Surface Water Hydrology and Watersheds

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This booklet is part of a series of educational brochures and slide sets that focuses on various aspects of water source protection. The series has been prepared jointly by the University of California Agricultural Extension Service and the California Department of Health Services.

For further information about this and other documents in the series, contact the project team leader (see below) or visit the following website:

www.dhs.ca.gov/ps/ddwem/dwsap/DWSAPindex.htm

Authors: Rhea Williamson, Department of Civil and Environmental Engineering, San Jose State University, San Jose, Calif., and John Klamut, Sunnyvale, Calif.

Editor: Larry Rollins, Davis, Calif.

Layout crew: Larry Rollins and Pat Suyama

Photo credit (cover): California Department of Water Resources

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Project Team leader: Thomas Harter, Department of Land, Air, and Water Resources, University of California at Davis

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Hydrology is the scientific study of water: its properties, its influences, and its distribution over and under the earth's surface. A multidisciplinary subject, hydrology draws upon and at the same time encompasses such areas of study as geology, geomorphology, biology, and chemistry. This booklet will focus on introducing the topic of *surface water* hydrology. It will also suggest ways in which surface hydrology concepts and knowledge can be applied when one assesses the quality, safety, and reliability of a drinking water source.

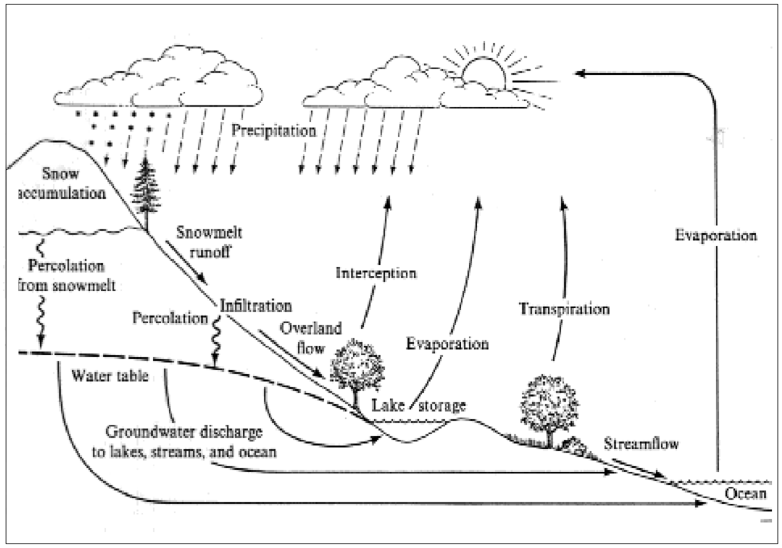

Figure 1. The hydrologic cycle (Dunne, 1978).

Hydrologic Cycle and Budget

The hydrologic cycle describes the processes by which water moves around the earth. Figure 1 is a schematic representation of the cycle. Water is evaporated from the oceans and forms moist air masses that move inland. Once over land, if conditions are right, precipitation forms and falls on the land. It is then dispersed in several ways. Part of the precipitation will be retained in the soil and then evaporated back into the atmosphere. Another portion will be utilized by plants and returned to the atmosphere in the form of transpiration. Some of the precipitation becomes overland flow or direct runoff and feeds directly into streams. Lastly, the remainder of the water infiltrates the soil and either percolates further down, as groundwater recharge, or becomes interflow—water that flows downslope to a stream or lake. The hydrologic cycle can also be understood quantitatively, in the form of a hydrologic budget.

The hydrologic budget is a very simple yet very important part of hydrology. The budget is simply an equation showing all of the inputs into the system minus the outputs of the system, resulting in the change of the amount of water in the system under consideration. Equation 1 shows a form of the hydrologic budget (Bedient, 1992).

Hydrologic Budget $P - R - G - E - T = \Delta S$ Eq. 1

where: P is precipitation, R is surface runoff, G is ground water flow, E is evaporation, T is transpiration, and ΔS is change in storage

When interpreting Equation 1, the following must be kept in mind:

- Infiltration—a loss from the system—is not shown explicitly in Equation 1 because it is a loss from the surface flow to the ground water flow.
- Infiltration may flow downslope as interflow, which moves below the ground surface but above the water table. Interflow typically moves much faster than groundwater flow. This type of water movement can be hard to estimate but usually can be considered to be part of the surface runoff.
- Evaporation and transpiration are sometimes lumped together as evapotranspiration. This is done because it can be hard to measure these processes separately and because a total measurement can be made of both processes when the terms are combined.

All forms of the hydrologic equation, whether very complex or simple, represent the basic continuity relationship shown in Equation 2.

Basic Continuity Equation $I - O = \Delta S$ Eq. 2

I = Inputs

O = Outputs

ΔS = Change in Storage

Analyzing Extreme Events

Several of the processes studied by hydrologists are subject to extreme events—for example, precipitation and storm runoff. These events can reshape the landscape, destroy buildings, and cause the loss of life. The prediction of extreme events, in terms of frequency and size, is necessary in order to design earthworks and other structures to stand up to such events. Prediction also can help to save lives, by keeping people out of danger-prone areas. Two types of extreme events will be examined here: the extreme precipitation event and the extreme runoff event. These events are predicted in similar ways.

