runoff from pervious and impervious areas to develop an instantaneous runoff hydrograph. The instantaneous hydrograph is then routed through an imaginary reservoir that causes a time delay equal to the time of concentration of the watershed.

The computation are carried over constant time intervals of Δt .For any time interval the ordinate of the instantaneous hydrograph is calculated, using a consistent unit system, as

$$I = [i^*d + i_e(1.0 - d)]\ A$$

Where I = ordinate of the instantaneous hydrograph

i = rate of rainfall

i_e = rate of rainfall excess for pervious area

d = impervious area as a fraction of total area

A = total drainage area

The runoff hydrograph at the watershed outlet is determined using

$$Q_i = Q_{j-1} + k_r\ (I_{j-1} + I_J - 2Q_{J-1})$$

$$\mathbf{K_r} = \frac{\Delta t}{2Tc + \Delta t}$$

Where Q = watershed discharge

T_c = time of concentration

The subscripts j-1 and j denote sequent time intervals. In the above equation T_c and Δt must have the same unit of time.

SCS Time of Concentration Method

The soil concentration service method identifies the flow types occurring in a watershed as sheet flow, shallow concentrated flow, and channel flow. For shallow concentrated and channel flows, the travel time is defined as

$$\mathbf{T_f} = \frac{L}{3600V}$$

Where T_f = travel time (hr)

L = flow length (ft)

V = average flow velocity (fps)

The time of concentration, Tc, is calculated as being the sum of the T_f values for the consecutive flow segments.

Formulae based on Area:

Dickens Formula:

$$Q = C*A^{3/4}$$

Where Q = maximum flood discharge (m^3/sec)

A = catchment area (km^2)

C = Dickens constant with value between 6 to 30

Ryves Formula:

$$Q = C*A^{2/3}$$

Where Q = maximum flood discharge (m^3/sec)

A = catchment area (km^2)

C = Ryves constant

Areas within 80 km from the coast is 6.75

Areas within 80 to 2400 km from the coast is 8.45

Limited areas near hills 10

Inglis formula:

$$Q = (124*A) / \mathrm{sqrt}(A+10.4)$$

Q is in m^3/sec and A is in km^2

Formulae with Recurrence Interval:

The formulae, which give the flood discharge in terms of the recurrence interval, are preferable as the flood event is actually random phenomenon.

Fuller's Formula:

$$Q_{avg} = C\,A^{0.8}$$

$$Q = Q_{avg} * (1 + 0.8 \log T_{r)}$$

$$Q_{max} = Q * (1 + 2.66\,A^{-0.3})$$

Where A is area in sq. km;

T_r is the return period in years;

Q_{avg} is yearly average flood;

Q is maximum 24 hour flood with return period of T_r years and

Q_{max} is the maximum instantaneous discharge.

The coefficient C varies from 0.026 to 2.77.

Horton's Formula:

$$Q = 114\,Tr^{\,0.25} / A$$

Where Q is flood discharge in m^3/sec per km^2 with a return period of T_r years, A is the drainage area in km^2.

Pettis Formula:

$$Q = C * (P * B)^{\,1.25}$$

Where Q= flood discharge with return period of 100 years in m^3/sec

P= one day rainfall with 100 years return period in cm.

B= the average width of the basin in km

C=a coefficient varying from about 1.51 in humid areas to 0.195 in desert areas.

Common Urban Hydrology Models

RRL: (Road Research Laboratory Method and Illinois Simulator) an urban runoff model that utilize the time -area runoff routing method. It was developed in England and described by Watkins 1962. The technique was developed specifically for the analysis of urban runoff and ignores completely all pervious areas and all impervious areas that are not directly connected to the storm drain system; hence estimates of peak flow rates and runoff volumes are likely to be low.

SWMM: (Storm Water Management Model) A very widely accepted and applied storm runoff simulation model was jointly prepared by Metcalf and Eddy 1971, Inc., the University of Florida, and Water Resources Engineers for use by the U.S. Environmental. Protection Agency (EPA). This model was designed to simulate the runoff of a drainage basin for any predescribed rainfall pattern. The total watershed is broken into a finite number of smaller units or sub catchments that can be readily described by their hydraulic properties.

ILLUDAS: (Illinois Urban Drainage Area Simulator) developed by Terstriep and Stall (1974). This model is an improved version of RRL that has a wider range of capabilities. It incorporates the impervious area neglected by RRL and is a demonstrated improvement over RRL.

UCURM: (University of Cincinnati Urban Runoff Model) This model is developed by the Division of Water Resources, the Department of Civil Engineering, University of Cincinnati in 1972. It is similar to EPA model and divides the drainage basin into sub catchments whose flows are routed overland into gutters and sewers pipes. Starting at the upstream inlet, the flows are calculated in successive segments of the sewer system, including discharges from inlets, to produce the total outflow.

EDI-QUAL-I: is developed by Willis, Anderson and Dracup (1975) and the modeling procedure consists of breaking up the river system into reach and routing the governing over each reach and finally determining initial concentration of conservative and non-conservative constituents for each reach.

HEC-l: (Flood Hydrograph Package) is designed for the simulation of flood events in watersheds and river basins. Similar model has been developed by Kidd, (1978); Falk and

Niemczynowicz (1979) to simulate rainfall-runoff, which are applicable on small, impermeable urban catchments.

GIUH: Gupta (1983) and Bhattacharya (1995) have developed similar numerical models for simulation of rainfall-runoff processes in urban catchments.

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