Surface Water Hydrology

Introduction

Water is a key component in the life cycles of all organisms because of its ability to dissolve many substances (universal solvent) and as a cooling agent. It is also an integral part of photosynthesis for plants and respiration for animals and microorganisms. The strong self-attraction of water molecules leads to capillary suction that help plants such as trees to provide life sustaining water to their highest branches, as well as helping hold water in soil for plant roots to access it. These are just a few of the many reasons why water is of great interest to humans.

Hydrologic Cycle

The study of the distribution and movement of water on earth is known as hydrology. Humans have learned much about the availability and movement of fresh water (relatively free of dissolved impurities), because being deprived of it for only a number of days can threaten human life. The never ending recycling of water above and beneath the earth's surface, transforming from liquid to gaseous forms and back, is known as the hydrologic cycle. Water trapped as ice or snow is removed from the cyclic movement from days to thousands of years until melting frees it again for movement within the cycle.

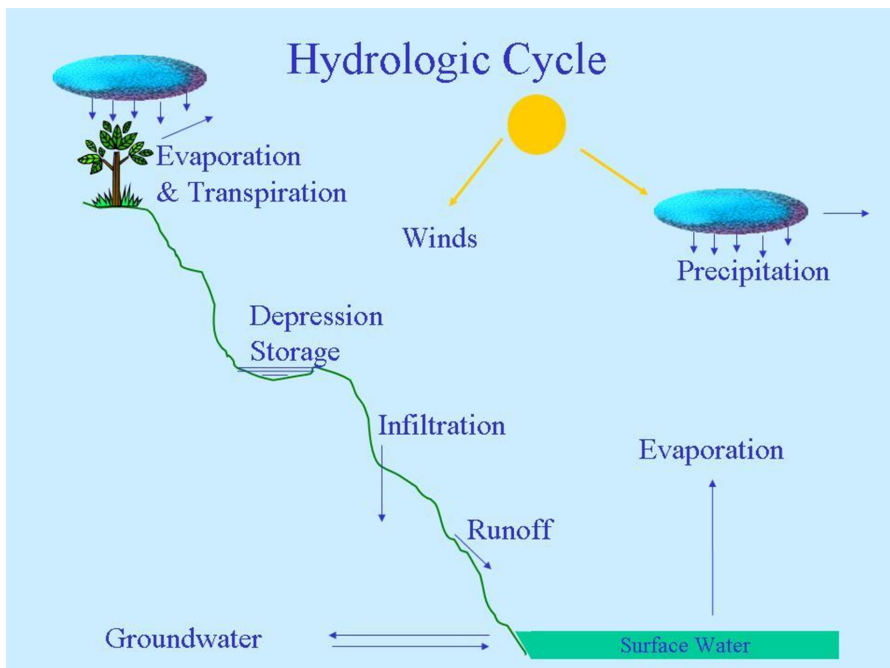


Figure 1. Hydrologic cycle components.

Figure 1 is a depiction of this cycle. The driving force for all water movement on earth is the sun. It causes redistribution of water vapor in the air by winds and weather systems. The energy of sunlight is also responsible for a constant supply of water vapor to the atmosphere through evaporation from collected water on the earth's surface such as lakes or the oceans. It is indirectly responsible for plant release of water vapor due to photosynthetic metabolism in what is known as transpiration. Due to the difficulty in separating these two vapor forming mechanisms, hydrologists combine the two and refer to the combination of the two as evapotranspiration. Water vapor condenses back to liquid in the atmosphere in the form of small droplets in collections that make up clouds. When clouds collect sufficient moisture that they no longer can stably suspend them, they are released as precipitation (rain or snow), and move back from the atmosphere back to the earths surface. Precipitation collects on the land surfaces in small puddles (depression storage), seeps into the soil and feeds deeper levels through infiltration, or flows over the land's surface toward lower elevations as runoff. Runoff collects into ditches or small streams which eventually are collected into larger streams or rivers. Freshwater lakes are fed by these streams and rivers, and remain as freshwater reservoirs so long as they have an outflow to flush out dissolved solids fed through the lake. The ultimate destination for stream and river flow is an ocean body, where the dissolved solids have no outlet and contribute to seawater salinity. Water vapor evaporating from seawater is a significant water source feeding back into the cycle.