A frequency analysis is conducted to determine a probability distribution function (pdf) that represents the data of interest. Generally, the process is performed in two different stages. First, a population curve is developed and evaluated for goodness of fit. Then the computed curve can be used to estimate the probability of occurrences. The first step is to determine the mean, standard deviation, and skew of the data (McCuen, 1989). These can be computed using equations 3, 4, and 5, respectively.

Mean $$\overline{X} = \frac{1}{n}\sum_{i=1}^{n} X_i$$ Eq. 3

Standard Deviation $$S = [\frac{1}{n-1}\sum_{i=1}^{n}(X_i - \overline{X})^2]^{0.5}$$ Eq. 4

Skew $$g = \frac{n\sum_{i=1}^{n}(X_i - \overline{X})^3}{(n-1)(n-2)S^3}$$ Eq. 5

The next step is to use rank-order data analysis to plot the data. This involves listing the storm events in order, from largest to smallest, and assigning each one a rank (m), as shown in Table 1. Each event is assigned a unique rank—if two events are the same size, they are nevertheless assigned different rankings, not the same one (this can be seen readily in Table 1). Once this is done, a plotting-position formula is used to determine the probability of a given event occurring. One of the more common formulas is the Weibull plotting position formula. It looks like this:

Weibull Formula $p_w = m / (n + 1)$ Eq. 6

where: m = rank, n = number of years of data record

These values are then plotted on probability paper, resulting in a graph similar to Figure 2. The distribution often can be assumed to be normal. Normality can be shown by fitting a normal line with the values of $(\overline{X} - S, 0.8413)$ and $(\overline{X} + S, 0.1587)$ (McCuen, 1989). Figure 2 shows this with a frequency curve plotted for $\overline{X} = 5$ and S = 1. This line is then used to make a graphical judgement of whether the plotted events approximate a normal distribution.

Once plotted, the exceedence probability can be acquired graphically from the plot by taking a storm event value and then obtaining the corresponding exceedence probability, or vice versa. Plotting provides an easily-read graph, useful for obtaining values quickly and for evaluating how closely the data set fits a given distribution. If the data appear to fit a normal distribution, then the following equations can be used to calculate the exceedence probability or the magnitude of the storm event (McCuen, 1989).

Exceedence Probability $$z = \frac{X - \overline{X}}{S}$$ Eq. 7

Magnitude $$X = \overline{X} + zS$$ Eq. 8

where: z is the probability coefficient, taken from the corresponding value on a z-table or probability coefficient table

When performing this type of analysis, events are often discussed in terms of return period. For example, the magnitude of a storm may be described as being a 100-year storm. This doesn't mean that 100-year storm events occur every hundred years, but rather, that the probability of the storm occurring is 1 time in 100. To convert a return period into an exceedence probability, Equation 9 (Dunne, 1978) is used, where p is probability and T is the time period.

Probability $$p = 1/T$$ Eq. 9

Example 1: Find the magnitude of a 100-year storm event with $\overline{X} = 30\frac{m^3}{s}$ and $S = 6\frac{m^3}{s}$.

Step 1. Convert the time period into an exceedence

Rank	q_p(ft^3/sec)	pp_w	Rank	q_p(ft^3/sec)	pp_w
1	21,500	0.0169	30	7,600	0.5085
2	19,300	0.0339	31	7,420	0.5254
3	17,400	0.0508	32	7,380	0.5424
4	17,400	0.0678	33	7,190	0.5593
5	15,200	0.0847	34	7,190	0.5763
6	14,600	0.1017	35	7,130	0.5932
7	13,700	0.1186	36	6,970	0.6102
8	13,500	0.1356	37	6,930	0.6271
9	13,300	0.1525	38	6,870	0.6441
10	13,200	0.1695	39	6,750	0.6610
11	12,900	0.1864	40	6,350	0.6780
12	11,600	0.2034	41	6,240	0.6949
13	11,100	0.2203	42	6,200	0.7119
14	10,400	0.2373	43	6,100	0.7288
15	10,400	0.2542	44	5,960	0.7458
16	10,100	0.2712	45	5,590	0.7627
17	9,640	0.2881	46	5,300	0.7797
18	9,560	0.3051	47	5,250	0.7966
19	9,310	0.3220	48	5,150	0.8136
20	8,850	0.3390	49	5,140	0.8305
21	8,690	0.3559	50	4,710	0.8475
22	8,600	0.3729	51	4,680	0.8644
23	8,350	0.3898	52	4,570	0.8814
24	8,110	0.4068	53	4,110	0.8983
25	8,040	0.4237	54	4,010	0.9153
26	8,040	0.4407	55	4,010	0.9322
27	8,040	0.4576	56	3,100	0.9492
28	8,040	0.4746	57	2,990	0.9661
29	7,780	0.4915	58	2,410	0.9831

Table 1. Annual maximum discharges (q_p) and expected exceedence probability (pp_w).

