1 Introduction

Adequate scientific evidence (e.g., IPCC, 2007) exists now to show that the global climate is changing. The three prominent signals of climate change, namely, increase in global average temperature, rise in sea levels, and change in precipitation patterns, convert into signals of regional-scale hydrologic change in terms of modifications in extremes of floods and droughts, water availability, water demand, water quality, salinity intrusion in coastal aquifers, groundwater recharge, and other related phenomena. Increase in atmospheric temperature, for example, is likely to have a direct impact on river runoff in snow-fed rivers and on the evaporative demands of crops and vegetation, apart from its indirect impacts on all other processes of interest in hydrology. Similarly, a change in the regional precipitation pattern may have a direct impact on magnitude and frequency of floods and droughts and water availability. Changes in precipitation patterns and frequencies of extreme precipitation events, along with changes in soil moisture and evapotranspiration, will affect runoff and river discharges at various time scales from sub-daily peak flows to annual variations. At sub-daily and daily time scales, flooding events are likely to cause enormous socio-economic and environmental damage, which necessitates the use of robust and accurate techniques for projections of flood frequencies and magnitudes under climate change, and development of flood protection measures to adapt to the likely changes. Knowledge about hydrologic modeling and use of GCMs is critical in planning and operation for flood management under climate change. The main objective of this book is to provide a basic background on hydrologic modeling, impact assessment methods, uncertainties in impacts, and use of satellite products for enhancing the capability of the models.

This chapter provides the background and a brief introduction to the topics covered in the book.

1.1 HYDROLOGIC MODELS

Hydrologic models are concerned with simulating natural processes related to movement of water, such as the flow of water in a stream, evaporation and evapotranspiration, groundwater recharge, soil moisture, sediment transport, chemical transport, growth of microorganisms in water bodies, etc. The hydrologic processes that occur in nature are *distributed*, in the sense that the time and space derivatives of the processes are both important. The hydrologic models are classified as distributed models or lumped models depending on whether the models consider the space derivatives (distributed) or not (lumped). The semi-distributed models account for spatial variations in some processes while ignoring them in others. On any time scale, the models may be discrete or continuous in time. Flood management requires models for two consecutive phases: planning and operation, which demand different kinds of models. Plate (2009) provides a classification of hydrologic models specifically for flood management. The different levels of hydrologic models considered by Plate (2009) are: (i) the data level, consisting of the GIS and data banks at different time scales, such as seasonal and event scales; (ii) the model level, consisting of (a) a basic hydrologic model incorporating the topography, digital terrain models, channel networks, sub-catchments, and long-term water and material balance and (b) a transport model operating at seasonal and event scales; (iii) the output level, which provides outputs in terms of maps and tables for use in decision-making; and (iv) the decision level, which uses information provided by the output level, for arriving at management decisions. Hydrologic models for floods function on the basis of partitioning the rainfall into various components. Several hydrologic models are available to estimate the peak flood discharge, flood hydrograph at specified locations in a catchment, and for flood routing. The models differ essentially with respect to the methods used for estimating the various hydrologic components and assumptions made, and with respect to how they account for the distributed processes on spatial scales. Hydrologic models typically operate at a river basin or a watershed scale. They play a significant role in providing an understanding of a range of problems dealing with water resources and hydrologic extremes at river basin and watershed scales. These problems could be, for example, the magnitude and duration of flood discharges for specified intensities and durations of rainfall, movement of a flood wave along a river extent of water backing up due to an obstruction to flow caused by a dam and other structure, sediment deposition and bank erosion, and so on. The inputs required by hydrologic models depend on the purpose for which the model is built. A river flow simulation model, for example, will need inputs such as precipitation, catchment characteristics such as the soil type, slope of the catchment, type of vegetation, type of land use, temperature, solar radiation groundwater contribution, etc. The typical output from such a model includes the river flow at a location during a period (such as a day, a week, or a month), and soil moisture and evapotranspiration during the period.

A number of hydrologic models, with user-friendly interfaces, are freely available today for useful applications. These include the hydrologic models developed by the US Army Corps of Engineers (e.g., the HEC-HMS and the HEC-RAS), the SWMM developed by the US Environmental Protection Agency (USEPA), the AVSWAT (Neitsch *et al*., 2000, 2001), and the VIC (Liang *et al*., 1994; Gao *et al*., 2010) models. Such models, along with the global data sets, are extremely useful in assessing the possible impacts of climate change on regional hydrology, especially in developing countries with limited resources, data, and capacity. Recently developed empirical models, such as those based on artificial neural networks and fuzzy logic, are useful in real-time flood forecasting.

1.2 REMOTE SENSING FOR HYDROLOGIC MODELING

Remote sensing (RS) is the art and science of obtaining information about an object or feature without physically coming into contact with that object or feature. It is the process of inferring surface parameters from measurements of the reflected electromagnetic radiation (EMR) from the Earth's surface. Satellite RS provides the essential inputs required for more effectively modeling different components of the hydrologic cycle. Remote sensing provides a means of observing hydrologic states or fluxes over large areas with a synoptic view. Remote sensing applications in hydrology have primarily focused on developing approaches for estimating hydrometeorological states and fluxes. The primary set of variables include land use, land cover, land surface temperature, near-surface soil moisture, snow cover/water equivalent, water quality, landscape roughness, and vegetation cover. The hydrometeorological fluxes of interest are evaporation and plant transpiration (or evapotranspiration) and snowmelt runoff.