The Rational Equation

Civil and environmental engineers and scientists are interested in predicting the rate of runoff flow from precipitation for several reasons. The most obvious is to provide sufficient flow capacity in conveyance pipes and channels to avoid flooding. Another important reason is the need to predict flows through rivers and lakes to describe the movement of transported contaminants. In many cases related to conveyance, merely knowing a peak expected flow is sufficient information for decision making. The simplest approach is to assume a simple linear relation to rainfall intensity (in/hr or cm/hr).

The Rational Equation is a ratio relationship describing the proportionality between the peak collected runoff Q_p (ft^3/s or m^3/s) from an area A, due to a rainfall distributed uniformly over the area at a steady intensity i. It is stated as

$$Q_p = C\,i\,A$$

where C is a non-dimensional runoff coefficient (= 1 for impervious).

It is best applied when the collecting area is less than 20 acres in size. Application of the equation is most easily understood by considering runoff from an asphalt parking lot whose surface area is reasonably approximated as a rectangle (see Figure 2). If rainfall begins to fall steadily at a uniform intensity over the area, almost all of the water will run off, with only a small amount seeping into the asphalt or through cracks in it (C = 0.9). Figure 3 is a plot of the collected outflow Q as a function of time assuming rainfall continues at intensity i for a long time. Once even the most distant point (flow-wise) is contributing to the outflow Q, it will level off at the peak outflow Q_p. The flow path for this case is shown in Figure 2 by the arrow showing the flow path from the most elevated parking spot to a collecting channel in the middle of the lot, followed by the path arrow down the middle of the lot. The time the water takes to flow overland along this path to the outflow point is called the time of concentration. It should be a property only of the collecting surface, and not the rainfall intensity.

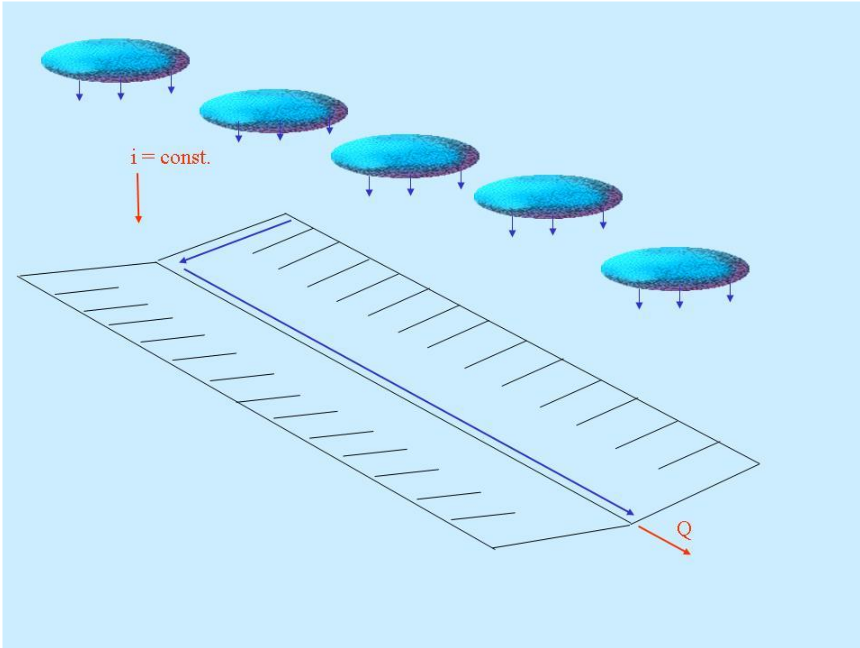


Figure 2. Parking lot runoff schematic.