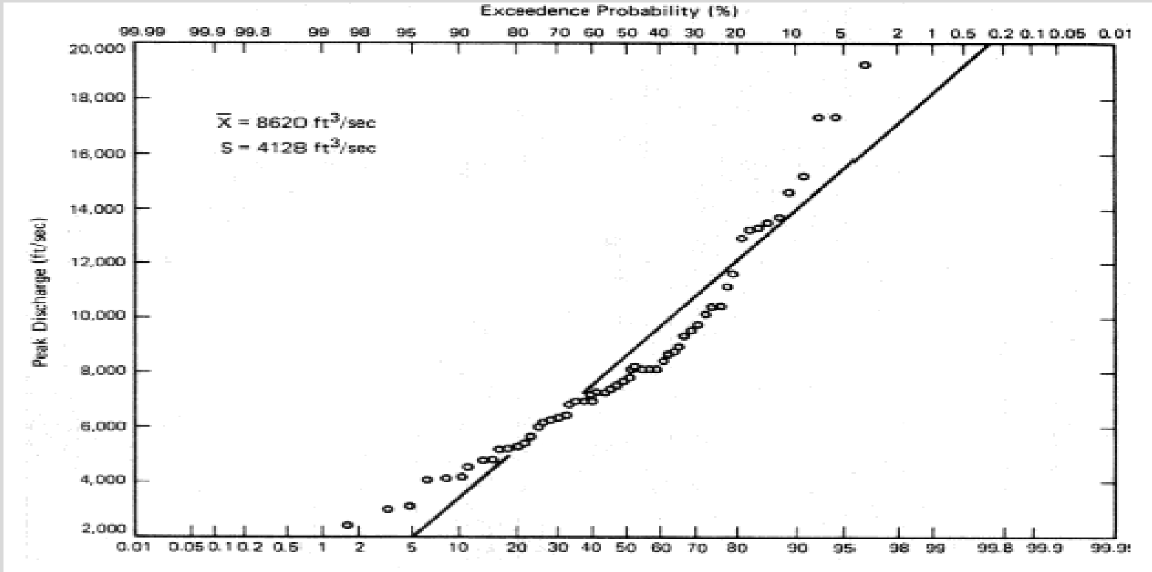

Figure 2. Piscataquis River near Dover-Foxcroft, Maine (McCuen, 1989).

probability.

$$p = 1/100 = 0.01$$

Step 2. Calculate the magnitude of the event with Equation 8. The corresponding z value for a probability of 0.01 is 2.327 (McCuen, 1989).

$$X = 30\frac{m^3}{s} + 2.327 * 6\frac{m^3}{s} = 43.96\frac{m^3}{s}$$

Example 2: Calculate the return period of a storm flow with a magnitude of $X = 38\frac{m^3}{s}$.

Step 1. Use Equation 7 to calculate the z value for the storm flow.

$$z = \frac{38 - 30}{6} = 1.33$$

Step 2: The corresponding probability for z=1.33, from a "z table", is approximately 0.1 (McCuen, 1989). The return period can then be calculated:

T = 1 / 0.1 = 10 year return period

This discussion is merely an introduction to the ideas of frequency analysis and probability concepts for the prediction of extreme storm events. If a more in-depth discussion is needed, consult a basic hydrology text that covers these concepts.

Applying Hydrology Concepts

Understanding surface hydrology is important when preparing a drinking water source assessment and protection (DWSAP) report or survey. Various methods are commonly used to study a watershed's hydrology. One of these, the *discharge hydrograph,* gives an idea of the amount and timing of runoff from a precipitation event for a given area. Another, the *rational method,* is used to obtain the peak discharge from a given area. A third, the *unit hydrograph* for a basin, is used to assess the amount of runoff from one inch of rainfall excess. Usually, it's best to employ more than one hydrologic method for each particular application (Walesh, 1989).

Many computer software packages are available to calculate hydrologic parameters and to analyze the surface hydrology of a water shed (e.g., Hydrosoft, or

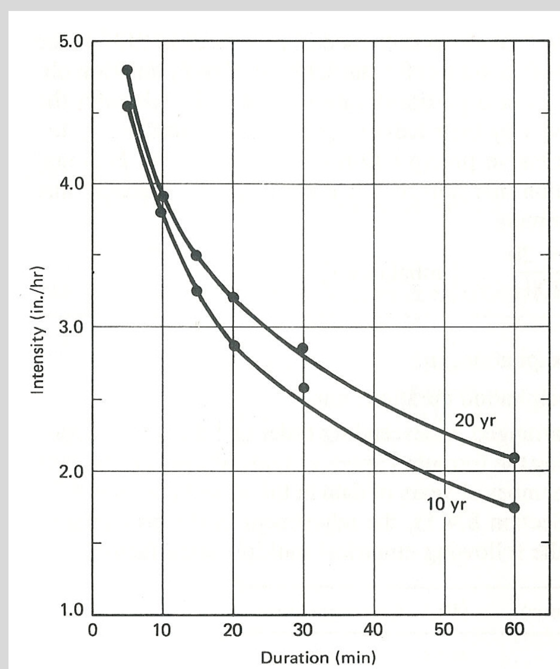

Figure 3. Intensity-duration-frequency curve (Gupta, 1989).