The spectral reflectance curve of a particular feature is a plot of the spectral reflectance of that feature versus wavelength. Spectral reflectance curves of different features on the Earth's surface, such as vegetation, soil, and water, help in identifying various spectral bands that are useful in estimating different land surface features. For example, for vegetation monitoring, the red and near-infrared (NIR) bands of EMR are useful.

The concepts of color composites and false color composites are essential to visualize and interpret the spectral reflectance information available beyond the visible region, such as in the NIR and thermal-IR regions of EMR. It is important to understand various characteristics of satellite RS systems, such as spatial resolution, spectral resolution, radiometric resolution, and temporal resolution, to interpret digital images. Digital image processing techniques are continually evolving for rectification, enhancement, and information extraction of satellite images. Information extraction from microwave and hyperspectral images requires special image processing techniques.

Satellite RS has played a significant role in identification of potential flood zones, flood hazard estimation, flood inundation mapping and mitigation. The distributed hydrologic models may be rendered more effective with use of data from satellite RS. In the recent past, specialized RS satellites and space missions have been launched to obtain detailed information on soil moisture and hydrometeorological fluxes. They include the Soil Moisture and Ocean Salinity (SMOS) Satellite, the Global Precipitation Measurement (GPM) Mission, the Tropical Rainfall Measuring Mission (TRMM), and Megha-Tropiques. Data available from these and other similar satellite missions will facilitate better modeling of various components of the hydrologic cycle and better estimation of hydrometeorological states and fluxes.

Many regions on the globe, such as oceans, deserts, polar regions, and uninhabited regions, suffer from lack of ground-based measurements of hydrometeorological variables. Prediction in ungauged basins is a major challenge for the hydrologist. Satellite RS plays a vital role in providing the essential inputs required in addressing this challenge.

1.3 GIS AND DEM FOR HYDROLOGIC MODELING

A geographic information system (GIS) is an excellent tool for stacking, analyzing, and retrieving large numbers of non-spatial and geo-spatial databases including RS images. It is essential to understand representations of spatial features and various formats in which spatial databases are stored on GIS. Distance-based proximity tools in GIS are useful for analyzing and interpreting multiple spatial databases. Web-based GIS facilitate integration of various spatial and non-spatial databases available at different locations for hydrologic modeling and dissemination of the results and decisions to remote locations in real time.

Digital elevation models (DEMs) are powerful tools to analyze the digital elevation data available at regular grid spacing. DEMs provide essential inputs about the topographical features of a river basin, such as slope/aspect, flow direction, flow pathways, flow accumulation, stream network, catchment area, upstream contributing area for each grid cell, etc. The D8 algorithm is very useful in interpreting digital elevation data to extract the above-mentioned features. Satellite and space shuttle missions are launched specifically to provide digital elevation data over the globe using radar interferometry and light detection and ranging (LIDAR). These missions include the Shuttle Radar Topography Mission (SRTM), the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) onboard the Terra satellite and LIDAR sensors.

Integration of RS, GIS, and DEM into a distributed hydrologic model will significantly improve the modeling of various components of the hydrologic cycle. Such integration has played a vital role in near-real-time monitoring of flood events, and their damage estimation and mitigation.

1.4 ASSESSMENT OF CLIMATE CHANGE IMPACTS

It is important to distinguish between climate change and climate variability. *Climate change* refers to a change in the state of the climate that persists for an extended period, typically decades or longer, as distinct from *climate variability*, which refers to variations in the mean state and other climate statistics, on all space and time scales. The year to year variations in the rainfall at a location, for example, indicate climate variability, whereas a change in the long-term mean rainfall over a few decades is a signal of climate change. In this book, we are concerned with assessment of the hydrologic impacts of *climate change*.

Climate change is generally expected to increase the intensity (flood discharges) and duration of floods. However, there will be a large variation in how the hydrology of different regions responds to signals of climate change. Regional assessment of the impacts of climate change is therefore important. A commonly adopted methodology for assessing the regional hydrologic impacts of climate change is to use the climate projections provided by the GCMs for specified emissions scenarios in conjunction with the process-based hydrologic models to generate the corresponding hydrologic projections. The scaling problem arising because of the large spatial scales at which the GCMs operate compared to those required in most distributed hydrologic models is commonly addressed by downscaling the GCM simulations to hydrologic scales. This commonly used procedure of impact assessment is burdened with a large amount of uncertainty due to the choice of GCMs and emissions scenarios, small samples of historical data against which the models are calibrated, downscaling methods used, and several other sources. Development of procedures and methodologies to address such uncertainties is a current area of research. Vulnerability assessment, adaptation to climate change, and policy responses all depend on the projected impacts, with quantification of the associated uncertainty.

