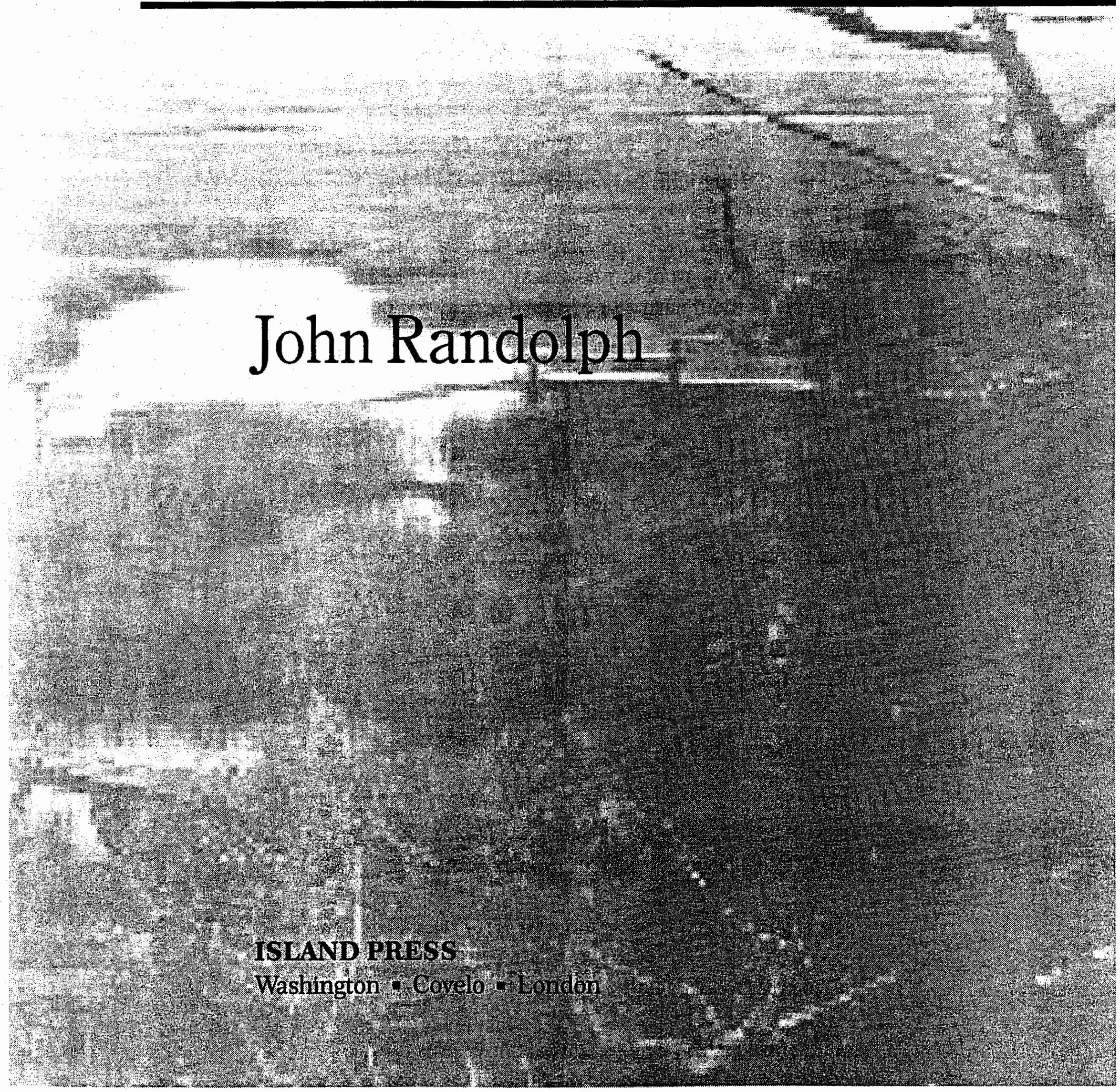
Environmental Land Use Planning and Management



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Land Use, Stream Flow, and Runoff Pollution

The next three chapters address hydrologic considerations in land use. This chapter discusses the effects of land use on stream flow, water quality, and stream integrity. Critical issues include storm flows and flooding that pose natural hazards to property and people, baseflows and low flows that affect aquatic ecology, and runoff pollution that affects both natural waters and sources of community water supplies. Chapter 14 discusses emerging approaches for stormwater management and stream restoration to address these impacts. Chapter 15 focuses on groundwater and land use. Chapters 9 and 10 also discuss related issues of watershed management and flood hazard mitigation.

The hydrologic cycle, described in figure 13.1, is intimately related to the land. Water evaporated from the land and the ocean ultimately precipitates as rain or snow. Precipitation that does not immediately evaporate and transpirate through vegetation back to the atmosphere has one of two fates: (1) it infiltrates the soil and contributes to soil moisture, subsurface flow, and groundwater recharge; or (2) it runs off on the surface, contributing to surface streams, lakes, and rivers. Although runoff contributes the most to **stormwater flows,** much of the infiltrated subsurface flow later seeps to the surface and contributes the most to **baseflow** or stream flow between storms. Ground and surface waters may be important existing or future sources of **water supply** for people and communities. Land use in watersheds of surface supply and in the recharge areas of groundwater aquifers has a significant effect on the quality and viability of those water sources.

Urbanization, with its smooth **impervious** parking lots, streets and rooftops, tends to reduce infiltration and increase the rate of accumulation and the amount of stormwater runoff, which in turn exacerbates drainage and flooding problems and **channel erosion** downstream. This runoff carries with it **non-point source (NPS) water pollutants** that now exceed industrial and municipal "point" discharges in contributing to the pollution of lakes, rivers, and estuaries in the United States.

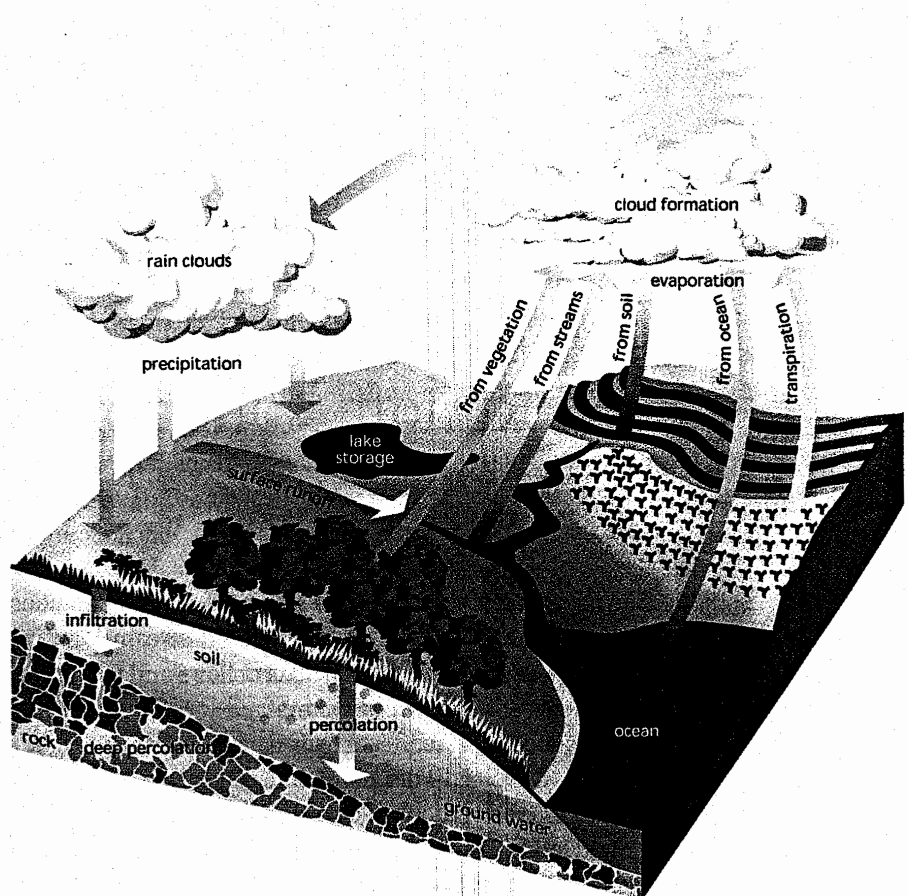


Figure 13.1 Hydrologic Cycle. The transfer of water from precipitation to surface water and groundwater, to storage and runoff, and eventually back to the atmosphere is an ongoing cycle. *Source:* FISRWG (1998).

The Water Balance

Precipitation patterns determine the distribution of water on and under the ground. The measurement of precipitation is straightforward, and gauging stations have been recording rainfall data throughout the United States for over 150 years. These historic data have been analyzed statistically to give average precipitation over a drainage basin or region and the frequency of storms of given intensities that are likely to occur in the future. Most of this analysis was done decades ago (U.S. Weather Bureau [USWB], 1961). This assumption that the future will resemble the past is a critical one in hydrology, and it assumes relatively constant climatic conditions. Climatic changes from global warming and other causes may affect this assumption and our use of long-term historic data.

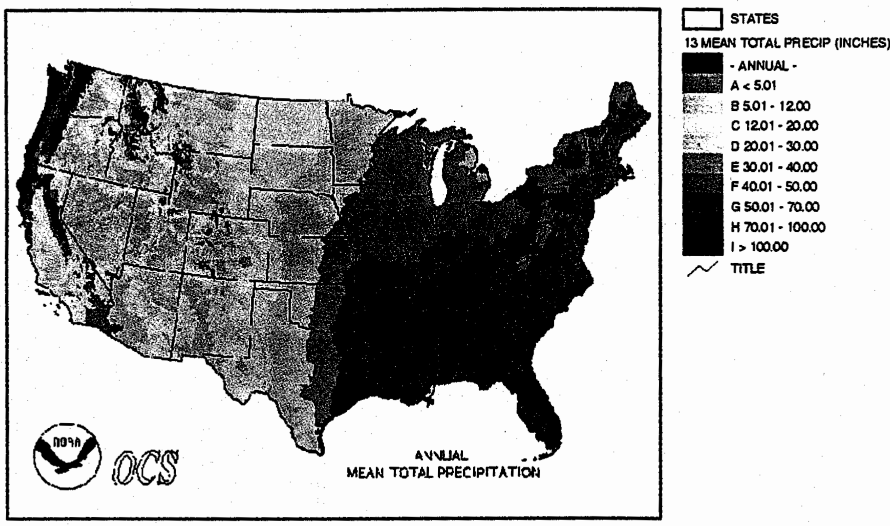


Figure 13.2 Annual Precipitation in United States

Figure 13.2 gives annual average precipitation for the United States. These data are available for most areas of the world. The semihumid eastern United States (30–60 inches per year) is distinguished from the semiarid west (0–30 inches per year). Not only do annual averages vary, but so do the seasonal variations and the **intensity** and **duration** of storms. It is this pattern of precipitation more than its average that determines runoff and flooding problems and stormwater management needs.

For this reason, historic precipitation data is analyzed in terms of the **frequency** of storms of different **durations** and **intensities,** and this information is available in a variety of forms. Maps such as figure 13.3 show intensity for storms of a specific duration and frequency; these maps are available for many durations and frequencies (see websites at USWB, 1961; National Weather Service [NWS], 2002). For a specific location, the intensity-duration-frequency data can be plotted in one curve as shown in figure 13.4. The figure shows the "return period" (frequency) for storms of different intensities (inches/hour) and durations. Figure 13.4 shows that although Seattle and Miami receive about the same annual precipitation on average (48 inches per year), the pattern of rainfall is far different in the two cities. For example, the recurrence of a one-hour, one-inch rainfall in Seattle is greater than 100 years, whereas the return period of such a storm in Miami is less than 2 years.

The frequency or return interval is a simple way of stating the probability of occurrence based on history. A 100-year storm does not mean that if we have such an event this year, we won't see another one for 100 years. It simply means that based on historic data the probability of the event occurring in any year is 1 in 100, or 1 percent. If we get such an event this year, we still have a 1 percent chance of a similar event next year, and we could get it next month.

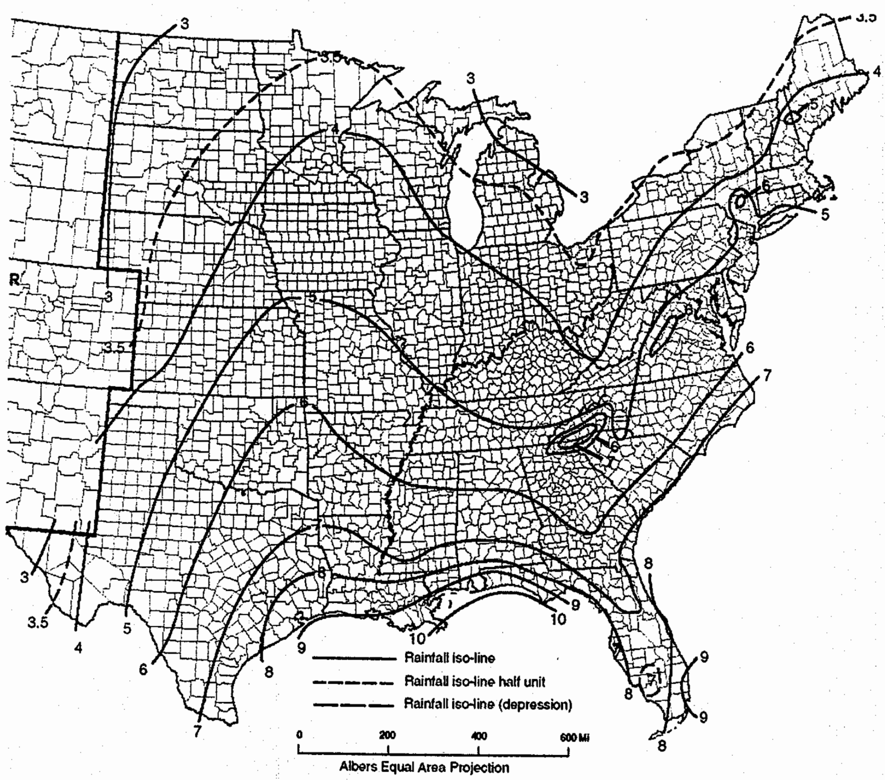


Figure 13.3 10-Year Frequency, 24-Hour Rainfall Inches Over Eastern and Midwestern United States. *Source:* USDA (1986).