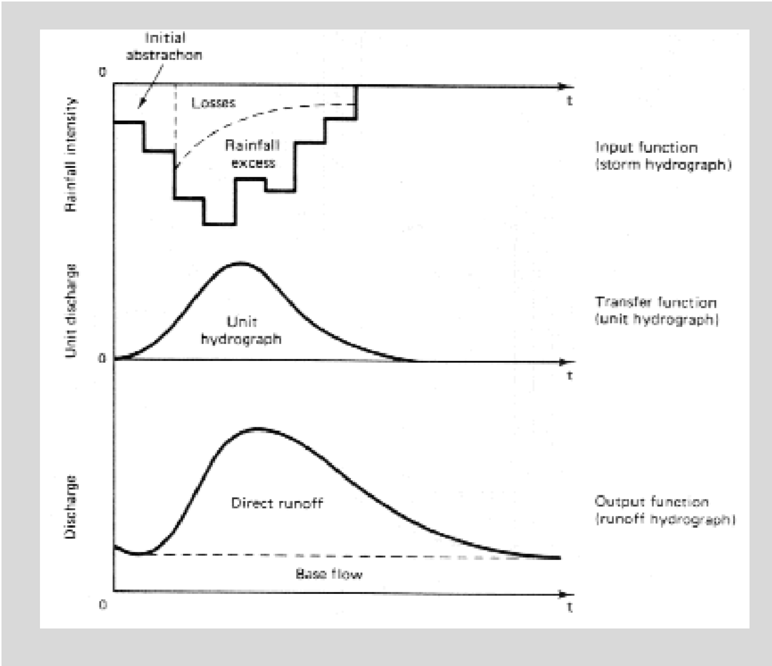

Figure 4. Rainfall-runoff hydrographs (Bedient, 1992).

HEC-1 and HEC-RAS, by the U.S. Army Corps of Engineers Hydrologic Engineering Center).

The rational method calculates the peak discharge (Q, ft^3/sec) from the drainage area (A, acres) and the rainfall intensity (i, in./hr) and the runoff coefficient (C). It is commonly used to estimate peak discharges from urban areas less than 20 square miles (Gupta, 1989).

Rational Method $Q = CiA$ Eq. 10

In the absence of rain gage data, the values for rainfall intensity can be obtained from an intensity-duration-frequency curve (Figure 3). The National Weather Service creates these curves for most areas in the United States. Using the curve, intensity can be derived for a given storm using its return period and setting its duration equal to the time of concentration. The time of concentration is the period of time it takes for a storm's runoff to travel from the most remote point of a drainage basin (watershed) to the outlet (Gupta, 1989).

In the rational method, the value of the runoff coefficient is a function of the land use, the cover condition, the soil group, and the watershed slope. C values for five to six year return period can be obtained from Table 2. The C value is obtained from the table by matching as closely as possible the watershed area in question with the description from the table. The rational method is not totally accurate; nevertheless, it is used widely because it gives a good idea of what the peak discharge will be from a given storm event.

It is important to note that the Soil Conservation Service has developed a *curve number method* for estimating runoff. The method was developed for use in small agricultural watersheds. To use the method, a curve number is selected from a table based upon the land's use, hydrologic condition, and soil type. Based on the appropriate curve number, a graph is then used to determine the peak discharge for a given amount of precipitation.

The purpose of *hydrograph analysis* is to analyze rainfall and runoff data to obtain an estimate of peak discharge. A *discharge hydrograph* is a graph of discharge rate versus time. The general shape of a hydrograph is a function of a storm's *hyetograph* (amount of rain in a given interval of time) and the effects of the basin's storage characteristics.Figure 4 shows the effects that watershed and channel storage

Description of Area	Runoff Coefficients
Business	
Downtown	0.70-0.95
Neighborhood	0.50-0.70
Residential	
Single –family	0.30-0.50
Multiunit, detached	0.40-0.60
Multiunit, attached	0.60-0.75
Residential (suburban)	0.25-0.40
Apartment	0.50-0.70
Industrial	
Light	0.50-0.80
Heavy	0.60-0.90
Parks, cemeteries	0.10-0.25
Playgrounds	0.20-0.35
Railroad yard	0.20-0.35
Unimproved	0.10-0.30

It often is desirable to develop a composite runoff coefficient based on the percentage of different types of surface in the drainage area.

Table 2. Runoff coefficients for the Rational Method (McCuen, 1989).

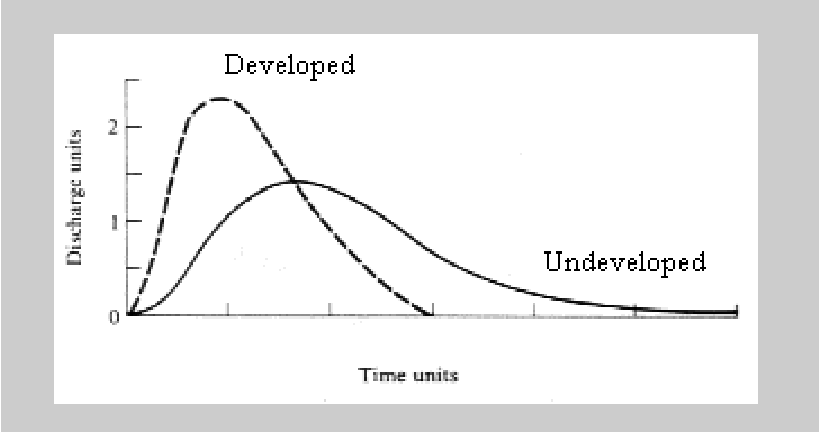

Figure 5. Hydrograph attenuation on a developed watershed (Dunne, 1978).

have on smoothing out the variations of a storm's hyetograph.