General circulation models, also commonly known as global climate models, are the most credible tools available today for projecting the future climate. The GCMs operate on a global scale. They are used for weather forecasting, understanding climate, and projecting climate change. They use quantitative methods to simulate the interactions of the atmosphere, oceans, land surface, and ice. The most frequently used models in the study of climate change are the ones relating air temperature to emissions of carbon dioxide. These models predict an upward trend in the surface temperature, on a global scale. A GCM uses a large number of mathematical equations to describe physical, chemical, and biological processes such as wind, vapor movement, atmospheric circulation, ocean currents, and plant growth. A GCM relates the interactions among the various processes. For example, it relates how the wind patterns affect the transport of atmospheric moisture from one region to another, how ocean currents affect the amount of heat in the atmosphere, and how plant growth affects the amount of carbon dioxide in the atmosphere and so on. The models help in providing an understanding of how the climate works and how the climate is changing. A typical climate model projection used in the impact studies is that of global temperatures over the next century. GCMs project an increasing trend in the global average temperature over the next century, with some estimates even showing an increase of more than 4 °C with respect to the temperature during 1980–99 (e.g., see IPCC, 2007). Such projections of temperature and other climate variables provided by GCMs are used to obtain projections of other variables of interest (but which are not well simulated by GCMs), such as precipitation and evapotranspiration, in the impact studies.

GCMs are more skillful in simulating the free troposphere climate than the surface climate. Variables such as wind, temperature, and air pressure can be predicted quite well, whereas precipitation and cloudiness are less well predicted. Other variables of key importance in the hydrologic cycle, such as runoff, soil moisture, and evapotranspiration are not well simulated by GCMs. Runoff predictions in GCMs are over-simplified and there is no lateral transfer of water within the land phase between grid cells (Xu, 1999a; Fowler *et al.*, 2007). The GCM simulation of rainfall has been found to be especially poor. The ability of GCMs to predict spatial and temporal distributions of climatic variables declines from global to regional to local catchment scales, and from annual to monthly to daily amounts. This limitation becomes particularly pronounced in assessing likely impacts of climate change on flood frequencies and magnitudes of flood peak flows. Flood peak flows in a catchment are generated by high-intensity storms of durations typically ranging from a few hours to a few days. At these time scales the simulations provided by GCMs are almost of no direct consequence. Stochastic disaggregation techniques have been used to disaggregate the longer time simulations provided by the GCMs to the shorter time events necessary in flood hydrology studies. The spatial scale mismatch between the scales of GCM simulations (with grid size of the order of tens of thousands of square kilometers) and those typically required for hydrologic modeling (with spatial scales of the order of a few hundred square kilometers and less) is classically addressed by spatial downscaling.

The impacts of climate change on floods are essentially assessed in the planning context by addressing the likely changes in the frequencies of given magnitudes of flood discharges. Flood frequencies are believed to be increasing due to climate change. High-resolution regional climate projections are necessary for assessing, with reasonable confidence, such impacts on flood frequencies. To overcome the limitations due to the coarse resolution of most existing GCMs, approaches such as stochastic weather generators and delta change methods are employed to examine the likely change in flood frequency due to climate change. Quantification of uncertainties in the projected impacts is particularly critical in the context of flood management, due to the huge economic implications of the adaptation measures.

1.5 ORGANIZATION OF THE BOOK

This book presents methodologies for hydrologic modeling of floods and for assessing climate change impacts on flood magnitudes and frequencies. The following topics are covered with a view to training the reader in the use of hydrologic models with climate change scenarios: (i) physical processes that transform precipitation into flood runoff; (ii) flood routing; (iii) assessing likely changes in flood frequencies and magnitudes under climate change scenarios and quantifying uncertainties; and (iv) use of RS, GIS, and DEM technologies in modeling of floods to aid decision-making. This chapter, Chapter 1, sets the scene and provides an introduction to climate change impacts on hydrology.

The objective of Chapter 2 is to provide the necessary background on hydrologic models for use in planning and operations related to floods. The chapter includes a brief review of hydrologic models and presents the use of empirical models for flood forecasting and flood routing.

Chapter 3 presents methodologies commonly employed to obtain projections of floods under future climate change, with GCMs and hydrologic models. The use of climate change scenarios developed by the Intergovernmental Panel on Climate Change (IPCC) and issues of spatio-temporal scale mismatches between GCMs and hydrologic models are explained in this chapter. A review of techniques for downscaling large-scale atmospheric variables to station-scale hydrologic variables is also provided. Applications of macroscale hydrologic models and hypothetical scenarios for generating future projections as an alternative to downscaling are discussed.

Chapter 4 introduces RS, covering the topics of spectral reflectance curves, RS platforms, digital images, and image processing including rectification, enhancement, and information extraction. The role of RS in hydrologic modeling is elaborated. Recent satellite missions for precipitation and soil moisture estimation are elaborated. Image processing techniques are demonstrated using MATLAB.

Chapter 5 presents GIS and DEMs for hydrologic modeling. Representation of spatial objects and different data formats in GIS is discussed. Types of DEMs, sources of DEM data, and extraction of drainage pattern and sub-watersheds using the D8 algorithm are explained and illustrated. The roles of RS and GIS in flood zone and flood inundation mapping are explained in the chapter. Web-based GIS and its role in integrating various spatial and non-spatial databases available at different locations for hydrologic modeling are also discussed.