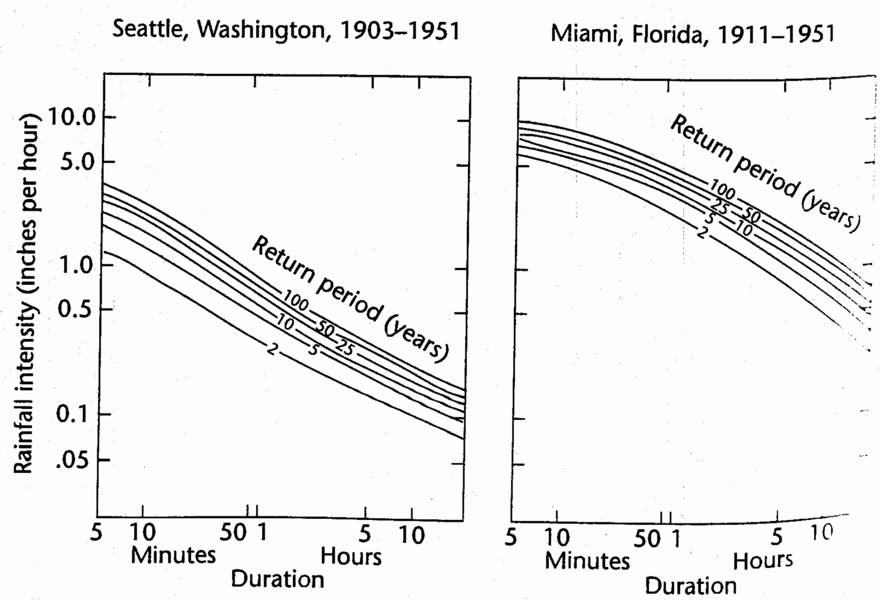


Figure 13.4 Intensity-Duration-Frequency Curves for Seattle and Miami. The differences between the two reflect differences in the climates of the two cities. *Source: Water in Environmental Planning* by Thomas Dunne and Luna Leopold, copyright © 1978. Reprinted with permission of W. H. Freeman and Company.

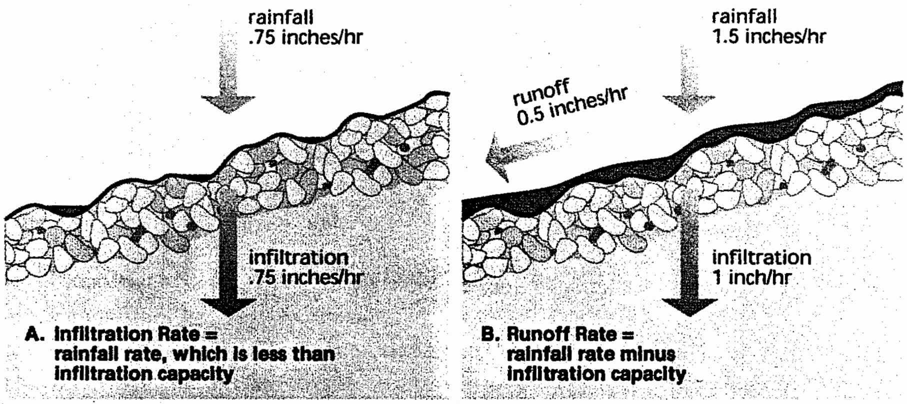


Figure 13.5 Precipitation Rate and Infiltration Rate Determine the Runoff Rate. Infiltration rate depends on soil texture, soil moisture, and vegetative cover. *Source:* FISRWG (1998).

Watersheds and Channel Processes

Precipitation that does not evaporate either infiltrates the ground or runs off on the surface as overland flow. Much of the infiltrated water ultimately seeps out of the ground, contributing to stream baseflow between storms. The texture of the soil determines its permeability and infiltration rate. But for all soils, as they become saturated from a given storm, a greater percentage of the precipitation will end up as surface runoff. Figure 13.5 shows this water balance between precipitation, infiltration, and runoff.

Overland Drainage: Runoff and Watersheds

Topography determines how surface water drains. It delineates **drainage basins,** also called **watersheds** or **catchments.** Rain falling within the **drainage boundary** or **divide** will drain through the basin exit channel. Other basin characteristics include:

- **basin or watershed area:** the area within the boundary;
- **basin length:** the distance from the first-order channel farthest upstream to the basin outlet; and
- **drainage density:** the length of all the channels divided by the basin area; generally, the greater the drainage density, the steeper the slopes in the basin and the higher the peak flows for a given rainfall.

Figure 13.6 shows a drainage basin and the convention for stream order classification. First-order channels are highest in the watershed and have no tributaries. First-order channels join to form second-order streams, second-order streams join to form third-order streams, and so on. Stream channels are also defined by how often water is present. **Perennial streams** (shown as a solid blue line on color topographic maps) normally run all year long. **Intermittent**

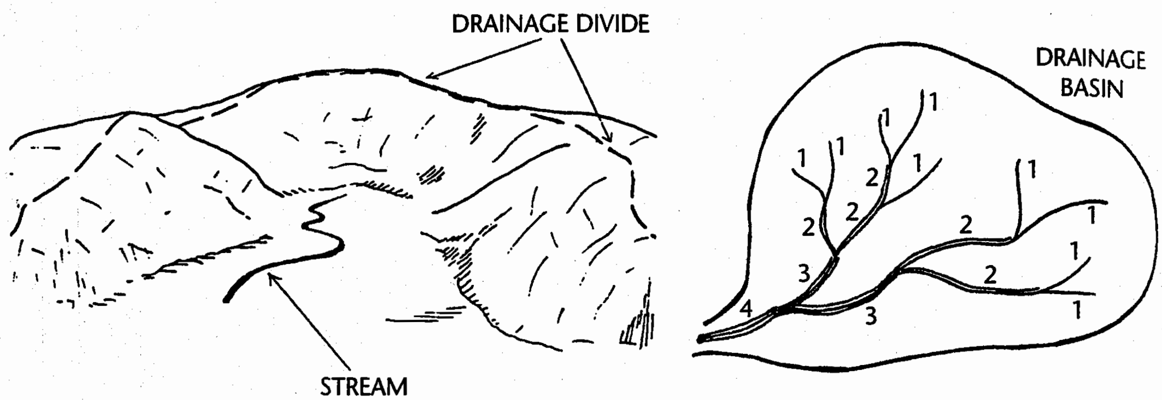


Figure 13.6 The Drainage Basin and Stream Order Classification. Headwater streams are first order, which combine to form second order streams, which combine to third order and so on.

streams (shown as dashed blue lines on topographic maps) run during the wet season. **Ephemeral streams** (not shown on topographic maps) run only during and immediately after storms.

Box 13.1 describes **watershed delineation,** a simple method for defining basins or watersheds using a topographic map. It is often important to identify "critical" watersheds or those deserving special attention. These may be a watershed of an existing or potential water supply reservoir, watersheds with potential drainage capacity problems, or those undergoing land development. It is the first step in watershed management (see chapter 10). The eight-step procedure begins by identifying the outlet point on a stream or river, which will define the watershed draining to that point. After identifying all of the "in" channels draining to the outlet, the procedure finds the "out" channels immediately outside the watershed, identifies high points between these "in" and "out" channels, and connects these high points by drawing connecting lines roughly perpendicular to the elevation contours.

Channel Processes and Geomorphology

Although topography affects drainage, drainage also affects topography through the processes of geomorphology, the formation of landforms by water erosion and deposition. The erosion and deposition processes of the river channel largely determine the landforms of the valley floor including the floodplain. Channels do not flow uniformly over time but are dynamic in nature. Channels have a natural tendency to meander or to develop a wavy pattern from a straight one. Figure 13.7 shows how the varying water velocities in the channel section produce this meandering effect. Faster water on the outside of the stream curves cause more erosion while slower velocities in the inside cause deposition of sediment. Over time these processes cause the curves to enlarge. This process also contributes to the deep pool, shallow and stony riffle, and unobstructed run sequence in natural stream segments. It is this meandering process, not flooding, that actually causes the development of floodplains and the distinct landforms common to river valleys.

BOX 13.1—Delineating Watershed Boundaries

1. Identify the **outlet point** on a stream or river that defines the watershed draining to that point.
2. Find and trace drainage **channels within** the watershed. On color topo map, they are blue lines. "V" shape of elevation contours point upstream.
3. Find and "X" out neighboring **channels outside** the watershed. The watershed boundary will be between the channels in the basin (step 2) and these outside channels.
4. Consider yourself a drop of water and **check** the direction of drainage by inspecting the slope direction between the "in" and "out" channels.
5. Find and **mark the high points** (peaks and saddles) between the "in" and "out" channels. These will be on the watershed boundary.
6. **Connect these points** with light pencil, intersecting the contour lines at roughly a right angle.
7. Consider yourself a drop of water again and **check** where you would go if you fell inside or outside the line. Make corrections as necessary.
8. **Finalize** Map.

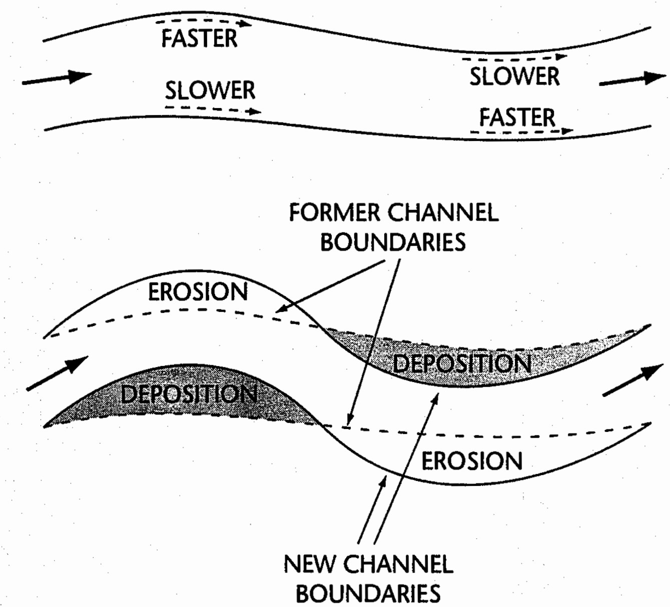


Figure 13.7 The Tendency of Streams to Meander at Shallow Slopes through Erosion and Deposition. This meandering process is what shapes floodplains.

Figure 13.8 delineates channel characteristics: bankfull depth and width and the hydrologic floodplain are channel dimensions with channel at maximum flow or its bankfull discharge. The bankfull discharge, also called the channel-forming or dominant flow, is defined as the flow that fills a stable alluvial channel to the elevation of the active or hydrologic floodplain. Greater flows will overtop the channel and spread out onto the topographic floodplain. Figure 13.9 gives the stream classification developed by Rosgen (1994). The system groups reaches of streams by slope, entrenchment in the valley, degree of meandering, bankfull width-depth ratio, and types of soils and geology (Riley, 1998). The figure shows channel types and corresponding slopes and flood-prone areas. A stream has a **longitudinal transition** along its length and a **lateral transition,** extending outward from the normal and bankfull channel to the floodplain to the extent of its riparian vegetation to its upland watershed boundary.

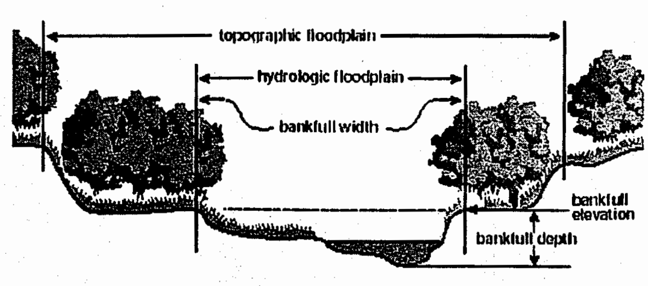


Figure 13.8 Bankfull Dimensions and Floodplain Definitions. *Source:* FISRWG (1998).

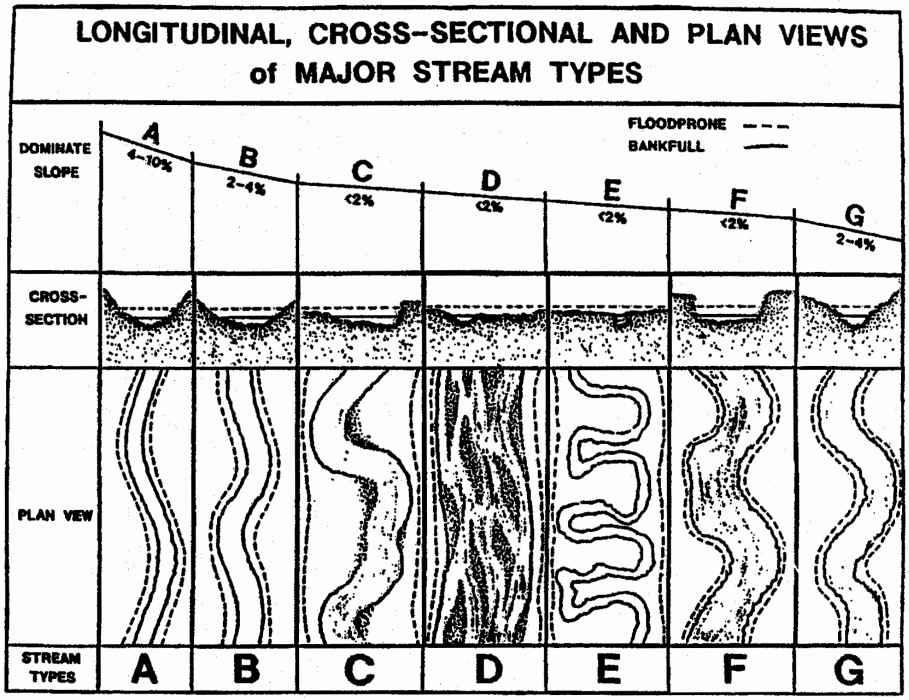


Figure 13.9 Stream Classification System. *Source:* Reprinted from *Catena*, vol. 22, David Rosgen, "A Classification of Natural Rivers," p.174, Copyright © 1994, with permission from Elsevier.