Small watersheds often do not require a hydrograph analysis; however, the analysis is a common tool on many watersheds. The analysis is very good at showing the effects of development on a basin. As a watershed is developed, areas are paved and built on. Those areas previously would have absorbed rainfall and provided storage that dampens the peak discharge from the area. After a watershed is developed, the discharge hydrograph changes, usually resulting in a shorter peak and a higher peak discharge. Figure 5 shows this effect on the hydrograph.

Separation of base flow and direct runoff (DRO) is an important part of the hydrograph analysis. Base flow can be defined as the groundwater which contributes to a stream during dry periods (Gupta, 1989). Direct runoff (DRO) is the surface flow and interflow which conribute to a stream during and immediately after a storm. By separating base flow and DRO, the actual volume of runoff from the storm can be estimated. Several techniques are available to accomplish this task. Some of them are mostly qualitative, such as drawing a line across the base of the hydrograph or construction of an exponential depletion curve. Neither of these qualitative techniques is entirely accurate, and both leave a lot to be desired. It should be noted that in many urban areas, or in areas without large amounts of base flow, the separation of base flow and DRO can be neglected, because almost all flow comes from direct runoff.

The amount of infiltration also needs to be determined before further analysis can occur. This can be done in different ways. One common and straightforward method is the Phi(ϕ)-Index method. The *phi index* equals the total volume of storm period loss distributed uniformly across the storm's hydrograph. This method is very simple in that the phi-index is matched up so that the amount of DRO from the hydrograph is equal to the amount of excess precipitation (Figure 6a). An excerpt from McCuen (1989) helps to clarify this:

> " In cases where the rainfall intensity is less than the initial estimate of ϕ, the first estimate of ϕ must be adjusted to ensure that the volume of DRO is equal to the estimate of rainfall excess. Assuming a volume of direct runoff 0.4-in. (depth of rain falling over the entire basin) and using the hyetograph in Figure 6b, the first estimate of ϕ would be ϕ=0.075in./hr. When superimposed on the hyetograph, it is evident that the ϕ is greater than the first ordinate. Thus, if the initial phi (ϕ=0.075in./hr) is used, the

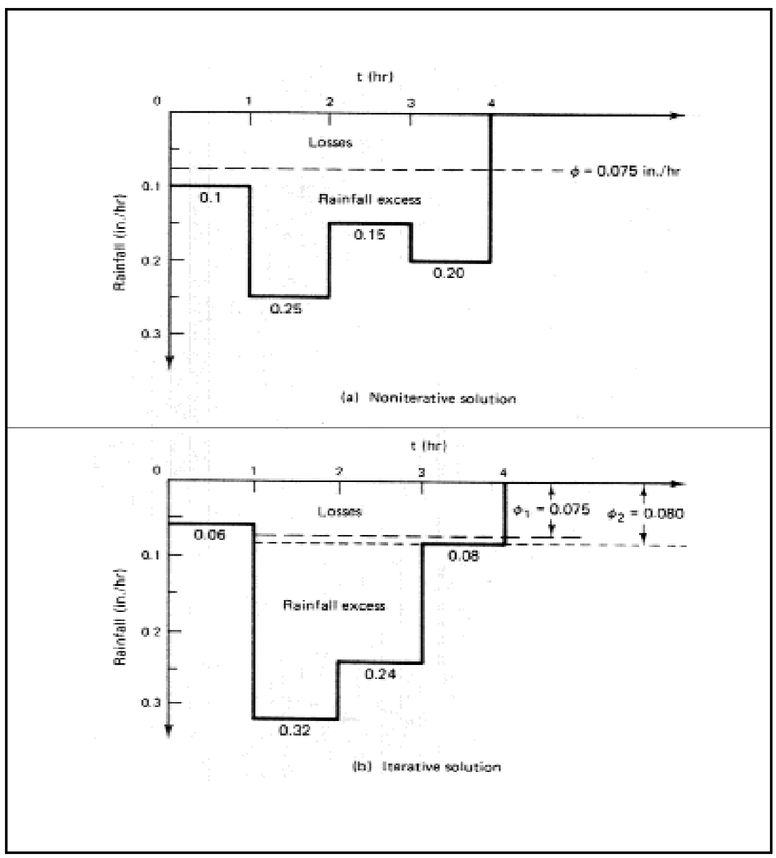

Figure 6. Separation of rainfall excess using the phi-index method (McCuen, 1989).