Synthesis of climate change impacts, uncertainties, RS, GIS, DEM, and hydrologic models is explained and demonstrated through two case studies in Chapter 6. Future perspectives on hydrologic modeling under climate change are presented in this chapter.

2 Hydrologic modeling for floods

2.1 INTRODUCTION

The objective of this chapter is to provide the necessary background on hydrologic models for use in planning and operations related to floods. Partitioning of precipitation into different components is discussed briefly first. These components include the channel flow, overland flow, unsaturated flow, groundwater flow, soil moisture storage, surface storage, infiltration, interception, and evapotranspiration. The concept of excess rainfall and direct runoff is introduced next. The commonly used SCS curve number method and the rational method to estimate the flood discharge in a watershed are introduced. Hydrologic and kinematic flood routing, empirical models of artificial neural networks, and fuzzy inference systems for forecasting river discharges and flood routing are discussed. A focus of the chapter is on the modeling approach to be adopted in data-scarce regions, especially in countries where many river basins are poorly gauged, and data on river discharges, soil types, land use patterns, and catchment characteristics are not readily available. Information on global data sets that may be useful in such situations is provided. A review of commonly used hydrologic models in decision-making for flood modeling is given, along with a list of references where model applications are discussed. On going through this chapter, it is expected that the reader will become well versed in procedures for estimating flood discharges and in the use of hydrologic models for estimating and predicting flood discharges for use in decision-making.

2.1.1 Partitioning of rainfall

Hydrologic models for floods function on the basis of partitioning the rainfall into various components. Several hydrologic models are available to estimate the flood hydrograph at specified locations in a catchment and for flood routing. The models differ essentially with respect to the methods used for estimating the various hydrologic components and assumptions made, and with respect to how they account for the distributed processes in spatial scales. In the context of floods, estimating the flood runoff volume and hydrograph resulting from a given storm is a critical exercise, and therefore generation of flood runoff from a storm is first discussed. Figure 2.1 shows the various processes that take place once the precipitation occurs. As the precipitation falls, part of it is *intercepted* by vegetation and other surfaces and this part will not be available for runoff immediately during a storm. Once the precipitation reaches the land surface, part of it may *infiltrate* into the soil. Part of the rainfall is also trapped by surface depressions including lakes, swamps, and smaller depressions down to the size of small grain size cavities. A small amount is also lost as *evaporation* from bare surfaces and, from vegetation, as *evapotranspiration*. The infiltrated water may join the stream (channel) as interflow or may add to the aquifer recharge and deep groundwater storage. The direct runoff, or rainfall excess, is that part of the rainfall from which all losses have been removed and which eventually becomes flood runoff. As seen from Figure 2.1, the direct runoff hydrograph consists of contributions from the channel input to the streamflow through various routes of overland flow, interflow (throughflow), and groundwater flow.

2.1.2 Overland flow

As the rainfall intensity increases, and exceeds the infiltration capacity of the soil, water starts running off in the form of a thin sheet on the land. This type of flow is called Hortonian overland flow. The runoff rate in a Hortonian overland flow may be simply estimated by $(I - f)$, where I is the rainfall intensity in cm/hr and f is the infiltration capacity of the soil, also in cm/hr. When the rainfall intensity is less than the infiltration capacity of the soil, all of the rainfall is absorbed by the soil as infiltration. Hortonion overland flow is the most commonly occurring overland flow. The sheet of overland flow is quite thin before it joins a channel, to become channel flow. The *detention storage* – the storage that is held by the sheet flow corresponding to the depth of overland flow – contributes continuously to the channel flow, whereas part of the *retention storage*, held by surface depressions, is released slowly to the streams in the form of subsurface flow or is lost as evaporation. Other parts of the retention storage may add to the infiltration and subsequently recharge the groundwater.

Hortonian overland flow occurs when the soil is saturated from above by precipitation. Saturated overland flow, on the other hand, occurs when the soil is saturated from below – most commonly