Streams and river channels change from headwaters to discharge to another receiving water body. Three zones vary in slope, stream discharge and mean flow velocity, channel width and depth, channel bed material grain size, and relative volume of stored alluvium or deposited materials from upstream. These include the following:

- Headwater zone with steeper slopes; higher velocity; larger bed material; and lower discharge, channel width and depth, and stored alluvium
- Transfer zone between headwaters and deposition zones
- Deposition zone with flat slope; lower velocity; smaller bed material; and higher discharge, channel width and depth, and stored alluvium

Effects of Land Use on Stream Flow and Predicting Peak Discharge

The **hydrograph** shows over time the response of channel flow at a specific point to a given storm over its watershed. A hypothetical hydrograph is shown in figure 13.10. The rainfall is generally given in a histogram showing the depth of rainfall

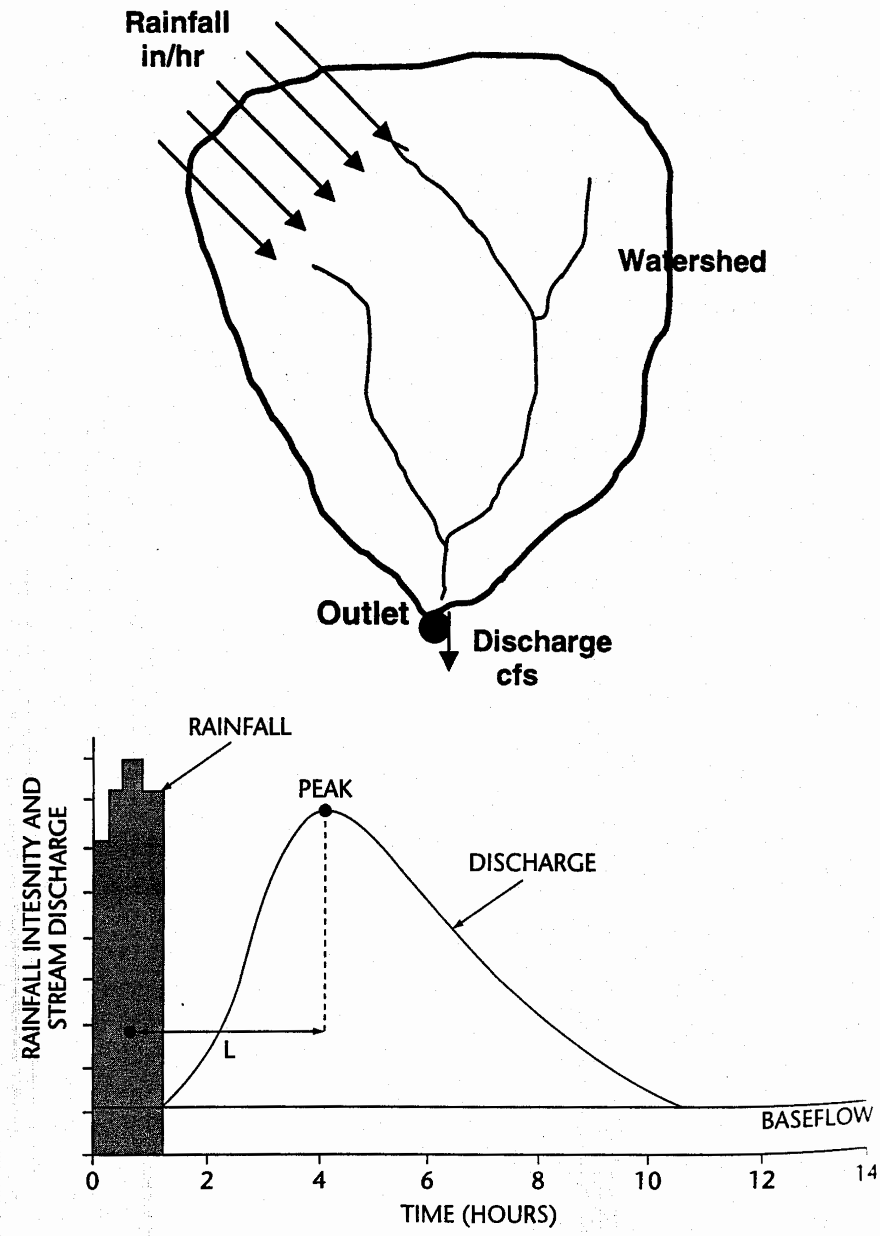


Figure 13.10 Hypothetical Hydrograph Showing the Response of Stream Flow. "L" is the lag time to peak discharge. Baseflow is stream flow without storm event.

for each hour of the storm. The curve that follows shows the channel discharge response as a flow rate that builds up to a peak, then drops back to the original baseflow. Important to note are the timing and magnitude of the peak. The peak will occur at some time after the center of mass of the storm, called the **lag time**. The **peak flow** is the maximum flow, at which time the water flow elevation is highest and flooding is the worst. The hydrograph relationship of rainfall to discharge depends on several characteristics of the watershed, principally soil

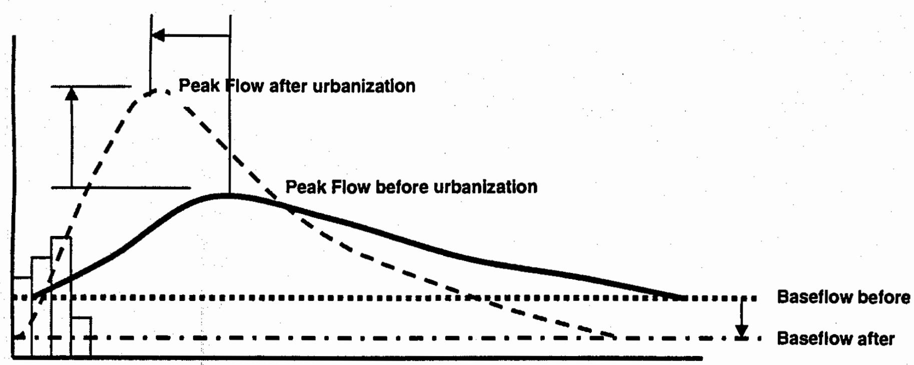


Figure 13.11 Effect of Urbanization's Impervious Surfaces on Peak Flows and Baseflows

slope, and channel length. Given the relationship, hydrologists can generate a peak discharge frequency based on rainfall frequency.

Land cover and drainage characteristics affect the accumulation of stormwater flow as well as the amount of baseflow between storms. The process of urbanization, that is, paving and covering the land with impervious surfaces and constructing drainage pipes and lined channels, acts to increase the peak discharge from a given storm event by (a) reducing the amount of water that infiltrates the ground, thus *increasing the volume* of surface runoff and, more important, and (b) *increasing the rate* at which the runoff accumulates, reducing the hydrograph lag time. Because of impervious surfaces, less water infiltrates the ground, and, thus, less is available for groundwater-contributed baseflow between storms, especially in dry weather periods. As a result, urban streams run faster and higher during storms, and often run dry between storms.

As shown in figures 13.11 and 13.12, the peak flows from a given storm event will be greater from a watershed after it has experienced land development than before. It also shows that the baseflow between storms will be much less. Baseflow and summer low flows are critical to support stream ecology and riparian vegetation. Finally, the stream geometry shows higher flood flows and a broader floodplain.

Land development and urbanization cause hydrologic changes, which have a number of damaging effects in the following list. This section focuses on the first. The latter three are discussed in following sections. Chapter 14 addresses measures and management practices to reduce these impacts.

1. The increased flows caused by land development can exacerbate **flooding downstream.**
2. Urban runoff carries **water contaminants** affecting the quality of receiving water; generally, as urban runoff increases, so does the pollution it carries.
3. Reduced infiltration reduces groundwater storage and reduced dry weather stream flows.
4. Urbanization directly and indirectly causes the **destruction of natural creeks and streams.**

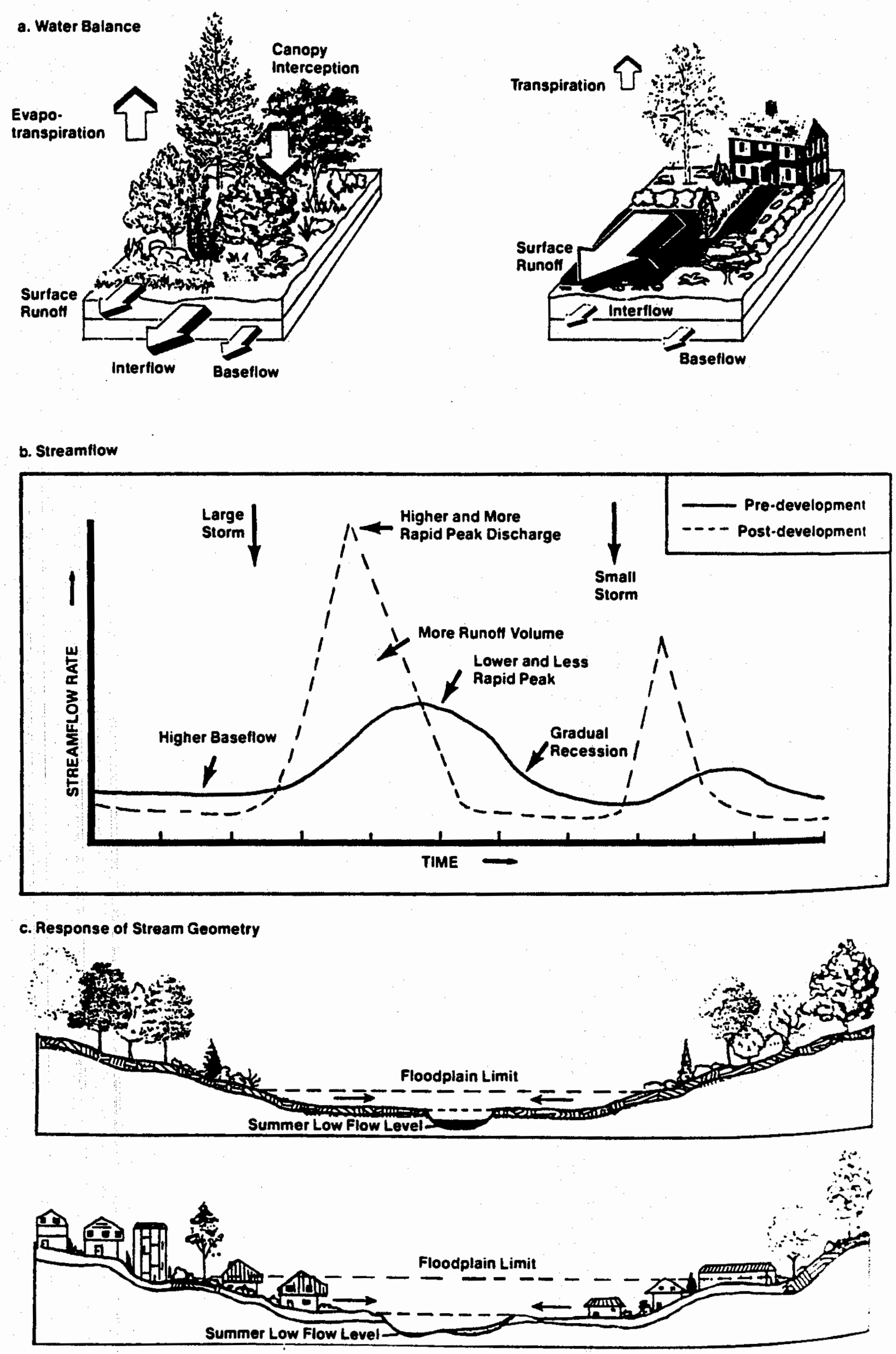


Figure 13.12 Changes in Watershed Hydrology as a Result of Urbanization. Note increase peak flow, decrease in baseflow, and higher flood levels. *Source: Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban BMPs*, by Tom Schueler, 1987. Reprinted with permission of Metropolitan Washington Council of Governments, 777 North Capitol NE, Ste. 300, Washington, D.C. 20002-4239, 202-962-3256.

TABLE 13.1 **Hydrologic Cycle Changes of Impervious Surface Associated with Urbanization**

Land Use/Cover	*Imperviousness* (%)	*Evapotranspiration* (%)	*Infiltration* (%)	*Runoff* (%)
Natural Cover	0	40	50	10
Low Density Resid.	10–20	35	42	23
Urban Residential	35–50	35	35	30
Urban Center	75–100	30	15	55

(Source: EPA 1993)

Many analysts have argued that **impervious surface coverage** in a watershed is a good indicator of potential impact on stream health (see section on stream integrity). Table 13.1 shows the water cycle changes associated with impervious surfaces. Increasing density of urbanization increases imperviousness, which reduces infiltration and increases runoff.

Planning and designing stormwater drainage systems and managing land use effects on runoff require the ability to predict runoff flows from storm events. Planners and engineers also need to be able to assess the capacity of channels to carry stormwater flows and to design mitigation measures to reduce peak flows. In the past 30 years, a number of sophisticated computer simulation methods have been developed that model stormwater response to precipitation and estimate effects of land use and control measures on flows. A number of these runoff models are listed in table 13.2.

Some of the simpler techniques are presented here to illustrate how these models work and to understand the factors that influence land use impacts on water flows. They describe methods to estimate the peak discharge of a stream for a

TABLE 13.2 **Comparison of Stormwater Model Attributes and Functions**

	Model				
Attribute	*HSPF*	*SWMM*	*TR-55/TR-20*	*HEC-1*	*Rational Method*
Sponsoring agency	USEPA	USEPA	NRCS (SCS)	CORPS (HEC)	
Simulation type	Continuous	Continuous	Single event	Single event	Single event
Water quality analysis	Yes	Yes	None	None	None
Rainfall/runoff analysis	Yes	Yes	Yes	Yes	Yes
Sewer system flow routing	None	Yes	Yes	Yes	None
Dynamic flow routing equations	None	Yes	Yes	None	None
Regulators, overflow structures	None	Yes	None	None	None
Storage analysis	Yes	Yes	Yes	Yes	None
Treatment analysis	Yes	Yes	None	None	None
Data and personnel requirements	High	High	Medium	Medium	Low
Overall model complexity	High	High	Low	High	Low

Source: PGC-DEM, 1999

storm of a given duration and intensity under current conditions and under conditions brought about by proposed development. Chapter 14 describes a method to size on-site detention to mitigate the expected impacts. Appendix 13.D describes methods for determining channel capacity and channel erosion problems, necessary techniques in natural drainage design, and stream corridor protection and restoration programs. Working through the techniques provides the reader the opportunity to understand quantitatively the factors that influence peak discharge, channel capacity, and stormwater detention.

The Rational Method

This technique, based on Mubraney's formula developed in 1851, has provided the design basis for almost all of the urban drainage systems built in the world up to about 1980. However, the method has been criticized for such applications as being unnecessarily conservative, leading to expensive and oversized systems. As a result, the 1970s saw considerable improvements in design methods. Still, the Rational Method provides a reasonable "first cut" approximation of peak discharge. The use of the Rational Method is limited to drainage areas of less than 200 acres. It involves the following simple equation for peak discharge:

$$Q = CiA \qquad (Eq.\ 13\text{–}1)$$

where, Q = peak discharge (cubic ft per second—cfs)
C = rational runoff coefficient, based on land cover
i = rainfall intensity (inches/hour)
A = drainage area (acres)

Values of the **runoff coefficient** (C) for various rural and developed land uses are given in table 13.3. If a drainage area of interest is made up of one or more types of soil cover, a weighted average can be computed by simply summing the products of the individual subarea's coefficient times its fraction of the total area. (See the following example.) The **rainfall intensity** (i) is determined from a rainfall intensity-frequency-duration curve such as figure 13.4 or figure 13.1. The intensity is read from the curve for a desired frequency and a duration equal to the **time of concentration** (T_c) for the drainage area (i.e., the time of flow from the most remote point in the basin to the design point, in minutes). The T_c depends on the length of travel, the drainage slope, the land cover, and channel type. It can be approximated by the nomograph given in figure 13.14.

Rational Method Example

Using the Rational Method, determine the peak discharge resulting from a 10-year frequency storm falling on an 80-acre drainage area in Richmond, Virginia, comprised of 30 percent rooftops, 10 percent streets and driveways, 20 percent lawns at 5 percent slope on sandy soil, and 40 percent woodland. The height of the most remote point above the outlet is 100 feet and the maximum length of travel is 3,000 feet; assume the combination of land covers produces the equivalent of a natural basin on bare earth.

TABLE 13.3 **Runoff Coefficients for Rational Method**

Land use	*C*
Business:	
Downtown areas	0.70–0.95
Neighborhood areas	0.50–0.70
Residential:	
Single-family areas	0.30–0.50
Multi-units, detached	0.40–0.60
Multi-units, attached	0.60–0.75
Suburban	0.25–0.40
Industrial:	
Light areas	0.50–0.80
Heavy areas	0.60–0.90
Parks, cemeteries	0.10–0.25
Playgrounds	0.20–0.35
Railroad yard areas	0.20–0.40
Unimproved areas	0.10–0.30
Streets:	
Asphaltic	0.70–0.95
Concrete	0.80–0.95
Brick	0.70–0.85
Drives and walks	0.75–0.85
Roofs	0.75–0.95
Lawns:	
Sandy soil, flat, 2%	0.05–0.10
Sandy soil, average, 2–7%	0.10–0.15
Sandy soil, steep, 7%	0.15–0.20
Heavy soil, flat, 2%	0.13–0.17
Heavy soil, average, 2–7%	0.18–0.22
Heavy soil, steep, 7%	0.25–0.35
Agricultural land:	
Bare packed soil	
Smooth	0.30–0.60
Rough	0.20–0.50
Cultivated rows	
Heavy soil no crop	0.30–0.60
Heavy soil with crop	0.20–0.50
Sandy soil no crop	0.20–0.40
Sandy soil with crop	0.10–0.25
Pasture	
Heavy soil	0.15–0.45
Sandy soil	0.05–0.25
Woodlands	0.05–0.25

Note: The designer must use judgment to select the appropriate C value within the range. Generally, larger areas with permeable soils, flat slopes and dense vegetation should have lowest (C) values. Smaller areas with dense soils, moderate to steep slopes, and sparse vegetation should be assigned highest (C) values.