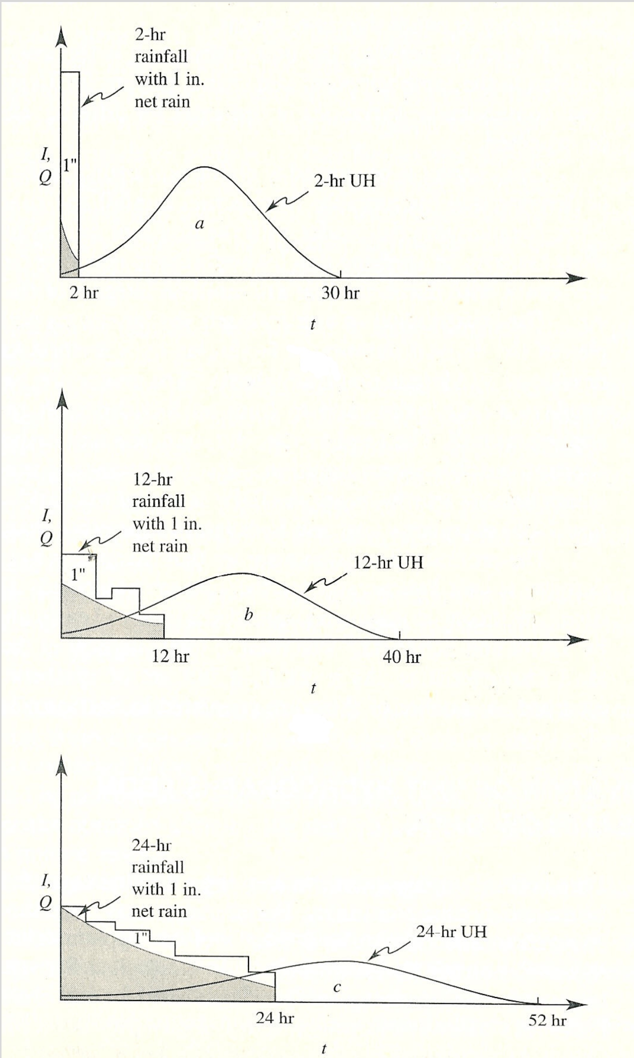

Figure 7. Illustration of 2-hr., 12-hr., and 24-hr. unit hydrographs for the same watershed (Viessman and Lewis, 1996).

volume of rainfall excess would end up being 0.415 in, which is too high. This means that the value has to be adjusted, meaning a higher ϕ value has to be chosen. Given that ϕ should be increased by (0.415-0.400)/3=0.005 in./hr, or ϕ=0.08. Using this value of phi gives a rainfall excess value of 0.4 in., which is equal to the amount of direct runoff."

The *unit hydrograph* is defined as "basin outflow resulting from one inch (or one centimeter) of direct runoff generated uniformly over the drainage area at a uniform rate during a specified rainfall duration" (Bedient, 1992). The following method of deriving a unit hydrograph for a watershed is taken from *Hydrology and Floodplain Analysis*; it is a good explanation of the steps required to derive a unit hydrograph.

First, the timing aspects of a standard hydrograph need to be obtained.

1. Lag time (t_p): Time from the center of mass of rainfall excess to the peak of the hydrograph.
2. Precipitation time (t_r): unit of time in which the precipitation of one inch occurs. This can vary as shown in Figure 7 (Viessman and Lewis, 1996).
3. Time of Concentration (t_c): time of equilibrium of the watershed, where outflow is equal to net inflow; also, the time for a wave to propagate from the most distant point in the watershed to the outlet.
4. Time Base (T_b): total duration of the DRO hydrograph.

The following general rules should be observed in developing unit hydrographs from gauged watersheds:

1. Storms should be selected with a simple structure with relatively uniform spatial and temporal distributions.
2. Watershed size should generally fall between 100 acres and 1000 square miles.
3. Direct runoff should range from 0.5 to 2.0 inches.
4. Duration of rainfall excess (D) should be approximately 25-30% of lag time t_p.
5. A number of storms of similar duration should be analyzed to obtain an average unit hydrograph for that duration.
6. Step 5 should be repeated for several durations.

The following are the essential steps for developing a unit hydrograph from a single storm hydrograph:

1. Analyze the hydrograph and separate baseflow.
2. Measure the total runoff volume of DRO under the hydrograph and convert this to inches over the watershed.
3. Convert total rainfall to rainfall excess by subtracting the amount of infiltration from the total amount of rainfall.
4. Divide the ordinates of the DRO hydrograph by the total direct runoff volume in inches and plot these results versus time as the unit hydrograph for the basin. The time base t_b is assumed constant for the storms of equal duration and thus it will not change.