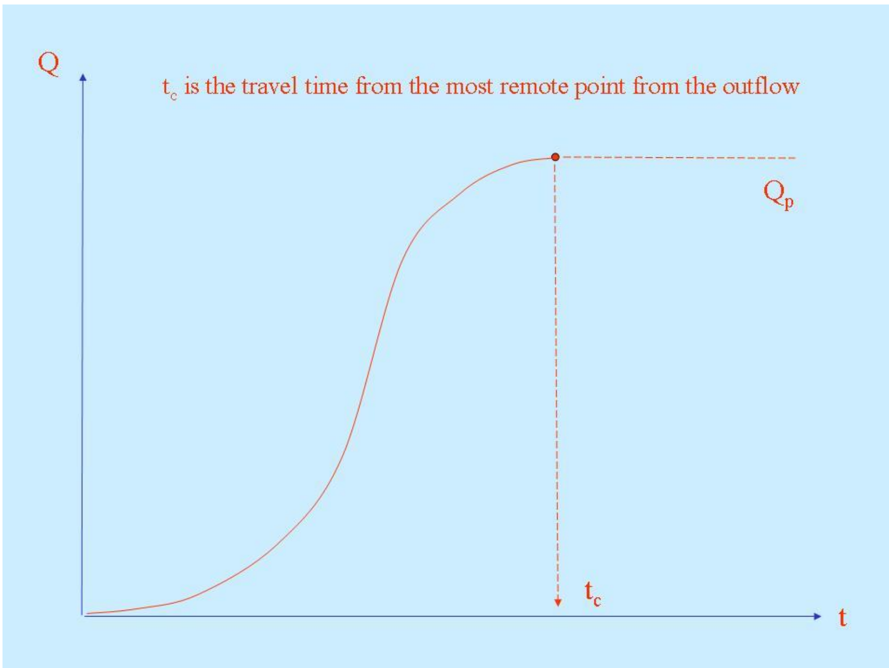


Figure 2. Parking lot runoff schematic.

There are a number of empirical relations that have been developed to predict t_c, but the most directly applicable to paved areas is the FAA equation based on the total maximum travel length L (ft) and the mean slope S (ft/ft) along that path.

Figure 3. Runoff flow approach to maximum.

$$t_c = \frac{0.388(1.1-C)L^{1/2}}{S^{1/3}}$$

where C is the Rational Eq. constant and t_c is in minutes.

Example 1.
The south Engineering Building parking lot at SIUC can be approximated as a rectangle sketched in Figure 4. Assuming C = 0.9, L = 540 ft, w = 150 ft, and the slope is along the length from elevation 439ft above sea level to 436 ft. Find the time of concentration for the lot.

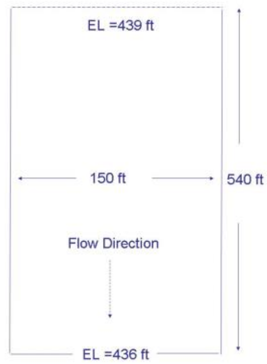


Figure 4. Parking Lot.

Solution:

$$S = \frac{(439\,\text{ft} - 436\,\text{ft})}{540\,\text{ft}} = 0.0056 \quad (\text{relatively flat})$$

$$t_c = \frac{0.388(1.1-C)L^{1/2}}{S^{1/3}} = \frac{0.388(1.1-0.9)(540)}{(0.0056)^{1/3}} = 10.1\,\text{min} \Leftarrow$$

General practice for using the rational equation on small areas such as this is to limit the time of concentration to 20 – 30 minutes with an arbitrary 15 minutes used without reference to topography. The practical implication in this instance is that only one inlet would be enough for this lot, but typically several are used.