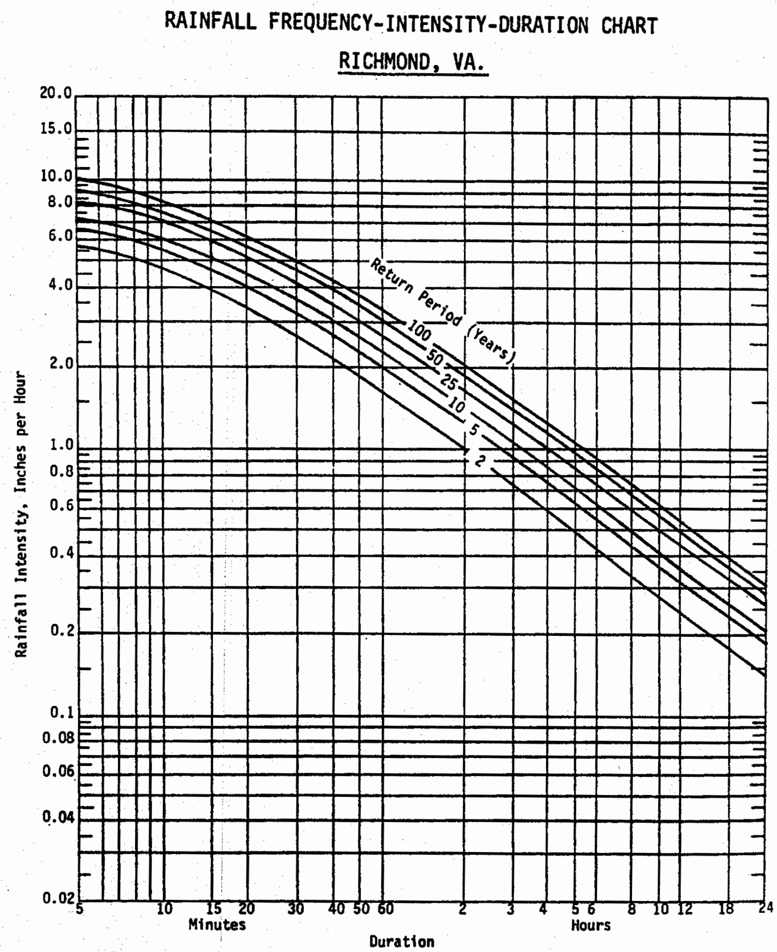


Figure 13.13 Rainfall Intensity-Duration-Frequency Curve for Richmond, Virginia. *Source:* VDCR (1992).

$C = (.9)(.30) + (.9)(.10) + (.15)(.20) + (.10)(.40) = .43$

(rooftops) (streets) (lawns) (woodland) (from table 13.3)

T_c = 14 minutes (from figure 13.14, ht = 100, length = 3,000)

i = 5.4 inches (from figure 13.13, dur. = 14 min, freq. = 10 yr)

A = 80 acres

Q = CiA = (.43)(5.4)(80) = 185.76 cubic feet per sec.

TR 55 Peak Discharge Graphical Method

This technique is described in the Soil Conservation Service (now NRCS) Tec[illegible] cal Release No. 55 (TR 55), *Urban Hydrology for Small Watersheds* (U.S[illegible] 1986). It is considered more accurate than the Rational Method for larger [illegible] drainage areas (up to about 2,000 acres) because it takes into account mor[illegible] tors and involves less judgment on the part of the user (particularly in the [illegible] of the time of concentration). The peak discharge method can also be use[illegible] duce hydrographs for larger areas (up to 20 sq. miles) using a tabular hyd[illegible]

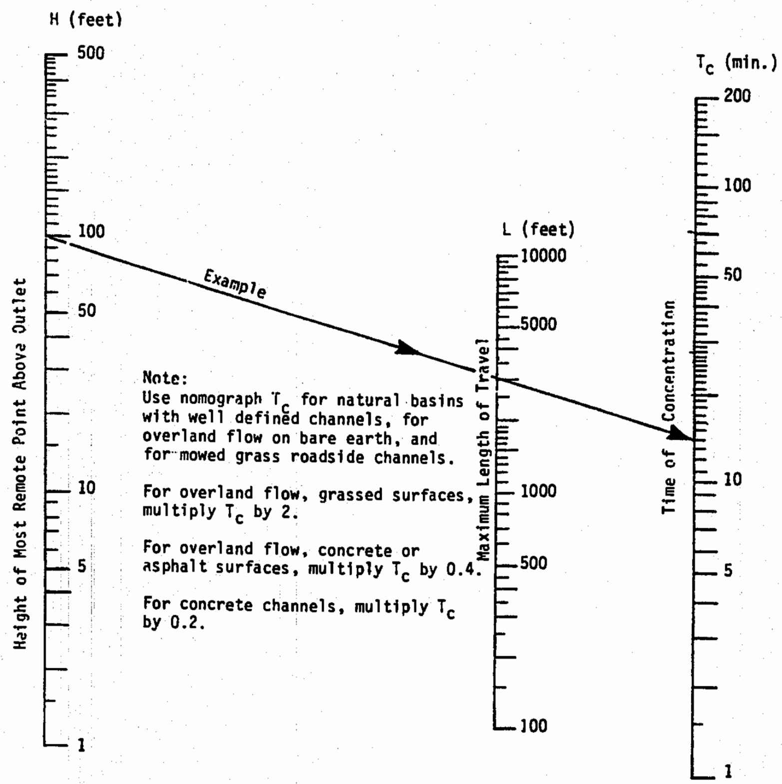


Figure 13.14 Time of Concentration for Small Drainage. *Source:* VDCR (1992).

method also described in TR 55. For further information on this hydrograph method, see SCS (USDA, 1986) http://www.wcc.nrcs.usda.gov/hydro/hydro-tools-models-tr55.html. Though it is less sophisticated than many computer models, TR 55 is heavily used in state and local stormwater and erosion and sediment control programs (see section on stormwater management practices in chapter 14) and land analysis software like CITYgreen (see chapter 16).

The TR 55 graphical peak discharge method described here determines the peak flows resulting from a "design" 24-hour storm over a specific drainage area. By modifying the land use and cover conditions in the drainage area, it can be used to predict the peak discharge effects of different land use scenarios. The process is illustrated in table 13.4. The method employs a number of data tables, charts, and four worksheets. For blank worksheets see http://www.wcc.nrcs.usda.gov/water/quality/common/tr55/tr55.pdf. We will only be working with Worksheets 2, 3, and 4 in this chapter and Worksheet 6 in the next. The worksheet, figure, and example numbering from TR 55 have been retained to ease cross-referencing the source.

STEP 1 Worksheet 2 computes the watershed Curve Number (*CN*) and Runoff (*Q*).

(Data needed: Design 24-hour storm (inches), watershed acres, acres in various land uses/covers, HSG)

TABLE 13.4 TR-55 Process for Graphical Discharge Method

Data to calculate Tc?	If no, TR 55 not applicable
Hydrograph or subareas required?	If no, proceed below. If yes, consult TR-55 document, chapter 5
Step 1: Compute Watershed Curve Number and Runoff:	Worksheet 2
Step 2: Compute Watershed Time of Concentration (Tc):	Worksheet 3
Step 3: Compute Peak Discharge:	Worksheet 4
Step 4: Compute Storage to Reduce Peak Discharge:	Worksheet 6

TABLE 13.5a Runoff Curve Numbers for Urban Areas (TR55 table 2–2)

Cover Description	*Curve Numbers For*				
	Avg % impervious[1]	*Hydrologic Soil Group (HSG)*			
Cover Type and Hydrologic Condition		*A*	*B*	*C*	*D*
Open space (lawns, parks, golf courses, cemeteries, etc.)[2]:					
Poor condition (grass cover <50%)		68	79	86	89
Fair condition (grass cover 50% to 75%)		49	69	79	84
Good condition (grass cover >75%)		39	61	74	80
Impervious areas:					
Paved parking lots, roofs, etc.		98	98	98	98
Streets and roads: Paved; curbs and storm sewers		98	98	98	98
Gravel (including right-of-way)		76	85	89	91
Urban districts:					
Commercial and business	85	89	92	94	95
Industrial	72	81	88	91	93
Residential districts:					
1/8 acre or less (town houses)	65	77	85	90	92
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84
2 acres	12	46	65	77	82

[1]The average percent impervious shown was used to develop the composite CN's. Other assumptions are as follows: impervious areas are directly connected to the drainage system and have a CN of 98, and pervious areas are considered equivalent to open space in good hydrologic condition. CN's for other combinations of conditions may be computed using figure 13.20.

[2]CN's shown are equivalent to those of pasture. Composite CN's may be computed for other combinations of open space cover type.

TABLE 13.5b **Runoff Curve Numbers for Cultivated and other Agricultural Lands (TR55 table 2–2)**

Cover Type	*Cover Description* Treatment	*Hydrologic* Condition	*Curve Numbers For Hydrologic Soil Group* A	B	C	D
Fallow	Bare soil	—	77	86	91	94
	Crop residue cover (CR)[1]	Poor	76	85	90	93
		Good	74	83	88	90
Row crops	Straight row (SR)[1]	Poor	72	81	88	91
		Good	67	78	85	89
	SR + CR[1]	Poor	71	80	87	90
		Good	64	75	82	85
Pasture, grassland, or range[2]		Poor	68	79	86	89
		Fair	49	69	79	84
		Good	39	61	74	80
Meadow—mowed for hay		—	30	58	71	78
Brush—brush-weed-grass[2]		Poor	48	67	77	83
		Fair	35	56	70	77
		Good	30	48	65	73
Woods—grass combination (orchard or tree farm).[3]		Poor	57	73	82	86
		Fair	43	65	76	82
		Good	32	58	72	79

[1]Poor: Factors impair infiltration and tend to increase runoff.
Good: Factors encourage average and better than average infiltration and tend to decrease runoff.
[2]Poor: <50% ground cover or heavily grazed with no mulch.
Fair: 50 to 75% ground cover and not heavily grazed.
Good: >75% ground cover and lightly or only occasionally grazed.
[3]Poor: Forest litter, small trees, and brush are destroyed by heavy grazing or regular burning.
Fair: Woods are grazed but not burned, and some forest litter covers the soil.
Good: Woods are protected from grazing, and litter and brush adequately cover the soil.

The curve number (*CN*) is a measure of the land cover influence on infiltration and runoff, similar to the *C* factor in the Rational Method. It ranges in value from about 30 to 98. It depends on the vegetative or impervious cover, land use practice, and hydrologic soil group (HSG). Based on their texture and infiltration rates, soils are classified in HSG A (sands and sandy loams), B (silt loam and loam), C (sandy clay loam), and D (clay, clay loam, sandy clay, silty clay). Other factors, like soil compaction or high water table, can supercede the effect of texture. Soil surveys list HSG for different soils and map units.

Table 13.5 gives *CN* values for various agricultural and urban land covers and uses. Values range from 30 (for meadow and woods in HSG A) to 98 (for impervious surfaces). The first step in Worksheet 2 is to compute a weighted average *CN* value for the drainage area or watershed. The various land covers of the area and their acreages are entered on the worksheet; *CN* values for these covers are looked up on table 13.5 and entered. The *CN* values are multiplied by the acreage, and the sum of these products is divided by the total acreage to yield the average CN value.

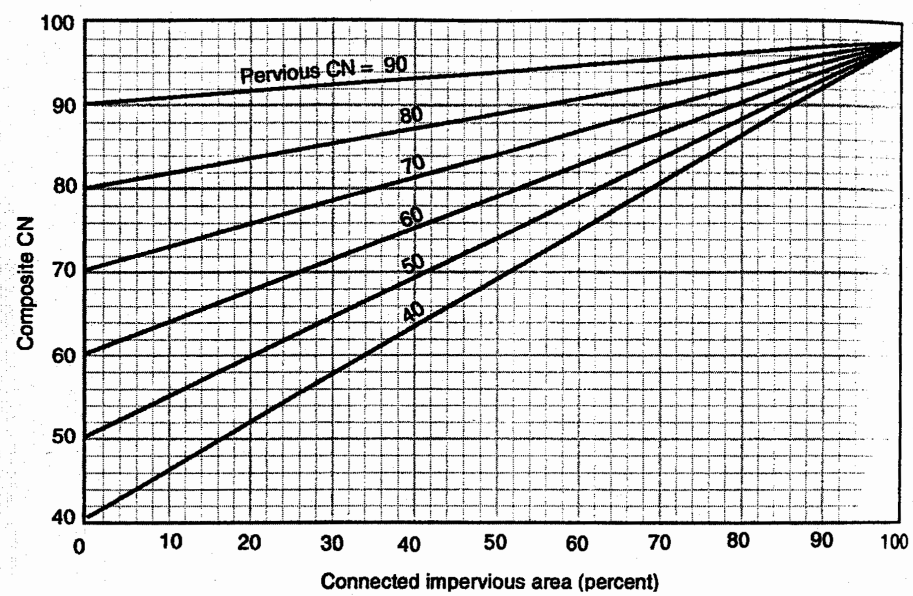


Figure 13.15a Composite Curve Number with Connected Impervious Area (TR55 figure 2–3). *Source:* USDA (1986).

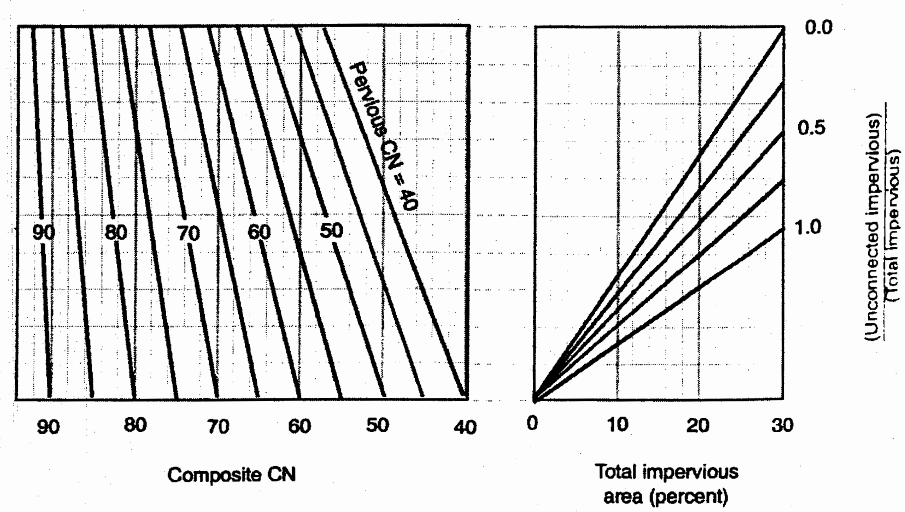


Figure 13.15b Composite Curve Number with Unconnected Impervious Areas (TR55 figure 2–4). *Source:* USDA (1986).

$$CN\ \text{average} = \frac{\sum CN_i \times A_i}{\sum A_i} \qquad (Eq.\ 13\text{–}2)$$

where CN_i is the CN for each land cover, i

A_i is the area for each land cover, i

Table 13.5 values assume that urban uses have the percent impervious cove[r] ... the table and that the surfaces are hydraulically connected to drainage works ... determine *CN* when all or part of the impervious area is not directly connected ...