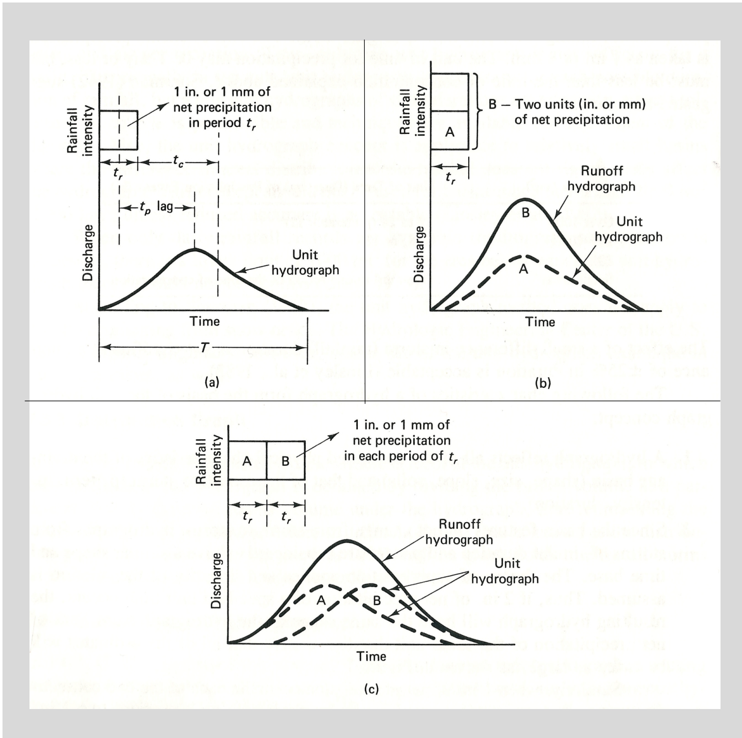

Figure 8. Principles of unit hydrograph: (a) unit hydrograph; (b) runoff hydrograph for two units of precipitation of t_r duration; (c) runoff hydrograph from unit precipitation for two consecutive periods of t_r duration (Gupta, 1989).

5. Check the volume of the unit hydrograph to make sure it is 1.0 inch, and graphically adjust ordinates as required.

Figure 8 illustrates how the principle of the unit hydrograph can be used to derive larger storm events. Figure 8b shows that if a two-inch net-precipitation storm occurs, the shape of the hydrograph will be the same as that of the unit hydrograph, except that all of the ordinates will be twice as large. Similarly, Figure 8c shows how to consecutive unit hydrographs can be summed to derive a hydrograph for a two-inch precipitation event, which precipitates for a time of $2(t_r)$.

To understand the flow of water through large watersheds or watersheds that contain reservoirs and lakes, *flow routing* needs to be discussed. When a watershed is large, various hydrologic processes start to have a greater effect on the flow of water through the watershed. A reservoir has a similar effect: it is a means of storage and it slows down the flow of water through the watershed. *Channel routing* refers to routing the flow down a channel, and *reservoir routing* refers to routing the flow of a stream through a reservoir.

Channel routing can be a mathematically intense endeavor. Many different methods and models have been devised for routing the flow through a watershed properly. All of the methds, however, rely on certain basic principles and equations. One of these, the continuity equation, is key to any type of routing analysis.

Continuity Equation: $I - O = \frac{\Delta S}{\Delta t}$ Eq. 11

I and *O* are the inflow and outflow that create a change in storage, ΔS, during a time interval, Δt. For stream flow routing, *I* and *O* would be the upstream and downstream hydrographs (Figure 9) at two times, t_1 and t_2. Using these terms the routing equation (Equation 12) is given as:

Channel Routing Equation:

$\frac{1}{2}(I_1 + I_2) - \frac{1}{2}(O_1 + O_2) = \frac{S_2 - S_1}{\Delta t}$ Eq. 12

The Muskingum method is one way that a storm event can be routed through a channel. The method relies on a waiting factor, X, as shown in Figure 10. The method varies X between 0 and 0.5. As seen in Figure 10, if X is 0.5, the river has no buffering or storage effect on the storm and the inflow equals the outflow. If X equals 0.0, the river has a maximum storage effect on the storm and the hydrograph becomes smooth (Viessman and Lewis, 1996).

For further discussion on channel routing, refer to the books *Hydrologic Analysis and Design*, by Richard McCuen (1989), *Hydrology and Floodplain Analysis,* by Philip Bedient (1992), and *Design of Small Dams,* by the Bureau of Reclamation (1987). All of these texts

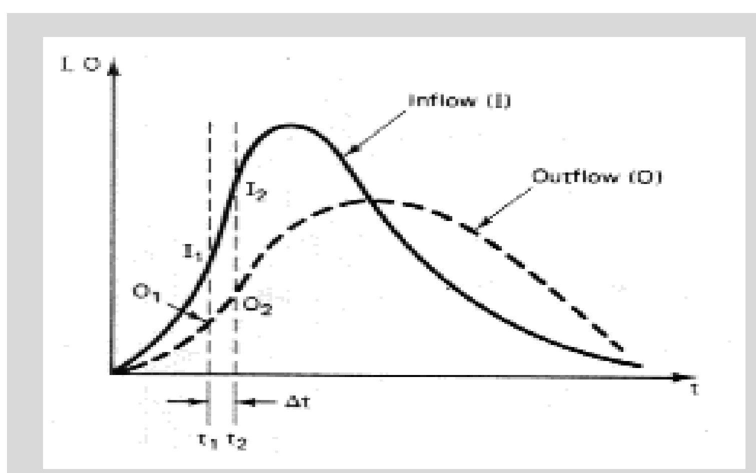

Figure 9. Diagram of upstream (I) and downstream (O) hydrographs (Bedient, 1992).

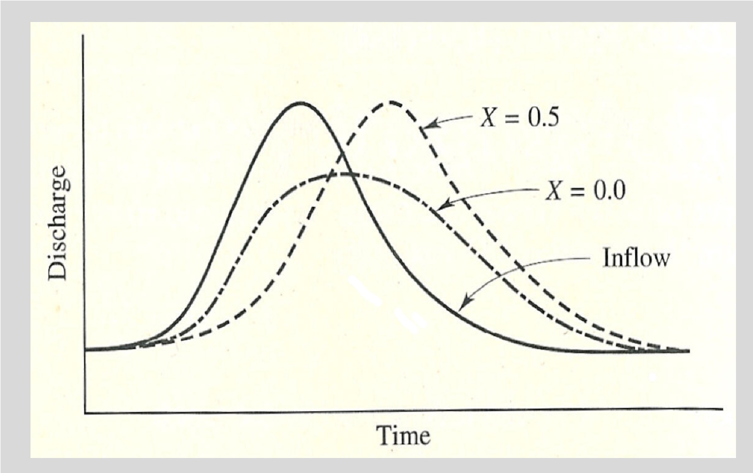

Figure 10. Effect of the waiting factor on channel routing (Viessman and Lewis, 1996).

include a thorough description of the various methods of channel and reservoir routing techniques.