Intensity-Duration-Frequency Curves

The time of concentration can be used in application of the Rational Eq. to determine a design storm intensity by use of Intensity-Duration-Frequency (I-D-F) curves. Detailed examination of precipitation records all the construction of these curves. For a measured rainfall event of duration D_r and total collected precipitation measured as P_r, the average storm intensity is

$$i_{avg} = \frac{P_r}{D_r}$$

The probability P of occurrence of a given intensity event in any given year is estimated by ranking the intensities over as many years of reliable records as available, and then relating to a return period of T_r (yrs) as

$$T_r = \frac{1\text{ yr}}{P}$$

An I-D-F constructed in such a fashion for the region of our parking lot example is shown in Figure 5 taken from an asphalt manufacturers manual.

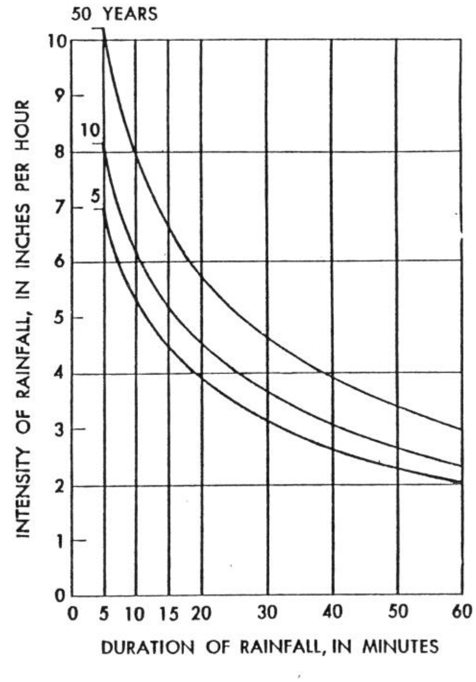


Figure II-12.—Intensity curves for storms in the vicinity of Cairo, Illinois.

Figure 5. I-D-F for SIUC lot.

The “frequency” of the I-D-F curve is actually $1/T_r$, but the return period is commonly referred to as the frequency. Designers of parking lot drainage systems use a return period of 5 or 10 years. By choosing one of these curves and using the time of concentration as the duration, a design storm intensity can be determined.

Example 2.

The taking the time of concentration determined for the south Engineering Building parking in Ex. 1, estimate the design peak flow. Remember that t_c = 10.1 min, C = 0.9, L = 540 ft, and w = 150 ft.

Solution:

$$\text{From Fig. 5, with } D_r = 47\,\text{min} \;\&\; T_r = 10\,\text{yr} \quad i = 6.2\,\text{in/hr}$$

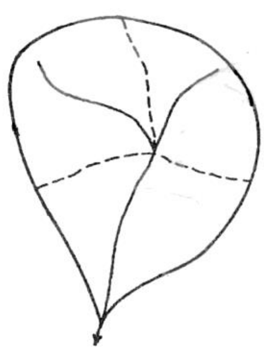
$$A = (540\,\text{ft})(150\,\text{ft}) = 81{,}000\,\text{ft}^2 = 1.86\,\text{ac} \quad (1\,\text{ac} = 43{,}500\,\text{ft}^2)$$

$$Q_p = (0.9)(6.2\,\text{in/hr})(1.86\,\text{ac}) = 10.38\,\frac{\text{ac}\cdot\text{in}}{\text{hr}} \simeq 10.46\,\frac{\text{ft}^3}{\text{s}} \Leftarrow$$

$$\text{note}: 1\,\frac{\text{ac}\cdot\text{in}}{\text{hr}} = 1.008\,\frac{\text{ft}^3}{\text{s}} = 1.008\text{ cfs}$$

Hydrographs

There are times when planners need more information about runoff than just the peak flow. For larger collecting surface areas on the order of square miles (watersheds), a time series of flow values a collection point of the watershed describes what is known as a hydrograph. A predictive tool that can produce an accurate hydrographic response to extreme rainfall events can help planning to mitigate flooding effects. It is also valuable to know flow variations in collecting streams, so that the effects of contaminant loads in runoff water or discharged directly to the streams can be assessed. Figure 6 shows a hydrograph depicting the runoff produced from a rainfall event for the watershed area to the left. The outline of the watershed describes a divide, which is a crest on the land surface about which precipitation landing inside the watershed boundary produces runoff flowing toward the collection point (noted by the arrow), and precipitation outside the boundary produces runoff for some other watershed. Water is collected inside the watershed into the streams indicated as the internal solid lines. Divides indicating areas contributing to the three stream branches are noted as dashed lines inside the watershed.