TABLE 13.6 C... (CN) (TR55 ta...

CN→	40
Rainfall	
1.0	0.00
1.2	.00
1.4	.00
1.6	.00
1.8	.00
2.0	.00
2.5	.00
3.0	.00
3.5	.02
4.0	.06
4.5	.14
5.0	.24
6.0	.50
13.0	.84
8.0	1.25
9.0	1.71
10.0	2.23
11.0	2.78
12.0	3.38
13.0	4.00
14.0	4.65
15.0	5.33

TABLE 13.6 **Converting from Rainfall Depth to Runoff Depth for Different Curve Numbers (CN) (TR55 table 2–1)**

CN→						*Runoff Depth for Curve Number of—*							
	40	45	50	55	60	65	70	75	80	85	90	95	98
Rainfall						*inches*							
1.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.08	0.17	0.32	0.56	0.79
1.2	.00	.00	.00	.00	.00	.00	.03	.07	.15	.27	.46	.74	.99
1.4	.00	.00	.00	.00	.00	.02	.06	.13	.24	.39	.61	.92	1.18
1.6	.00	.00	.00	.00	.01	.05	.11	.20	.34	.52	.76	1.11	1.38
1.8	.00	.00	.00	.00	.03	.09	.17	.29	.44	.65	.93	1.29	1.58
2.0	.00	.00	.00	.02	.06	.14	.24	.38	.56	.80	1.09	1.48	1.77
2.5	.00	.00	.02	.08	.17	.30	.46	.65	.89	1.18	1.53	1.96	2.27
3.0	.00	.02	.09	.19	.33	.51	.71	.96	1.25	1.59	1.98	2.45	2.77
3.5	.02	.08	.20	.35	.53	.75	1.01	1.30	1.64	2.02	2.45	2.94	3.27
4.0	.06	.18	.33	.53	.76	1.03	1.33	1.67	2.04	2.46	2.92	3.43	3.77
4.5	.14	.30	.50	.74	1.02	1.33	1.67	2.05	2.46	2.91	3.40	3.92	4.26
5.0	.24	.44	.69	.98	1.30	1.65	2.04	2.45	2.89	3.37	3.88	4.42	4.76
6.0	.50	.80	1.14	1.52	1.92	2.35	2.81	3.28	3.78	4.30	4.85	5.41	5.76
13.0	.84	1.24	1.68	2.12	2.60	3.10	3.62	4.15	4.69	5.25	5.82	6.41	6.76
8.0	1.25	1.74	2.25	2.78	3.33	3.89	4.46	5.04	5.63	6.21	6.81	7.40	7.76
9.0	1.71	2.29	2.88	3.49	4.10	4.72	5.33	5.95	6.57	7.18	7.79	8.40	8.76
10.0	2.23	2.89	3.56	4.23	4.90	5.56	6.22	6.88	7.52	8.16	8.78	9.40	9.76
11.0	2.78	3.52	4.26	5.00	5.72	6.43	7.13	7.81	8.48	9.13	9.77	10.39	10.76
12.0	3.38	4.19	5.00	5.79	6.56	7.32	8.05	8.76	9.45	10.11	10.76	11.39	11.76
13.0	4.00	4.89	5.76	6.61	7.42	8.21	8.98	9.71	10.42	11.10	11.76	12.39	12.76
14.0	4.65	5.62	6.55	7.44	8.30	9.12	9.91	10.67	11.39	12.08	12.75	13.39	13.76
15.0	5.33	6.36	7.35	8.29	9.19	10.04	10.85	11.63	12.37	13.07	13.74	14.39	14.76

the drainage system, (1) use figure 13.15a (TR 55 figure 2–3) if total impervious area is less than 30 percent or (2) use figure 13.15b (TR 55 figure 2–4) if the impervious area is equal to or greater than 30 percent, because the absorptive capacity of the remaining pervious areas will not significantly affect runoff. See Appendix 13.A for examples using these figures.

Once the average *CN* value is calculated, the runoff (*Q*) can be determined for the design storm (*P*) from table 13.6, and the value is entered in the last entry on the worksheet. The design storm depends on the recurrence frequency of the 24-hour storm. Figure 13.2 gives data for a 10-year event for the eastern and midwestern United States. The TR 55 document gives data for 2-, 10-, 25-, and 100-year 24-hour storms (USDA, 1986; see the web address given previously).

TR 55 Step 1 Example: The watershed covers 250 acres in Dyer County, northwestern Tennessee. Seventy percent (175 acres) is a Loring soil, which is in HSG C. Thirty percent (75 acres) is a Memphis soil, which is in group B. The event is a 25-year frequency, 24-hour storm with total rainfall of 6 inches. Cover type and conditions in the watershed are different for each example. The example illustrates how to

Worksheet 2: Runoff curve number and runoff

Project: Heavenly Acres	By: WJR	Date: 10/1/85
Location: Dyer County, Tennessee	Checked: NM	Date: 10/3/85

Check one: ☐ Present ☒ Developed — 175 Acres residential

1. Runoff curve number

Soil name and hydrologic group (appendix A)	Cover description (cover type, treatment, and hydrologic condition; percent impervious; unconnected/connected impervious area ratio)	CN [1/] Table 2-2	CN Figure 2-3	CN Figure 2-4	Area ☒ acres ☐ mi² ☐ %	Product of CN x area
Memphis, B	25% impervious 1/2 acre lots, good condition	70			75	5250
Loring, C	25% impervious 1/2 acre lots, good condition	80			100	8000
Loring, C	Open space, good condition	74			75	5550
				Totals ➡	250	18,800

[1/] Use only one CN source per line

CN (weighted) = $\frac{\text{total product}}{\text{total area}} = \frac{18,800}{250} = 75.2$; Use CN ➡ 75

2. Runoff

		Storm #1	Storm #2	Storm #3
Frequency	yr	25		
Rainfall, P (24-hour)	in	6.0		
Runoff, Q (Use P and CN with table 2-1, figure 2-1, or equations 2-3 and 2-4)	in	3.28		

use TR 55 Worksheet 2 to compute *CN* and Q. Two other examples with different land use situations that illustrate use of figure 13.15 are given in appendix 13.A.

Example 2–2: Seventy percent (175 acres) of the watershed, consisting of all the Memphis soil and 100 acres of the Loring soil, is 1/2-acre residential lots with lawns in good hydrologic condition. The rest of the watershed is scattered open space in good hydrologic condition. Using table 13.5 *CN* values, the worksheet calculates a composite *CN* of 75. Given the 24-hour design storm of 6 inches, the runoff Q from table 13.6 is 3.28 inches.

STEP 2 **Worksheet 3 computes the time of concentration (T_c).**

(Data needed: hydraulic parameters, channel length, slope, shape, and surface roughness for the top of watershed to outlet.) (See figure 13.16.)

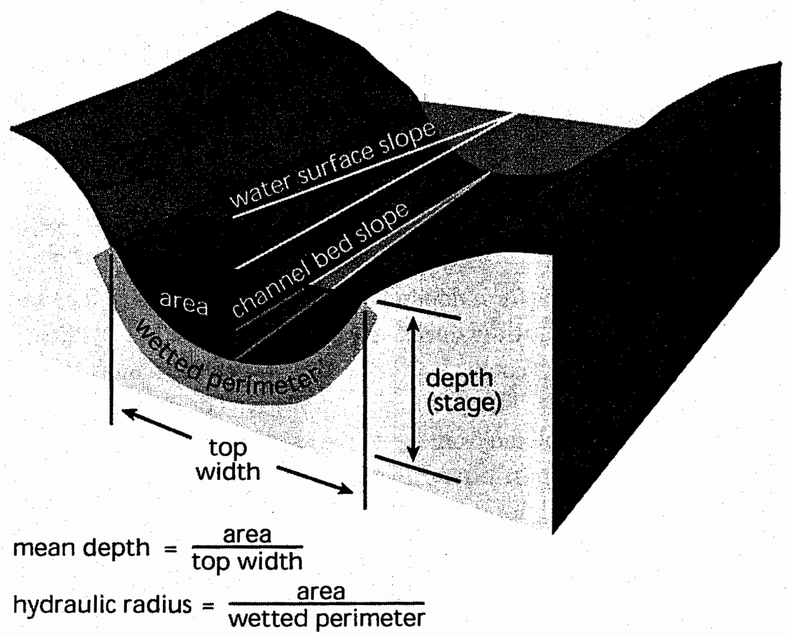


Figure 13.16 Hydraulic Parameters. *Source:* FISRWG (1998).

The time of concentration (T_c) is time for the runoff to travel from the hydraulically most distant point of the watershed to the point of interest or outlet. It is the sum of the travel times (T_t) for consecutive channel segments.

$$T_c = T_{t1} + T_{t2} + T_{t3} + \ldots.\ T_{tm} \qquad \textit{(Eq. 13–3)}$$

where T_c = time of concentration (hr)
T_t = travel time (hr)
m = number of flow segments

$$T_t = \frac{L}{3600V} \qquad \textit{(Eq. 13–4)}$$

where T_t = travel time (hr)
L = flow length (ft)
V = average velocity (ft/s)
3600 = conversion factor from seconds to hours

The tricky part of Worksheet 3 is determining the flow velocity, *V*. There are three ways to calculate it depending on the type of water flow.

Sheet flow is flow over plane surfaces and usually occurs in the headwater of streams. It depends on the frictional resistance to flow, measured by Manning's roughness coefficient, *n*. For sheet flow of less than 300 feet, the following equation applies:

$$T_t = \frac{0.007\,(nL)0.8}{(P_2)^{0.5}\,s^{0.4}} \qquad \textit{(Eq. 13–5)}$$

where n = Manning's roughness coefficient
L = flow length (ft)
P_2 = 2-year, 24-hour rainfall (in)
s = slope of hydraulic grade (land slope, ft/ft)

Values for n depend on surface conditions and can be estimated from table 13.7.

Shallow concentrated flow is the fate of sheet flow after a maximum of 300 feet. Velocity, V, is dependent on channel slope and can be estimated with figure 13.17 (TR 55 figure 3–1) for paved or unpaved channels. Travel time can then be calculated from equation 13–4.

Open channel flow applies to intermittent and perennial channels (where blue lines appear on USGS quadrangle sheets). Flow velocity is determined by Manning's equation, which requires information on channel shape, slope, and roughness. (See appendix 13.D for open channel roughness [n].)

$$V = \frac{1.49 r^{2/3} s^{1/2}}{n} \qquad \text{(Manning's equation)} \qquad \textit{(Eq. 13–6)}$$

where V = average velocity (ft/s)
r = channel full hydraulic radius (ft)
$r = a/p_w$, where a = cross-sectional flow area (ft²)
p_w = wetted perimeter (ft) (see figure 13.16)
s = slope of hydraulic grade line (channel slope, ft/ft)
n = Manning's roughness coefficient for open channel flow

TABLE 13.7 **Roughness Coefficients (Manning's n) for Sheet Flow (TR55 table 3–1)**

Surface Description	*n*
Smooth surfaces (concrete, asphalt, gravel, or bare soil)	0.01[illegible]
Fallow (no residue)	0.0[illegible]
Cultivated soils:	
Residue cover ≤20%	[illegible]
Residue cover >20%	[illegible]
Grass:	
Short grass prairie	[illegible]
Dense grasses[2]	[illegible]
Bermudagrass	[illegible]
Range (natural)	[illegible]
Woods:[3]	
Light underbrush	[illegible]
Dense underbrush	[illegible]

[1]The n values are a composite of information compiled by Engman (1986) [illegible]

[2]Includes species such as weeping lovegrass, bluegrass, buffalo grass, blue gra[illegible] native grass mixtures.

[3]When selecting n, consider cover to a height of about 0.1 ft. This is the only par[illegible] cover that will obstruct sheet flow.

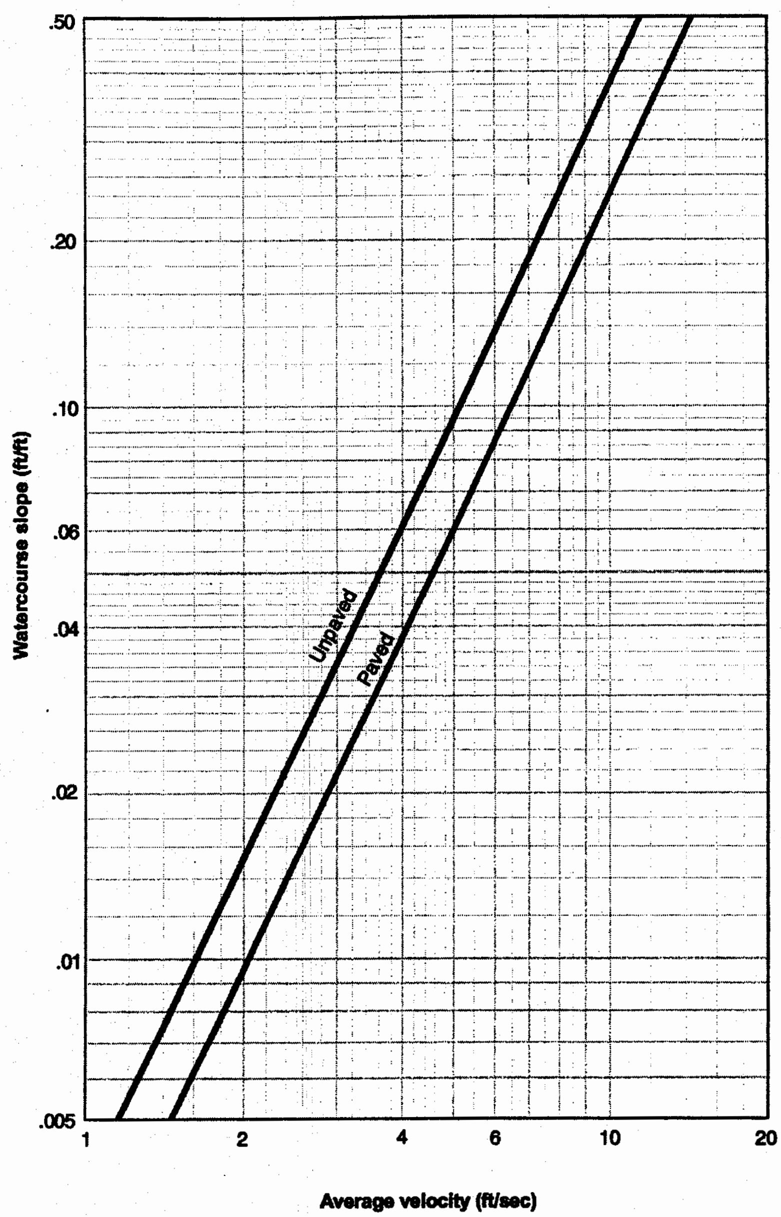
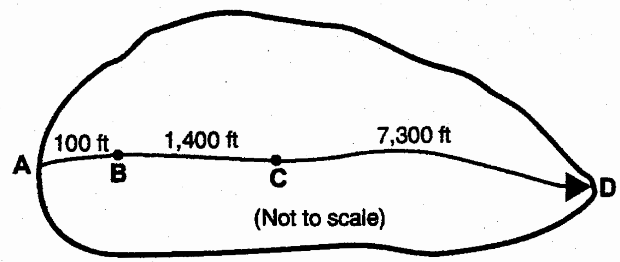


Figure 13.17 Velocity for Shallow Concentrated Flow. (TR55 figure3–1) *Source:* USDA (1986).