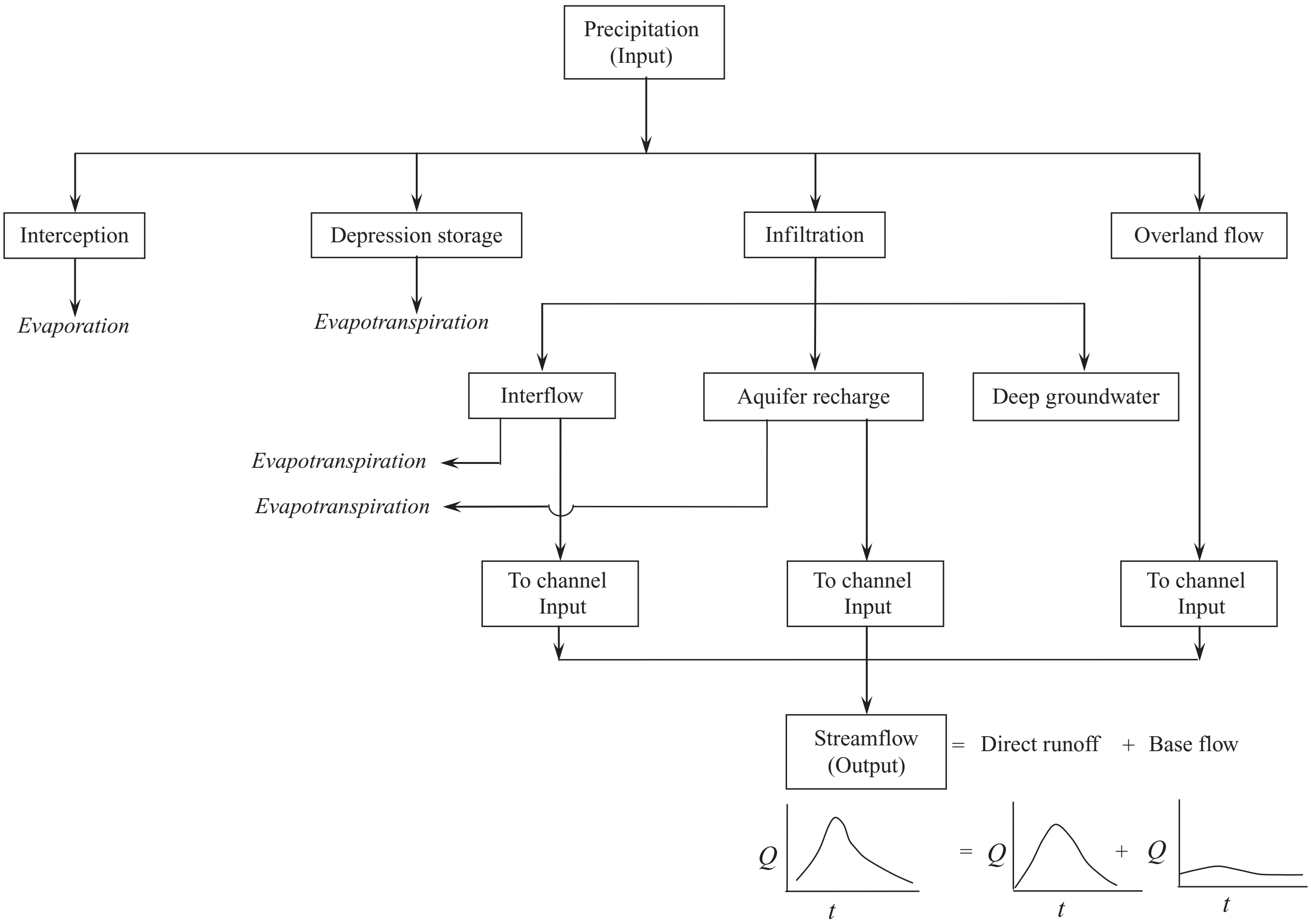

Figure 2.1 Partitioning of precipitation (Modified from Viessman *et al*., 1989; Mays, 1996).

because of subsurface flow. Saturation overland flow occurs commonly at valleys and near river banks. *Throughflow* occurs through macropores in the soil such as cracks, animal holes, and roots. Throughflow reaches the stream channel relatively quickly.

All three types of overland flows – Hortonian overland flow, saturated overland flow, and throughflow – may occur simultaneously during a storm. It is also possible that only a part of a drainage basin – and not the entire basin – may be contributing to the flood runoff at a location. This part of the drainage area, called the *source area*, may be different for different storms in the drainage basin and may also change within the same storm as the storm evolves.

2.1.3 Excess rainfall and direct runoff

Excess rainfall is that part of the rainfall that directly contributes to the runoff – it is neither retained in storage nor is lost as infiltration, interception, and evapotranspiration. Direct runoff is caused by excess rainfall after it travels over the surface as Hortonian overland flow. In flood studies, obtaining the direct runoff hydrograph (DRH) from an observed total runoff hydrograph is an important step. Procedures for obtaining a DRH from a total runoff hydrograph and methods of estimation of various losses or abstractions are available in standard textbooks (e.g., Chow *et al*., 1988; Singh, 1992), and are not discussed here.

Two procedures – the SCS curve number method and the rational formula – for estimation of flood runoff are discussed here. These methods may be used for estimating flood runoff and flood peaks for hydrologic designs, even with limited data. Many commonly used hydrologic models employ these methods for flood runoff estimation.

2.2 ESTIMATION OF FLOOD PEAK DISCHARGE

2.2.1 Soil Conservation Service curve number method

Estimating flood runoff from a given storm involves estimating losses from the rainfall. The Soil Conservation Service (SCS) – now called the Natural Resources Conservation Service (NRCS) –

curve number method (Soil Conservation Service, 1969) is the most commonly used and simple method for practical applications. It is based on accounting for infiltration losses from rainfall depending on the antecedent moisture content (AMC) and the soil type. The rainfall is assumed to occur uniformly over the entire watershed, during the storm. The fundamental basis for the SCS curve number method is that the runoff starts after initial losses due to abstractions, I_a, are accounted for. These losses consist of interceptions due to vegetation and built area that prevent the rainfall from reaching the ground immediately after it occurs, surface storage consisting of water bodies such as lakes, ponds, and depressions, and infiltration. An assumption in developing the curve numbers is that the ratio of actual retention of rainfall in the watershed to potential retention, S, in the watershed is equal to the ratio of direct runoff to rainfall minus the initial abstractions, I_a (before commencement of the runoff).