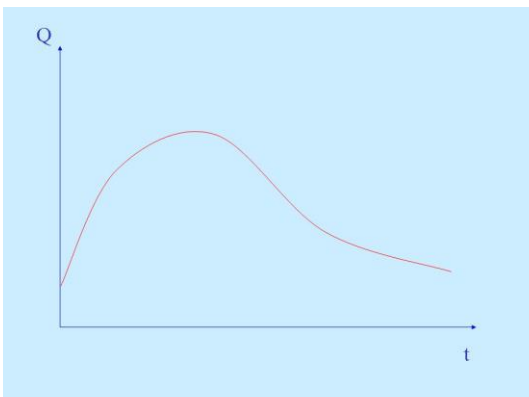


Figure 6. Hydrograph (right) for watershed (left).

One of the most common methods of predicting runoff hydrographs is to assume that a characteristic unit hydrograph (UH) can be constructed, and hydrographic response to any magnitude rainfall event can be described in terms of multiples of this base response. The key aspect of the unit hydrograph is that it produces one unit of runoff (one in or one cm). There are two UH forms described by NRCS. Figure 7 is a graphical description of the time variation prescribed for its UHs. The shape more like that of Fig. 6 is called the natural UH, and the triangular UH is a piecewise linear approximation to the natural shape. Both forms will produce 1 in of runoff if one uses the following equations to calculate Q_p and t_p.

$$Q_p = \frac{464\,A}{t_p}(\text{cfs}) \quad \& \quad t_p = \frac{2}{3}t_c\ (\text{hr})$$

$$\text{for a storm of duration } D = \frac{t_c}{7.5} \quad \& \text{ A in mi}^2$$

Using the above equations, the base time length of the triangular UH must be 2.67 times t_p to produce 1 in of runoff. Before a UH can be applied, an estimate of the fraction of the rainfall producing runoff must be made. A simplified NRCS approach is presented here as an attempt to simplify the discussion, but the reader is directed to the more complete discussions available in a variety of hydrology textbooks. A constant similar to the rational C is the NRCS curve number (CN). It is a function both of the soil properties and how the land surface is being used. For example a grassed area on swelling clay soils would have a CN = 80, whereas for sandy silt type soils that drain more easily, CN = 40. The curve number can be thought of as a percentage rating for runoff from precipitation. If the average intensity i_{avg} of a storm of duration D is

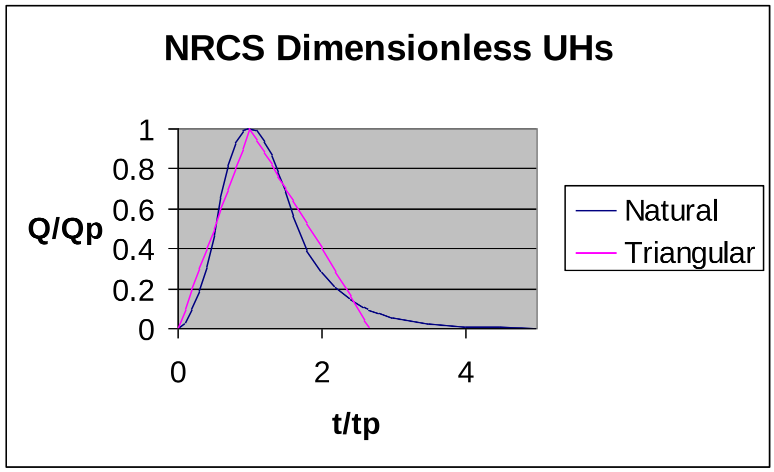


Figure 7. NRCS natural and triangular UHs.

$$i_{avg} = \frac{P}{D}$$

$$\text{then } Q_{avg} = \left(\frac{CN}{100}\right) i_{avg}\,A$$

Where P is the total (rain gauge collected) precipitation. This description can also be thought of as runoff being caused by excess precipitation, where it is calculated as P_{excess} = (CN/100) P.