The T_t is calculated for each flow segment using Worksheet 3. The T_c is the sum of the T_ts.

Example 3-1: The sketch below shows a watershed in Dyer County, northwestern Tennessee. The problem is to compute T_c at the outlet of the watershed (point D). The 2-year 24-hour rainfall depth is 3.6 inches. All three types of flow occur from the hydraulically most distant point (A) to the point of interest (D). To compute T_c, first determine T_t for each segment from the following information (see Worksheet 3):



Segment AB: Sheet flow; dense grass; slope (s) = 0.01 ft/ft; and length (L) = 100 ft.
Segment BC: Shallow concentrated flow; unpaved; s = 0.01 ft/ft; and L = 1,400 ft.
Segment CD: Channel flow; Manning's n = .05; flow area (a) = 27 ft2; wetted perimeter (pw) = 28.2 ft; s = 0.005 ft/ft; and L = 7,300 ft.

Worksheet 3: Time of Concentration (T_c) or travel time (T_t)

Project: Heavenly Acres	By: DW	Date: 10/6/85
Location: Dyer County, Tennessee	Checked: NM	Date: 10/8/85

Check one: ☐ Present ☒ Developed

Check one: ☒ T_c ☐ T_t through subarea

Notes: Space for as many as two segments per flow type can be used for each worksheet.
Include a map, schematic, or description of flow segments.

Sheet flow (Applicable to T_c only)

Segment ID	AB			
1. Surface description (table 3-1)	Dense Grass			
2. Manning's roughness coefficient, n (table 3-1)	0.24			
3. Flow length, L (total L ≤ 300 ft) ... ft	100			
4. Two-year 24-hour rainfall, P_2 ... in	3.6			
5. Land slope, s ... ft/ft	0.01			
6. $T_t = \frac{0.007\ (nL)^{0.8}}{P_2^{0.5}\ s^{0.4}}$ Compute T_t ... hr	0.30	+		= 0.30

Shallow concentrated flow

Segment ID	BC			
7. Surface description (paved or unpaved)	Unpaved			
8. Flow length, L ... ft	1400			
9. Watercourse slope, s ... ft/ft	0.01			
10. Average velocity, V (figure 3-1) ... ft/s	1.6			
11. $T_t = \frac{L}{3600\ V}$ Compute T_t ... hr	0.24	+		= 0.24

Channel flow

Segement ID	CD			
12. Cross sectional flow area, a ... ft^2	27			
13. Wetted perimeter, p_w ... ft	28.2			
14. Hydraulic radius, $r = \frac{a}{p_w}$ Compute r ... ft	0.957			
15 Channel slope, s ... ft/ft	0.005			
16. Manning's roughness coefficient, n ...	0.05			
17. $V = \frac{1.49\ r^{2/3}\ s^{1/2}}{n}$ Compute V ... ft/s	2.05			
18. Flow length, L ... ft	7300			
19. $T_t = \frac{L}{3600\ V}$ Compute T_t ... hr	0.99	+		=
20. Watershed or subarea T_c or T_t (add T_t in steps 6, 11, and 19) ... Hr				

TABLE 13.8 I_a Values for Runoff Curve Numbers (TR55 table 4–1)

Curve Number	I_a (in)	Curve Number	I_a (in)
40	3.000	70	0.857
41	2.878	71	0.817
42	2.762	72	0.778
43	2.651	73	0.740
44	2.515	74	0.703
45	2.444	75	0.667
46	2.348	76	0.632
47	2.255	77	0.597
48	2.167	78	0.564
49	2.082	79	0.532
50	2.000	80	0.500
51	1.922	81	0.469
52	1.816	82	0.439
53	1.77	83	0.410
54	1.704	84	0.381
55	1.636	85	0.353
56	1.571	86	0.326
57	1.509	87	0.299
58	1.448	88	0.273
59	1.360	89	0.247
60	1.333	90	0.222
61	1.279	91	0.198
62	1.226	92	0.174
63	1.175	93	0.151
64	1.125	94	0.128
65	1.077	95	0.105
66	1.000	96	0.083
67	0.985	97	0.062
68	0.941	98	0.041
69	0.899		

STEP 3 Worksheet 4 computes the peak discharge.

(Needed: drainage area, design storm (P), *CN*, and Q [from Worksheet 2], T_c [from Worksheet 3])

The peak discharge, q_p, for the design 24-hour storm over the watershed is calculated by the following equation:

$$q_p = q_u A_m Q F_p \qquad \text{(Eq. 13–7)}$$

where q_p = peak discharge (cfs)
q_u = unit peak discharge (csm/in: cfs per mi^2 per inch of runoff)
A_m = drainage area (mi^2)
Q = runoff (in)
F_p = pond and swamp adjustment factor

The drainage area, A_m, is known and the runoff, Q, was calculated in Worksheet 2. The pond and swamp adjustment factor, F_p, takes account of the potential

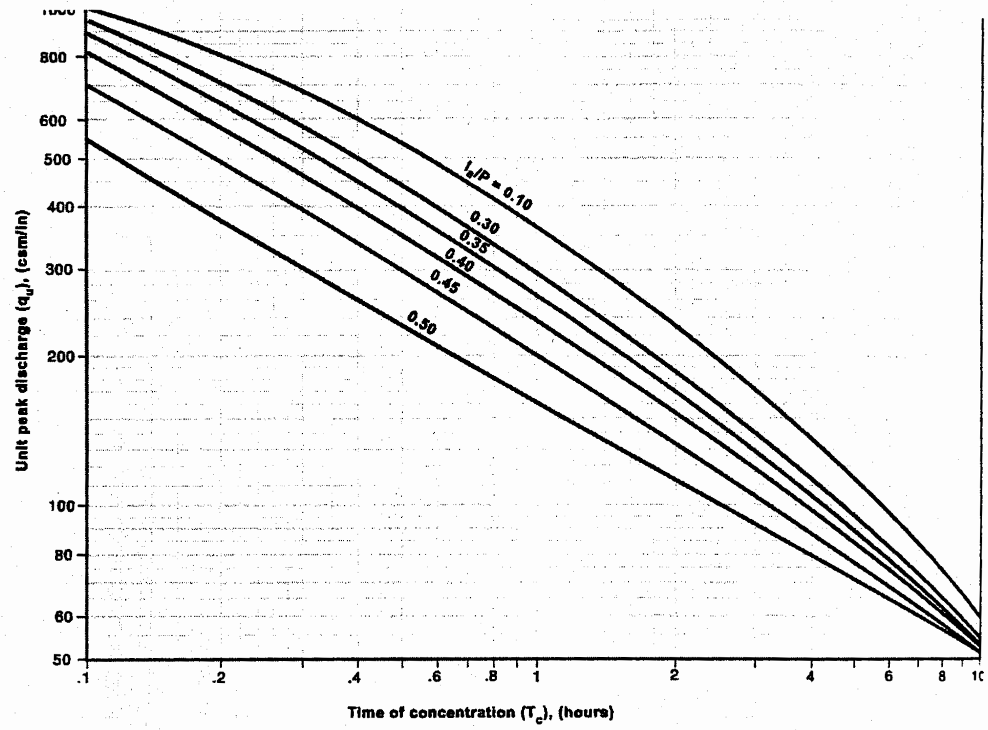


Figure 13.18 Unit Peak Discharge for Type II Rainfall Distribution. (TR55 exhibit 4–II) *Source:* USDA (1986).

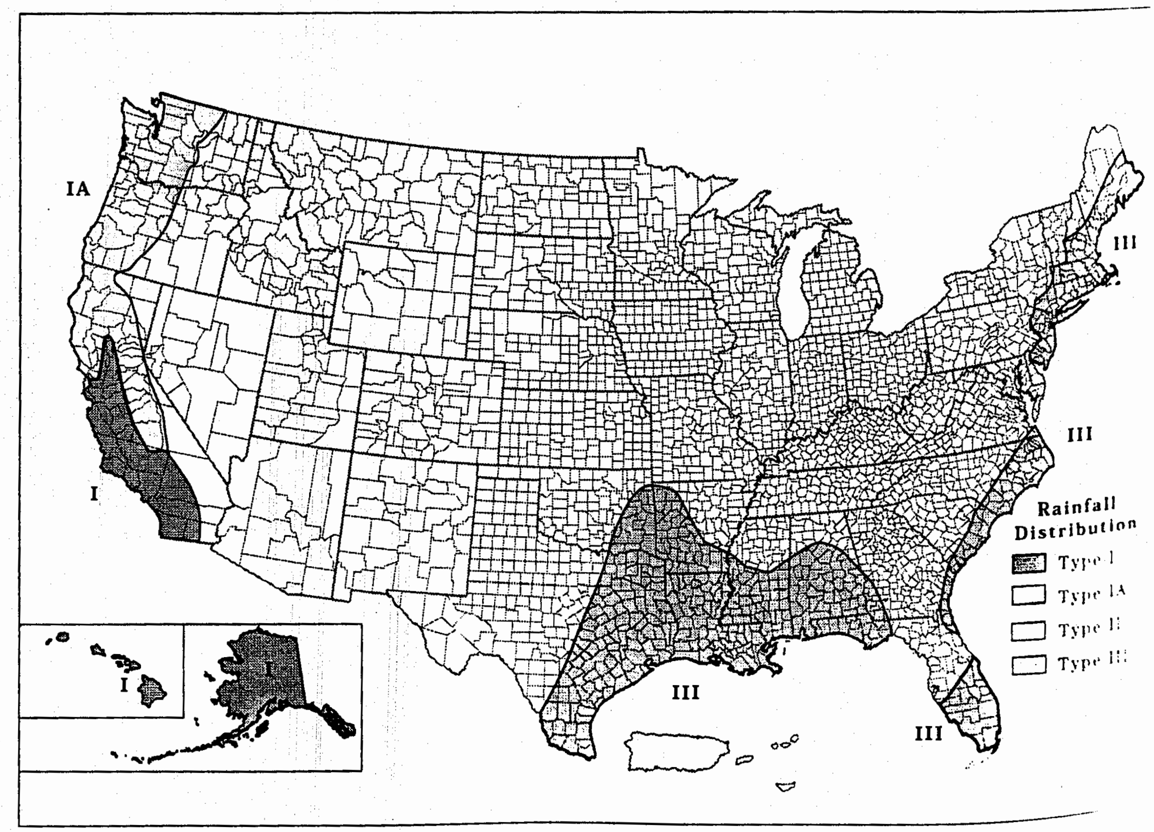


Figure 13.19 Rainfall Distribution Types. *Source:* USDA (1986).

Worksheet 4: Graphical Peak Discharge method

Project: Heavenly Acres	By: RHM	Date: 10/15/85
Location: Dyer County, Tennessee	Checked: NM	Date: 10/17/85

Check one: ☐ Present ☒ Developed

1. Data

Drainage area .... A_m = 0.39 mi² (acres/640)

Runoff curve number .... CN = 75 (From worksheet 2), Figure 2-6

Time of concentration .... T_c = 1.53 hr (From worksheet 3), Figure 3-2

Rainfall distribution .... = II (I, IA, II III)

Pond and swamp areas sprea throughout watershed .... = -- percent of A_m (-- acres or mi² covered)

	Storm #1	Storm #2	Storm #3
2. Frequency .... yr	25		
3. Rainfall, P (24-hour) .... in	6.0		
4. Initial abstraction, I_a .... in (Use CN with table 4-1)	0.667		
5. Compute I_a/P	0.11		
6. Unit peak discharge, qu .... csm/in (Use T_c and I_a/P with exhibit 4– II)	270		
7. Runoff, Q .... in (From worksheet 2). Figure 2-6	3.28		
8. Pond and swamp adjustment factor, F_p .... (Use percent pond and swamp area with table 4-2. Factor is 1.0 for zero percent pond ans swamp area.)	1.0		
9. Peak discharge, q_p .... cfs (Where $q_p = q_u A_m Q F_p$)	345		

reduction in time of concentration, and therefore peak discharge, caused by ponding or wetlands in the watershed. Table 13.9 gives values for F_p for pond and swamp areas up to 5 percent of the watershed area. The unit peak discharge, q_u, is the peak discharge per square mile per inch of runoff. It is estimated using figure 13.18, based on the rainfall distribution type, time of concentration (T_c), and a ratio, I_a/P, called the initial abstraction over P. Values of I_a depend on CN values and are given in table 13.8. Rainfall distribution type is given in figure 13.19. Worksheet 4 is used to calculate q_p.

Example 4–1: Compute the 25-year peak discharge for the 250-acre watershed described in examples 2–2 and 3–1: CN = 75, Q = 3.28 in., T_c = 1.53h. Worksheet 4 is used to compute q_p as 345 cfs.

TABLE 13.9 **Adjustment Factor (*Fp*) for Pond and Swamp Areas that are Spread Throughout the Watershed (TR55 table 4–2)**

Percentage of Pond and Swamp Areas	*Fp*
0	1.00
0.2	0.97
1.0	0.87
3.0	0.75
5.0	0.72

Effects of Land Use on Water Quality

In addition to affecting runoff quantity, land use also impacts water quality as surface runoff from cultivated, disturbed, and developed land carries water contaminants to receiving waters. Before focusing on land use and nonpoint source pollution, the following section provides some water quality fundamentals.

Water Quality Fundamentals

In the United States, we have made considerable progress in the past 30 years cleaning up our waterways and improving the safety of water for humans and aquatic life, primarily through improved engineering treatment at municipal sewage treatment plants and industrial facilities. We have doubled the number of waterways safe for fishing and swimming, doubled the number of Americans served by adequate sewage treatment, and reduced soil erosion from cropland by one-third. However, much remains to be done (U.S. EPA, 2000a, 2000b, 2002

- In 1998, about 70 percent of Americans lived within 10 miles of polluted waters, and 300,000 miles of rivers and 5 million acres of lakes did not meet water quality standards.
- One-third of the 1,062 beaches reporting to the EPA had at least one health advisory or closing.
- More than 2,500 fish consumption advisories or bans were issued where fish were too contaminated to eat.
- The EPA estimates at least a half-million cases of illness annually can be attributed to microbial contamination of drinking water. In 1999, community water systems serving 1 of every 10 people reported a health standard violation.

- Of our waters that were monitored in 2000, 39 percent of river miles, 45 percent of lake area, and 54 percent of estuary area were too polluted for safe fishing or swimming.

The primary focus has shifted from municipal and industrial dischargers to runoff pollution from nonpoint sources (NPS). Indeed, national water quality assessments indicate that 60 to 70 percent of the nation's waters not meeting water quality standards are impaired by NPS pollution.