The parameter S depends on the catchment characteristics of soil, vegetation, and land constituting the soil–vegetation–land (SVL) complex (Singh, 1992), and the AMC. With a parameter, CN, to represent the relative measure of water retention on the watershed by a given SVL complex, the potential retention in a watershed with a given SVL complex is calculated as

$$S = \frac{25400}{\mathrm{CN}} - 254 \text{ in millimeters} \tag{2.1}$$

The parameter CN is called the curve number; it takes values between 0 and 100. The value of CN depends on the soil type and the AMC in the watershed. CN has no physical meaning. The equation for runoff (rainfall excess) is given as

$$P_e = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{2.2}$$

The following points must be kept in mind while using the SCS curve number method:

1. CN is a parameter that ranges from 0 to 100. A value of 100 indicates that all of the rainfall is converted into runoff and that there are no losses. Completely impervious and water surfaces are examples of this. For normal watersheds, CN < 100. A value of CN close to 0 indicates that almost all of the rainfall is accounted for losses, indicating highly dry conditions and therefore negligible runoff results.
2. CN has no physical meaning. Since it is the only parameter used to compute the runoff from rainfall, it accounts for the combined effects of soil type, AMCs, and vegetation type on the runoff.
3. The soil group is assumed to be uniform throughout the watershed. The rainfall is assumed to be uniformly distributed over the watershed.
4. When a watershed consists of different soil types, AMCs and vegetation types, a composite CN may be determined for the watershed, as an area-weighted CN.
5. The SCS method, when used to estimate runoff from rainfall that has actually occurred, may produce poor results and is rather heavily dependent on the AMCs assumed for the watershed. It is more useful for estimating design flood runoff resulting from a design storm (see for example, Maidment, 1993).
6. The SCS method may over-predict the volume of runoff in a watershed (Maidment, 1993).
7. The method is generally used for non-urban catchments.

Soils are classified into four groups, A, B, C, and D, based on their runoff potential, with soil group A comprising soils having the lowest runoff potential and soil group D having the highest runoff potential. The AMC accounts for the moisture content in the soil preceding the storm for which the runoff is to be computed. The AMC of the watershed is classified into three groups, I, II, and III, based on the rainfall in the previous 5 days and based on whether it is a growing season or a dormant season.

The SCS curve numbers (now referred to as the NRCS curve numbers) are available in standard textbooks (e.g., Chow *et al.*, 1988; Singh, 1992) and on the Web (e.g., http://emrl.byu.edu/gsda/data_tips/tip_landuse_cntable.html, accessed December 17, 2011).

2.2.1.1 FLOOD HYDROGRAPH FROM THE SCS METHOD

For most hydrologic designs for floods, the peak flood discharge rather than the total flood runoff is of interest. The following procedure may be adopted for constructing the design flood hydrograph, once the flood runoff has been estimated (Maidment, 1993). The time to peak, Tp, is estimated by

$$Tp = 0.5D + 0.6t_c \tag{2.3}$$

where, Tp is the time to peak (hours), D is duration of the rainfall excess in hours, and t_c is the time of concentration in hours. The time of concentration is the time it takes from the beginning of the storm for the entire watershed to contribute to the runoff, and is given by the time it takes for the rain to reach the mouth of the watershed from the remotest part of the watershed. Empirical expressions commonly used to estimate the time of concentration for a watershed are available in standard textbooks (e.g., Chow *et al.*, 1988) The most commonly used is the Kirpich formula (Kirpich, 1940), given below:

$$\begin{aligned} t_c &= 0.0078L^{0.77}S^{-0.385} \\ L &= \text{length of channel/ditch from head water to outlet, ft} \\ S &= \text{average watershed slope, ft/ft} \end{aligned} \tag{2.4}$$

Equating the total runoff volume, V_Q, computed from the SCS method to the area of the triangular direct runoff hydrograph

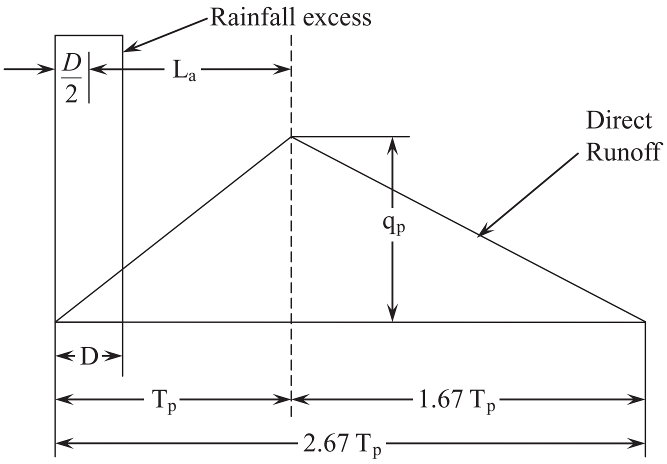

Figure 2.2 SCS triangular hydrograph.

shown in Figure 2.2, the peak discharge, q_p, can be expressed as

$$q_p = \frac{0.208 A V_Q}{0.5D + 0.6t_c} \quad \text{SI units} \tag{2.5}$$

where A is the watershed area in square kilometers, V_Q is runoff in mm, D and t_c are in hours. In Figure 2.2, L_a is the basin lag, which is the time from the centroid of the excess rainfall hyetograph to the centroid of the hydrograph, which in the figure also coincides with the time to peak.