Example 3.

Treating swelling clay soil underlying the parking lot of Ex. 2, estimate the runoff flow hydrograph prior to the grassed area being paved over, for a storm of intensity 3 in/hr over 40 minutes. Assume t_c increases to 60 min.

Solution:

$$\text{Take CN} = 80$$

$$D = \frac{t_c}{7.5} = \frac{60\,\text{min}}{7.5} = 8\,\text{min}$$

$$P_{excess} = \left(\frac{80}{100}\right)\left(\frac{3\text{in}}{\text{hr}}\right)\left(\frac{2\ \text{hr}}{3}\right)$$

$$= 1.6\,\text{in}$$

$$i_{avg} = \frac{1.6\,\text{in}}{40\,\text{min}} = 0.04\,\text{in}/\text{min}$$

$$\text{over } D\,(=8\,\text{min})$$

$$P_{excess} = (8\,\text{min})\frac{0.04\,\text{in}}{\text{min}}$$

$$= 0.32\,\text{in}$$

So the 40 minute storm is 5 applications of 8 min UHs

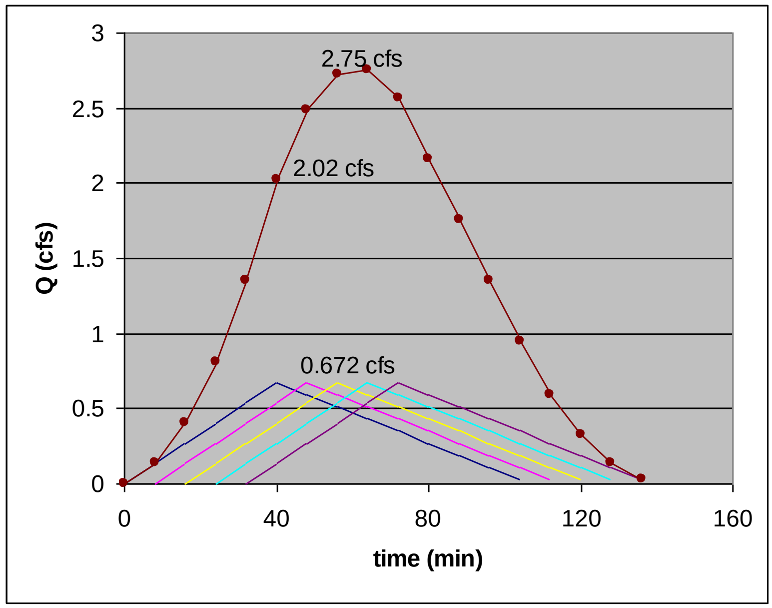


Figure 8. Outflow hydrograph.

$$\text{For each UH } Q_p = \frac{484\left(\dfrac{1.86\,\text{ac}}{640\,\text{ac}/\text{mi}^2}\right)}{2/3\,\text{hr}} = 2.11\,\text{cfs}$$

$$\text{Each } 8\,\text{min peak} = 0.32(0.675\,\text{cfs}) = 0.675\,\text{cfs}$$

$$@\ 40\,\text{min } Q = 0.675\,\text{cfs}\left(1+0.8+0.6+0.4+0.2\right) = 2.02\,\text{cfs}$$

complete time history by spreadsheet, plotted above.

Note that the overall peak of 2.75 cfs is more than three times smaller than after pavement being added as in Example 1. The increase is typical of the greater flow rates due to what is referred to as urbanization.