Before addressing NPS pollution, this section introduces some water quality fundamentals, including water pollutants and standards. The following sections review stream quality assessment and sources and impacts of NPS. Measures and programs to control stormwater quality problems are discussed in the next chapter.

Water Pollutants

Water quality is a complex subject, and it is useful to provide an overview of some basic scientific concepts. Table 13.10 describes the major classes of water contaminants, including sources, effects, measurement, and controls. Major pollutants carried by surface runoff include the following:

- **Oxygen-demanding** or **organic wastes** deplete water's **dissolved oxygen (DO)** that is needed to support aquatic life through biological decomposition. Water bodies gain oxygen from atmospheric aeration and photosynthesizing plants. But they also consume oxygen through respiration by aquatic life, decomposition, and various chemical reactions. Wastewater from runoff or treatment plants contains organic materials that are decomposed by microorganisms, using oxygen in the process. The strength of the wastes is measured by the oxygen required to decompose them, so-called biochemical oxygen demand (BOD). Biological treatment uses the natural decomposition process to stabilize organic waste.
- **Plant** or **inorganic nutrients,** such as phosphorus and nitrogen, contribute to excessive growth of algae and other undesirable aquatic vegetation in water bodies. Phosphorus is the limiting nutrient in most fresh waters, so even a modest increase in phosphorus can set off a chain of undesirable events in a stream, including accelerated plant growth, algae blooms, low dissolved oxygen, and the death of certain aquatic animals. Nitrogen is also an essential nutrient and is present in organic form as well as inorganic ammonia (NH_3), nitrates (NO_3), and nitrites (NO_2). Total Kjeldahl nitrogen (TKN) is the sum of ammonia and organic nitrogen. Together with phosphorus, nitrates and ammonia in excess amounts can accelerate aquatic plant growth and change the types of plants and animals that live in the stream. This, in turn, affects dissolved oxygen, temperature, and other indicators. Nutrients can be removed by advanced physical and chemical treatment, but biological treatment using vegetation uptake is also effective.

TABLE 13.10 **Water Pollutants, Sources, and Effects**

Water Pollutant	*Sources*	*Effects*	*Measurement*	*Controls*
Organic oxygen demanding wastes	Sewage, industry, runoff	Depletes DO; alters life forms; fish kills	BOD_5	Biological treatment
Plant nutrients	Sewage, agricultural and urban runoff, industry	Algae growth, waterweeds	Nitrogen, phosphorus	Advanced treatment, biological treatment
Thermal effluent	Power plants, industry, impervious surfaces	Accelerates decomp., biological activity; reduces DO solubility	Temperature	Cooling towers, ponds
Sediment, suspended particles	Runoff	Reduces clarity; smothers bottom life	Turbidity	Settling
Minerals, salts	Agricultural runoff	Taste; inhibits freshwater plants	Total dissolved solids (TDS)	Desalination; chemical treatment
Synthetic, volatile organic chemicals: e.g., oil, pesticides	Industry, spills, agri. runoff, air pollution	May be toxic to aquatic life, humans; subject to biomagnification	Chemical analysis	Activated carbon filtration
Inorganic chemicals (e.g. acids, heavy metals)	Industry, mining runoff, air pollution	May be toxic to aquatic life, humans; may be subject to biomagnification	Chemical analysis	Chemical treatment
Radioactive substances	Nuclear fuel cycle, medical wastes, industry	Toxic to aquatic life, humans	Chemical analysis, beta count	Isolation, chemical treatment
Pathogenic organisms	Sewage	Disease transmission	Fecal coliform count	Disinfection

- **Suspended solids** cause sedimentation in receiving waters. They include particles that will not pass through a 2-micron filter, including silt and clay, plankton, algae, fine organic debris, and other particulate matter. They can serve as carriers of toxics like pesticides, which readily cling to suspended particles. Solids are removed by settling in detention facilities.
- **Dissolved solids** consist of calcium, chlorides, nitrate, phosphates, iron, sulfur, and other ions particles that will pass through a filter with pores of around 2 microns (0.0002 cm). Dissolved solids affect the water balance in the cells of aquatic organisms. Removal requires advanced physical treatment like reverse osmosis or desalination.
- **Acidity and alkalinity** are measured by pH on a scale from 1.0 (very acidic) to 14.0 (very alkaline), with 7.0 being neutral. pH affects many chemical and biological processes in the water. For example, different organisms flourish within different ranges of pH. Most aquatic animals prefer a range of 6.5–8.0. pH outside this range reduces the diversity in the stream. Low pH can also allow toxic compounds to become available for uptake by aquatic plants and animals. Alkalinity is a measure of the capacity of water to neutralize acids.

- **Synthetic volatile organic chemicals (VOC)** are used in petroleum products and pesticides, which are toxic to humans and aquatic life. Biological treatment can reduce concentrations, but carbon filtration is most effective.
- **Inorganic chemicals,** such as toxic heavy metals, include mercury, lead, zinc, copper, and cadmium. They can biomagnify in concentration in higher levels of the food chain and are a prevalent cause of fish advisories.
- **Disease-causing microorganisms** include pathogenic bacteria, viruses, and protozoans that also live in human and animal digestive systems. Members of two bacteria groups, coliforms and fecal streptococci, are used as indicators of possible sewage contamination because they are commonly found in human and animal feces. Disinfection reduces microbial contamination. In addition, natural waters can provide breeding areas for carriers of disease, such as mosquitoes, which carry malaria and the West Nile virus.

Water Bodies and Beneficial Uses

The effects of these pollutants depend on the quality and beneficial uses of the natural waters that receive them. The major types of water bodies include freshwater streams and rivers, freshwater lakes and wetlands, mixed fresh- and saltwater estuaries, coastal and marine waters, and groundwater. **Streams'** self-flushing and aerating action gives them some assimilative capacity for conventional pollutants such as organics, nutrients, suspended particles, and waste heat. However, the natural quality of streams varies widely from pristine headwaters to more nutrient-enriched downstream waters. Streams and rivers are used for a wide range of **beneficial uses,** including water supply, recreation, fish propagation, agricultural and industrial use, and waste assimilation.

Lakes have much lower assimilative capacity because of poor flushing. As a result, pollutants tend to accumulate in lakes; sediments fill up lake bottoms, nutrients contribute to growth of algae and other undesirable vegetation, and organics consume dissolved oxygen. This is a natural process called **eutrophication,** or aging of lakes, and it will ultimately reduce the lake's beneficial uses for water supply, fish propagation, recreation, and aesthetics. Under natural conditions this process may take centuries. However, runoff pollution containing nutrients and sediments can accelerate this natural process. This human-induced "cultural" eutrophication can occur in decades. Natural lakes and human-made reservoirs are both subject to the same process of aging. Lakes have a much longer residence time (so pollutants will accumulate more) but have a smaller watershed (which may be easier to manage). Reservoirs have a shorter residence time and more through-flow and flushing, but their much larger watersheds can contribute more pollutants and be more difficult to control.

Estuaries are subject to some of the same processes as lakes and rivers, since some have flows and flushing (including intertidal mixing) like rivers, and others are more stagnant bays that behave like lakes. As important breeding and development habitats for fish and shellfish, estuaries have special needs because pollution can easily disrupt fish growth or contaminate populations with resulting economic impacts. **Coastal** and especially **marine waters** have the largest assimilative capacity for water pollutants, but pollution can impact coastal waters for recreation and fishing.

Groundwater is the fourth type of water body. As we shall see in chapter 15, groundwater encounters complex flow, filtering, and chemical processes. Because groundwater from private wells is often used for domestic water supply without treatment, groundwater quality concerns relate more to human health than to ecological health.

Water Quality Criteria and Standards

The 1972 federal Clean Water Act (CWA), as amended in 1977 and 1987, provides the framework for the nation's management of water quality. The Act sets forth a national goal of achieving a level of quality in all waters to support recreation and fish consumption, so-called *fishable and swimmable* quality. To define this threshold, the Act, and its administering agency the U.S. EPA, called on the states to establish water quality standards for their water bodies, monitor compliance, and manage pollutant discharges to meet these standards. The CWA's management programs for nonpoint sources are discussed in the next chapter.

The process of establishing water quality standards begins by the states' designating the beneficial uses of individual water bodies. The Act's goals call for minimum standards for recreation and propagation of aquatic life, but certain water bodies or reaches of streams may have beneficial uses (e.g., sources of community water supply or trout waters) that require higher standards. The states then determine criteria, such as chemical-specific thresholds or descriptive conditions, that aim to protect these beneficial uses. In addition, the Act provides an antidegradation policy to prevent waters that meet the standards from deteriorating from current conditions (U.S. EPA, 2000a). Natural surface waters are classified based on their natural quality and their beneficial uses, and water quality standards are assigned to different classifications.

Table 13.11 gives the classification system used in Washington State as an illustration. Five different classes of waters are assigned to each water body in the state. The table lists the basic criteria for different classes of fresh water. The same classes are assigned to marine waters as well, but with different standards. Management of both point and nonpoint sources of water pollution aims to achieve and maintain these water quality standards (Washington State Code, 1997). For water quality standards (WQS) for each state see http://www.epa.gov/ost/wqs/.

Impaired Waters in the United States

Section 305(b) of the CWA calls on the states to assess every two years the health of their waters and progress toward meeting the standards and goals of the Act. In addition, section 303(d) requires the states to identify and prioritize all of their "impaired" waters, or those that do not meet their water quality standards. States group their assessed waters into the following categories:

TABLE 13.11 Classification of Waters and Fresh Water Quality Standards in Washington State[7]

Class	*Fecal Col*[1]	*DO*[2]	*Temp*[3]	*pH*[4]	*Turbidity*[5]	*Toxics*[6]
AA (outstanding)	50	9.5	16	6.5–8.5	5	Max. 31
A (excellent)	100	8.0	18	6.5–8.5	5	Max. 31
B (good)	200	6.5	21	6.5–8.5	10	Max. 31
C (fair)	200	4.0	22	6.5–8.5	10	Max. 31
Lake[8]	50	Nat'l	Nat'l	Nat'l	5	Max. 31

[1]Fecal coliform count: maximum colonies per 100 milliliters (ml)
[2]Dissolved oxygen: minimum milligrams/liter
[3]Temperature: maximum °C
[4]pH: within range
[5]Turbidity: maximum nephelometric turbidity units (NTU)
[6]Toxics: maximum levels of 31 listed toxic, radioactive, deleterious materials
[7]WQS also provided for marine waters; all fresh and marine waters are assigned a classification
[8]Lake class: DO, Temp, pH shall not exceed natural conditions
(Source: WAC, 1997)

1. Attaining WQS
   a. Good/Fully Supporting: meets WQS
   b. Good/Threatened: meets WQS but may degrade in near future
2. Impaired, Not Attaining WQS
   a. Fair/Partially Supporting: meets WQS most of the time but occasionally exceeds them
   b. Poor/Not Supporting: does not meet WQS
3. WQS not attainable
   a. Use-attainability analysis shows that one or more designated uses is not attainable because of specific conditions.

Table 13.12 summarizes the *2000 National Water Quality Inventory* results (U.S. EPA, 2002). It shows five types of surface water bodies, their total length or area, the percentage that was assessed, and the assessment ratings. This assessment is becoming more comprehensive each time it is done. In 2000, 180,000 more stream miles were assessed than in 1996. Percent impairment increased from 1998 to 2000 for all categories except the Great Lakes.

Table 13.13 shows the uses impaired and stressors (pollutants) and sources of impairment for rivers and streams, lakes, and estuaries. Common uses impaired for all three water bodies are aquatic life, fish consumption, and swimming. Thirty-eight percent of assessed rivers are impaired for fish consumption, 34 percent for aquatic life, 28 percent for primary contact like swimming, and 14 percent for drinking water supply. Several pollutants are problematic, led by pathogens, sil-

TABLE 13.12 **Quality of Nation's Waters, 2000**

Water Body	*Total Length or Area*	*Assessed (%)*	*Assessment*			
			Good (%)	*Good, But Threatened (%)*	*Impaired 2000 (%)*	*Impaired 1998 (%)*
Rivers, streams	3.69 million miles	19	53	8	39	35
Lakes, ponds, reservoirs	40.6 million acres	43	47	8	45	45
Estuaries	31,072 sq. mi.	36	45	<4	51	44
Ocean shoreline waters	66,600 miles	5	79	7	14	12
Great Lakes shoreline waters	5,500 miles	92	0	22	78	96

Source: U.S. EPA, 2000a, 2002

TABLE 13.13 **Causes and Sources of Impaired Waters in United States, 2000 (With Percent of Assessed Waters Impaired for Uses and by the Stressors and Sources)**

	Rivers and Streams	*Lakes, Ponds, and Reservoirs*	*Estuaries*
Uses Impaired	Fish consumption (38%)	Fish consumption (35%)	Aquatic life (52%)
	Aquatic life (34%)	Aquatic life (29%)	Fish consumption (48%)
	Swimming (28%)	Swimming (23%)	Shellfishing (25%)
	Drinking water (14%)	Drinking water (17%)	Swimming (15%)
Stressors	Pathogens (Bacteria) (35%)	Nutrients (50%)	Metals (Primarily mercury) (52%)
	Siltation (Sedimentation) (31%)	Metals (Primarily mercury) (42%)	Pesticides (38%)
	Habitat alterations (22%)	Siltation (Sedimentation) (21%)	Oxygen demanding (34%)
	Oxygen demanding (21%)	Total dissolved solids (19%)	Pathogens (30%)
	Nutrients (20%)	Oxygen demanding (15%)	Toxic organic (23%)
Sources	Agriculture (48%)	Agriculture (41%)	Municipal point sources (37%)
	Hydrologic modifications (20%)	Hydrologic modifications (18%)	Urban runoff/storm sewers (32%)
	Habitat modifications (14%)	Urban runoff/storm sewers (18%)	Industrial discharges (26%)
	Urban runoff (13%)	Other nonpoint sources (14%)	Atmospheric deposition (24%)

Source: EPA, 2002

tation, organics, nutrients, and metals. Main sources of impairment are agricultural and urban runoff and stream modification.

For lakes, 35 percent are impaired for fish consumption, 29 percent for aquatic life, 23 percent for primary contact, and 17 percent for drinking water supply. Main pollutants causing impairment are nutrients (50%), metals (42%), siltation, organics, and dissolved solids (each 15–20%). Main sources are agricultural runoff (41%), hydromodification (18%) and urban runoff (18%). Hydromodification is conversion of natural channels or shoreline construction. Pathogens, organics, pesticides, metals, and nutrients from municipal point sources, urban runoff, and atmospheric deposition are the major causes of impairment in estuaries. Fish consumption (48%), aquatic life (52%), and shellfishing (25%) are the main estuary uses not supported (U.S. EPA, 2000a).

The Great Lakes are the most assessed and impaired of the nation's waters. Major uses impaired are fish consumption (78%) and aquatic life (12%). Toxic organic and other organic chemicals, pesticides, and nutrients from atmospheric deposition and discontinued sources are the main sources of impairment. The discontinued industrial discharges and contaminated sediments are the legacy of past pollution (U.S. EPA, 2000a).

Figure 13.20 shows the percentage of impaired waters within watersheds for 1998. All of these data on the nation's water quality demonstrate that despite significant improvements in the past 30 years since the passage of the Clean Water Act, we are far from achieving the goals of the Act. They also show that the main sources of remaining pollution are not the traditional industrial and sewage pipe discharges, but more diffuse land runoff and atmospheric deposition.