Example 2.1

Compute runoff from 100 mm rainfall from 250 km^2 watershed with the data in Table 2.1. Assume the AMC III condition. Consider the time of concentration of 3 hr and rainfall duration of 3 hr.

Solution

The curve numbers are obtained for the AMC II condition, from Chow *et al.* (1988); the computed weighted curve numbers are presented in Table 2.2.

Table 2.1 *Land use conditions of a watershed*

Land use	Area (%)	Soil group
Residential (30% impervious)	40	B
Forest: Poor cover	20	C
Open space:		
Fair grass	15	D
Good grass	15	D
Impervious parking space, schools, shopping complex, etc.	10	B

Thus,

$$\text{Weighted CN(II)} = \frac{3860 + 1540 + 2460}{100} = 78.6$$

This is for the AMC II condition.

For the AMC III condition,

$$\text{CN(III)} = \frac{23\text{CN(II)}}{10 + 0.13\text{CN(II)}} = \frac{23 \times 78.6}{10 + 0.13 \times 78.6} = 89.41$$

$$S = \frac{25400}{89.41} - 254 = 30.08 \text{ mm}$$

Hence the rainfall excess

$$P_e = \frac{(P - 0.2S)^2}{P + 0.8S} = \frac{(100 - 0.2 \times 30.08)^2}{100 + 0.8 \times 30.08} = 71.19 \text{ mm}$$

The runoff hydrograph is formulated using the time of concentration of 3 hr and the duration of 3 hr.

Table 2.2 *Computation of weighted curve number for Example 2.1, for the AMC II condition*

	Hydrologic soil group								
	B			C			D		
Land use	%	CN	Product	%	CN	Product	%	CN	Product
Residential (30% impervious)	40	72	2880						
Forest: Poor cover				20	77	1540			
Open space:									
Fair condition							15	80	1200
Good condition							15	84	1260
Impervious parking space, schools, shopping complex, etc.	10	98	980						
Total			3860			1540			2460

The components of the SCS triangular hydrograph shown in Figure 2.2 are obtained as follows:

The peak discharge,

$$q_p = \frac{0.208 A V_Q}{0.5D + 0.6t_c}$$

where A: area of the catchment = 250 km^2,
P_e: rainfall excess = 71.19 mm,
D: duration of rainfall = 3 hr,
t_c: time of concentration of the catchment = 3 hr.

$$q_p = \frac{0.208 \times 250 \times 71.19}{0.5 \times 3 + 0.6 \times 3} = 1121.78 \text{ m}^3\text{/s}$$

Time to peak from the start of rainfall, $Tp = 0.5^* D + 0.6^* t_c = 0.5^*3 + 0.6^*3 = 3.3$ hr

Total time base of the hydrograph $= 2.67^* Tp = 8.81$ hr

2.2.2 Rational method

The rational method is most commonly used in urban flood designs but is also sometimes used for non-urban catchments. The rational formula is

$$Q_p = CIA \tag{2.6a}$$

where Q_p is the peak discharge, I is the rainfall intensity, A is the area of the watershed, and C is a dimensionless runoff coefficient. Originally developed in FPS units, the formula may be used in SI units with appropriate units for Q_p, I, and A. For example, if Q_p is in m^3/s, I is in mm/hr, and A is in square kilometers, the rational formula may be written as

$$Q_p = 0.278CIA \tag{2.6b}$$

The rational formula (Equation 2.6a) is developed based on the assumption that the intensity of rainfall, I, is constant over the duration and that the peak flow occurs once the entire watershed starts contributing simultaneously to flow at the outlet of the watershed. This duration is the same as the time of concentration defined earlier (Section 2.2.1).

The rational method is most commonly used for hydrologic designs, rather than for estimating peak flows from actual rainfall. The intensity of the rainfall for design purposes is obtained from the intensity–duration–frequency (IDF) relationship for the watershed (Section 2.3). The frequency used to determine the intensity is the same as that required for the design flood. That is, the average recurrence interval (ARI) or the return period chosen for the hydrologic designs is used as the frequency in the IDF relationship. Duration of the design rainfall is generally taken as the time of concentration, t_c, for design purposes.