Many conceptual models and computer software packages are available to help a hydrologist analyze a watershed's surface hydrology. Just a few of these are: the USGS Rainfall-Runoff Model, the U.S. Army Crops of Engineers software packages (for example, HEC-RAS and HEC-1), and the U.S. EPA's Storm Water Management Model. Such models typically require as inputs various parameters that describe the watershed. All of these software packages are widely available, and many can be downloaded via the Internet.

The USGS Rainfall Runoff model is commonly used to simulate urban runoff. The USGS website describes it further by stating: "A watershed model for routing storm runoff through a branched system of pipes and (or) natural channels using rainfall as input. DR3M provides detailed simulation of storm-runoff periods selected by the user." The software can be downloaded from http://water.usgs.gov/software/dr3m.html.

HEC-1 is a software package produced by the Army Corps of Engineers Hydrologic Engineering Center. HEC's website gives this expanded description of HEC-1: "A Flood Hydrograph Package that computes flood hydrographs using unit hydrograph, or kinematic wave methods. Various program options are provided for computing subbasin runoff, river routing and combining hydrographs to simulate catchment runoff response." HEC-1 is regarded by many as a good model for both urban and rural watersheds. The software can be downloaded from http://www.hec.usace.army.mil/software/software_distrib/index.html.

The U.S. EPA's Storm Water Management Model (SWMM) is another rainfall runoff simulation model. EPA's website says this about it: "SWMM is a dynamic rainfall-runoff simulation model, primarily but not exclusively for urban areas, for single-event or long-term (continuous) simulation. Flow routing is performed for surface and sub-surface conveyance and groundwater systems, including the option of fully dynamic hydraulic routing in the Extran Block. Nonpoint source runoff quality and routing may also be simulated, as well as storage, treatment and other best management practices (BMPs)." This software package can be downloaded from http://www.ccee.orst.edu/swmm/.

Description of Watershed

To properly conduct a DWSAP plan, the water source's watershed must be described fully and accurately. This entails cataloguing the watershed's natural setting, the existing hydrology, and the various land uses within the watershed. A variety of methods and sources are available to help a person gather all of the information needed.

To describe the natural setting of an area, the following should be provided:

1. Topography: The topography of an area should be described in terms of average slope percentage. The information about this can be obtained from a foot survey of the watershed, from topographic maps, from satellite image photos, or from the soil survey of an area.
2. Geology and Geomorphology: These should be described in terms of rock types, and any major geologic features that may have an impact on the watershed, such as faults or uplifts, should be noted. The information necessary to describe the geology and geomorphology of an area usually can be found in USGS descriptions of an area, or it can be obtained from foot surveys.
3. Soils: The soil description of an area can be done easily if an adequate soil survey was prepared for the watershed previously by others. The U.S. Natural Resources Conservation Service (formerly the Soil Conservation Service, SCS) has already performed soil surveys for much of the nation. In addition, many counties and state governments have conducted their own soil surveys.
4. Vegetation: Vegetation is often described in terms of the prominent plant forms in an area. Sometimes, the types of vegetation vary widely over a watershed, making it difficult to write a simple but accurate description: this can be noted in the report, though. Vegetation types usually

can be seen readily when conducting a foot or aerial survey of the watershed.

5. Wildlife: The wildlife of an area can affect water quality greatly. For this reason, a complete understanding and description of the types and amount of wildlife within the watershed is essential. The California Department of Fish and Game is a good first source for identifying the types of wildlife and populations within an area.

Compiling a complete and accurate description of the existing hydrology of an area is very important for a DWSAP plan, because hydrology directly influences water quality.

The DWSAP survey asks that the hydrology be described using the following framework:

1. Rivers and Streams: These should be described in terms of their stream order, such as a primary, secondary, or tertiary stream. In addition, key parameter values, such as peak discharge and flood frequency, should be provided. Most communities and states have collected large amounts of data concerning existing hydrology; the USGS is also a good source for streamflow data.
2. Lakes and reservoirs: These are often used as water supply sources. They can also affect the hydrology in various ways, by reducing flood peak and by maintaining stream flow at a more consistent rate. Information about lakes and reservoirs can be easily obtained from the reservoir operator(s).

Land use can have a tremendous effect on water quality. The DWSAP manual requires a detailed description of land uses because potential contaminating activities are directly related to the types of land use occurring in an area. Information about land uses can be obtained from zoning agencies and from agencies that issue permits. A visual survey of the watershed is very important too, however, since undocumented land uses are not uncommon.

Contacting a variety of information sources is key, since each source may have only a part of what is needed. The field survey is very important because subtleties can be found that way that cannot easily be obtained by reading permits or merely by looking at aerial photos.

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