Indicators of Water Quality

Water quality criteria and standards provide the basis for most indicators of water quality. Thousands of monitoring stations throughout the country operated by state and federal agencies measure many of the traditional physical and chemical constituents: dissolved oxygen, biochemical oxygen demand, forms of nitrogen and phosphorus, pesticides, heavy metals, and others. These data are stored in two national water databases, STORET (1999 and after) and the Legacy Data System (before 1999), and are accessible on the Internet (see http://www.epa.gov/storet/about.html). Some of these data are available in real time.

Water monitoring has historically focused on chemical and physical constituents. In the past decade, a broader range of indicators have been used to monitor water quality to represent expanding interests in aquatic ecology and watershed health. For example, the EPA has developed a database from various sources to indicate overall watershed integrity. Box 10.2 lists the 22 indicators of watershed integrity (IWI) (www.epa.gov/iwi/help/indic/fs1.html).

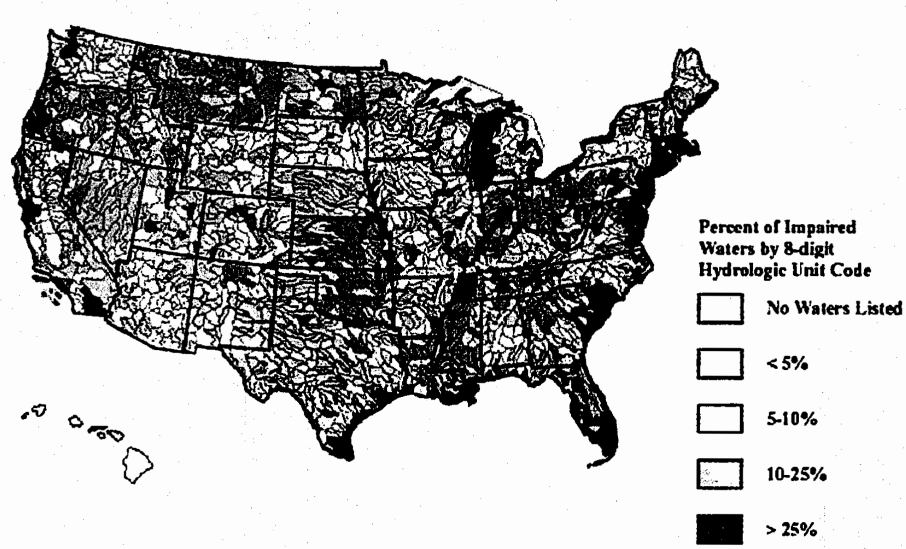


Figure 13.20 Percentage of Impaired Waters by Eight-Digit Hydrologic Unit Code. *Source:* U.S. EPA (2000b).

Biological monitoring samples fish and macroinvertebrate species that indicate overall health of water systems rather than a snapshot look at water quality constituents. Different approaches to water body assessment include watershed surveys and habitat assessment for measuring physical conditions, macroinvertebrate sampling to measure biological condition, and measuring water quality constituents to reveal chemical conditions. See later section and appendices 13.B–C.

Because national data monitoring cannot address all local water quality problems, agencies have encouraged volunteer groups to provide information they monitor. As discussed later in this chapter, volunteer water quality monitoring, through groups like the Izaak Walton League's Save Our Streams (SOS) program, has improved in sophistication and reliability. By the early 1990s, 38 states had volunteer programs with over 24,000 participants monitoring 1,000 streams; 2,800 lakes, ponds, and wetlands; and four major estuaries. These programs have gained the respect of state and federal environmental agencies, which have adopted volunteer-gathered data in their water quality databases.

Land Use Practices and Nonpoint Sources (NPS) Pollution

As already mentioned more than half of the pollutants entering the nation's waters comes from runoff. The most pervasive problem is agricultural sources (affecting more than 60% of all river basins), followed by urban sources (runoff, hydromodification, discharges) (affecting 50%), mining runoff (10%), and silvicultural runoff (10%).

Figure 13.21 gives an overview of land use practices that cause runoff pollution (first column), the results and consequences to receiving waters (second and third columns), and potential controls (fourth column). The table is divided into the major land uses and practices causing NPS pollution: agriculture crop production, agriculture animal production, forestry, mining, and urban development. Some examples include the following:

- **Soil disturbance** caused by agricultural cultivation and land development can result in erosion that will cause sedimentation of streams, lakes, or estuaries, which can smother bottom feeding or benthic organisms. Conservation tillage (which leaves some crop residue to reduce erosion), contour cropping, or filter strips aim to control agricultural erosion at the source, while level spreaders, filters strips, ponds, and wetlands can remove suspended solids before they enter waterways.
- **Excessive use of fertilizer** in agriculture or urban uses can result in runoff laden with plant nutrients, which can lead to algal growth in lakes and estuaries. Nutrient management programs aim to control excess application by calculating fertilizer loading to match plant uptake. Filter strips and vegetative buffers can absorb nutrients before they enter waterways.
- **Pesticides** used in agriculture, silviculture, and urban land uses, can be carried by runoff contributing to toxic pollution of receiving waters. Input management and integrated pest control (which relies on nonchemical means of pest management and selective chemical use) can reduce pesticide pollution.

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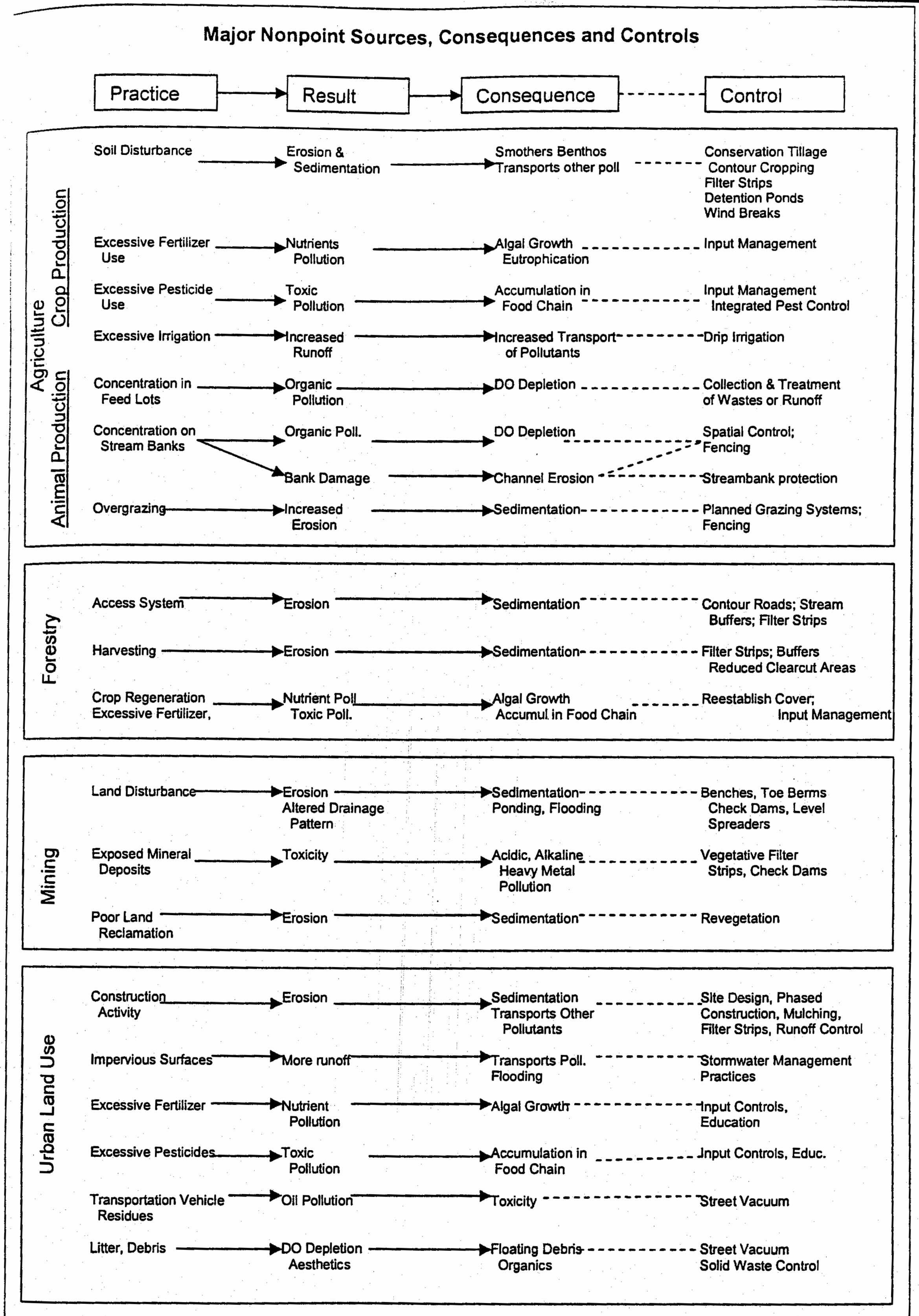

Figure 13.21 Major Nonpoint Sources, Consequences, and Controls

- **Animal concentration in feedlots** produces large amounts of organic wastes that can be carried by runoff in high concentrations and overload receiving waters, depleting the water's dissolved oxygen and causing fish kills. For such concentrated facilities, collection and treatment of runoff is generally required.
- **Animals grazing in open pasture** can overgraze available grass, exposing soil and creating erosion problems. In addition, animals tend to concentrate on stream banks, the so-called *cows-in-creeks syndrome,* which causes organic pollution and destruction of channel banks. Spatial control through fencing is necessary to reduce impact.
- **Mining disturbs the land,** not only creating conditions for erosion, but also often altering drainage patterns. Benches cut into slopes, check dams, and level spreaders can help alleviate runoff and pollution problems during operations. Extensive reclamation and revegetation of mined lands is necessary to solve long-term erosion and NPS problems.
- In forestry operations, **cutting of access roads and harvesting methods** increase erosion, particularly in proximity to stream channels and with greater land disturbance. Controls include building roads and trails along contours and providing vegetated or artificial filter strips to intercept runoff, and maintaining natural buffers along water bodies.
- **Urban runoff** carries
  - sediment from construction activities;
  - nutrients and pesticides from excessive uses on lawns, gardens, and golf courses;
  - organic material and floating debris from roadside litter; and
  - petrochemicals and toxic substances from transportation residues and air pollution fallout. More than one-half of the substances on EPA's list of 129 priority toxic chemicals have been found in urban runoff.
- **Hydraulic modification** of channels, shorelines, and riparian areas for drainage or land development is another source of pollution into waterways and cause of channel and habitat destruction.

Urban Runoff and the First Flush Effect

Urban runoff pollutants are carried in highest concentration during the first part of a storm event, the so-called **first flush** effect. Monitoring and modeling research in the early to mid-1970s established a simple standard that was adopted by many communities trying to control stormwater pollution: Size your stormwater control measure to capture the runoff from the first portion of a storm, and you'll treat 90 percent of the annual pollutant load. As a result, urban stormwater pollution control strategies normally focus on a storm's initial runoff or use a lower frequency or smaller design storm. For example, an area's 1-year 24-hour storm may be 2 inches and its 10-year 24-hour storm is 5 inches. Although we may wish to control stormwater from the larger storm to mitigate flooding, controlling runoff from the smaller storm may be sufficient to manage water quality.

For many years it was believed that this 90 percent objective could be achieved by capturing and treating the first half-inch of runoff in any storm. This "half-inch" rule was adopted in many ordinances, but field studies showed that though it was effective in areas of 30 percent and less impervious cover, the half-inch runoff carried less than 90 percent at greater imperviousness. One study showed that at 50 percent impervious cover, the first half-inch carried 75 percent of TSS, and at 70 percent it carried only 53 percent (Chang, Parrish, and Souer, 1990).

As a result, rather than assuming the first "half-inch" rule, stormwater controls now calculate the **"water quality volume"** (WQ_v) or the volume of storage needed to capture and treat 90 percent of the average annual stormwater pollutant load, based on impervious surface. These calculations are discussed in the next chapter.

Estimating Runoff Pollution: The Simple Method

The Simple Method was developed by Schueler (1987) to estimate pollutant loads from an urban site or catchment. The method has been shown to give reasonable results compared with more complex models (Ohrel, 1996).

The **pollutant load equation** for chemical contaminants is the following:

$$L = 0.226 \times R \times C \times A$$

where L = Annual load (lbs)
R = Annual runoff (inches)
C = Pollutant concentration (mg/l)
A = Area (acres)
0.226 = Unit conversion factor

The modified equation for bacteria is:

$$L = 103 \times R \times C \times A$$

where L = Annual load (Billion Colonies)
R = Annual runoff (inches)
C = Bacteria concentration (1,000/ ml)
A = Area (acres)
103 = Unit conversion factor

The **annual runoff (R)** is the product of annual rainfall, and a runoff coefficient (R_v).

$$R = P \times P_j \times R_v$$

where R = Annual runoff (inches)
P = Annual rainfall (inches)
P_j = Fraction of annual rainfall events that produce runoff (usually 0.9)
R_v = Runoff coefficient

TABLE 13.14 **Pollutant Concentrations from Source Areas**

Constituent	*TSS*	*TP*	*TN*	*F Coli*	*Cu*	*Pb*	*Zn*
Land Use/Units	mg/l	mg/l	mg/l	1000 col/ml	μg/l	μg/l	μg/l
Urban average	55	0.26	2.0	1.5	51	129	11.1
Residential roof	19	0.11	1.5	0.26	20	21	312
Res./com. parking	27	0.15	1.9	1.8	51	28	139
Residential street	172	0.55	1.4	37	25	51	173
Lawns	602	2.1	9.1	24	17	17	50
Gas station	31	—	—	—	88	80	290
Heavy industry	124	—	—	—	148	290	1600

Sources: New York, 2002; Schueler, 1999; Smullen and Cave, 1998; Clayton and Schueler, 1996; Steuer, et al., 1997

The **runoff coefficient (R_v)** is calculated based on impervious cover in the sub-watershed.

$$R_v = 0.05 + 0.9I_a$$

where I_a = Impervious fraction

The stormwater **pollutant concentration (C)** is usually estimated from national data. Table 13.14 gives average data from a number of monitoring studies of urban stormwater for concentrations of pollutants from various urban land uses. The Simple Method assumes these values. If a catchment or site has a mix of land covers, an average value weighted by the percentage of the land cover should be calculated.

Example:

Using the Simple Method, calculate the stormwater pollutant load of suspended solids (TSS) of a 2-inch, 24-hour storm from a 2-acre urban site that is 30 percent impervious and has typical urban runoff pollutant concentrations.

$$C = 55 \text{ mg/l}$$
$$R_v = 0.05 + 0.9(I_a) = 0.05 + 0.9(0.30) = 0.32$$
$$R = P \times P_j \times R_v = 2 \times 0.9 \times 0.32 = 0.52 \text{ in}$$
$$L = 0.226 \times R \times C \times A = 0.226 \times 0.52 \times 55 \times 2 = 12.9 \text{ lbs TSS}$$

Effects of Land Use on Stream Integrity

The effects of land use on peak flows and runoff pollution damage the physical and biological integrity of natural channels. In addition, reduced infiltration reduces groundwater storage and reduced dry weather stream flows. Urbanization directly and indirectly causes the **destruction of natural creeks and streams.**