Table 2.3 *Land use of catchment*

Land use	Area (%)
Residential (30% impervious)	40
Forest: Poor cover	20
Open space:	
Fair grass	15
Good grass	15
Impervious parking space, schools, shopping complex, etc.	10

Table 2.4 *Design rainfall intensity of catchment*

Catchment	Design rainfall intensity (mm/hr)
Residential	150
Forest	75
Open land	100

The coefficient of runoff, C, for a given watershed is a major source of uncertainty in the rational method. The coefficient, as seen from the rational formula, Equation 2.6a, aggregates the effect of soil type, AMC, vegetation, land use, degree of soil compaction, depression storage, catchment slope, rainfall intensity, proximity to water table, and other factors that determine the peak runoff for a given storm in a catchment. Suggested values for the coefficient C are given in Chow *et al*. (1988).

Example 2.2

Compute the peak discharge generated from the following catchment using the rational method. Total area of the catchment is 250 km^2, and the details are as shown in Table 2.3.

Divide this catchment into three sub-catchments and compute the maximum discharge generated from each of the sub-catchments. Take design intensity of rainfall as in Table 2.4.

Solution

The C values for different sub-catchments are calculated from the data given in Chow *et al*. (1988):

$$\text{Residential, } C = 0.5$$
$$\text{Forest, } C = 0.3$$
$$\text{Open land, } C = 0.2$$

The total catchment area is 250 km^2. From the given data, the peak discharge is computed for each sub-catchment, as shown in Table 2.5.

Table 2.5 *Peak discharge calculation for Example 2.2*

Sub-catchment	C value	Area (A)(km^2)	Rainfall intensity (I) (mm/hr)	Peak discharge = $0.278CAI$ (m^3/s)
Residential	0.56	125	150	2919
Forest	0.3	50	75	312.75
Open land	0.2	75	100	417

The following points must be noted with respect to the rational formula:

1. It is assumed in the rational formula that the frequency of the peak discharge is the same as the frequency of the rainfall.
2. The runoff coefficient C is the same for storms of different frequencies.
3. All losses are constant during a storm – the value of C does not change with hydrologic conditions (such as the AMC).
4. As the intensity of the rainfall is assumed to be constant over the duration considered, the rational method is valid for relatively small catchments. Some investigators believe that the maximum area should be about 100 acres (about 40 ha) (Maidment, 1993).
5. The rational method is generally used for urban storm-water drainage designs. It is also used for small non-urban catchments to estimate peak flows. Where the catchment size is large, it is divided into sub-catchments to obtain the peak flows from each sub-catchment and then the resulting hydrographs are routed using flood routing procedures (Section 2.4) to obtain the peak flow at the outlet.
6. To account for a non-linear response of the catchment to increasing intensities of rainfall, the value of C is sometimes assumed to increase as ARI increases. Chow *et al*. (1988) provide a table of runoff coefficients for various return periods (average recurrence intervals).
7. A probabilistic rational method (Maidement, 1993) may be used to obtain the runoff coefficient as a function of the ARI. The rational formula is written, in this case, as

$$Q_p(Y) = C(Y)\, I\, (t_c, Y)\, A \qquad (2.7)$$

indicating that the peak discharge is a function of the ARI, the intensity I is a function of the time of concentration and the ARI, and that the coefficient C can be determined as a function of the ARI. The probabilistic method may be employed in watersheds where the frequency analyses of peak flows and the durations of storms are available. However, such information is often not available for most watersheds, and increasing the value of C with ARI using judgment and experience may be necessary.

The rainfall intensity, I, is obtained from the IDF relationships. Derivation of the IDF relationship at a location is discussed in the next section.

2.3 INTENSITY–DURATION–FREQUENCY RELATIONSHIP

Hydrologic designs for floods require the peak flows expected to be experienced. The designs are normally developed for a given return period of a flood event. For example, an embankment along a river may be designed to protect against a flood of return period of 100 years, whereas the urban drainage systems may be typically designed for storms of return periods 2 to 5 years. The return period of an event indicates the ARI of the event.

As discussed previously in Section 2.2, a design rainfall depth or intensity is required for determination of peak flood flows. The design rainfall intensity is obtained from the IDF relationships developed for a given location. The IDF relationships provide the expected rainfall intensity (I) for a given duration (D) of the storm and a specified frequency (F). In this section, determination of IDF relationships for use in hydrologic designs is discussed.

IDF relationships are provided as plots with duration as abscissa and intensity as ordinate and a series of curves, one for each return period. The intensity of rainfall is the rate of precipitation, i.e., depth of precipitation per unit time. This can be either instantaneous intensity or average intensity over the duration of rainfall.

The average intensity is determined as

$$i = \frac{P}{t} \qquad (2.8)$$

where P is the rainfall depth and t is the duration of rainfall.

The frequency is expressed in terms of return period (T), which is the average length of time between the rainfall events that equal or exceed the design magnitude. If local rainfall data are available, IDF curves can be developed using frequency analysis. A minimum of 20 years of data is desirable for development of the IDF relationship.

The following steps describe the procedure for developing IDF curves:

Step 1: Preparation of annual maximum rainfall data series
From the available rainfall data, rainfall series for different durations (e.g., 1, 2, 6, 12, and 24 hr) are developed. For each duration, the annual maximum rainfall depths are calculated.

Step 2: Fitting a probability distribution
A suitable probability distribution is fitted to each of the selected duration data series.