Chapter 4
Hydrologic Considerations

Text Reading: pp. 134-159, 161-177, 180-187, 191-201

The Hydrologic Cycle

NPS pollution is a water-driven process. In order to understand and manage NPS pollution, we need to understand how water (and to a certain extent, air) moves in the environment. For nonpoint sources, we are concerned about water movement largely in natural systems, which are more complex than manmade systems for water transport. (Of course, it is usually human alteration of natural systems--through agriculture, urbanization, mining, timber harvest, etc.--that causes the pollution.)

The natural movement of water in the environment is called the **hydrologic cycle**. List the most important primary processes in the cycle in the space below.

Throughout the cycle, water moves as a result of energy gradients. Radiant energy from the sun is the ultimate source of energy driving the cycle via the evaporation of water. One might think of the hydrologic cycle as a complex hydraulic network with the sun as a pump. Since the rate of flow in the network is proportional to the magnitude of the energy gradient and inversely proportional to resistance, we often describe the flow processes using various forms of the diffusion equation. Darcy's Law, governing the flow of water in soils, is the most obvious example of such an equation.

$$q = -K(q)[dh/dx]$$

where q is the mass flux of water , K is the hydraulic conductivity (a function of water content, θ) and the term in brackets is the potential gradient in the x direction.

The flow of water in plants is also governed by a complex set of energy gradients and resistances to flow. In other parts of the system, the diffusion analogy is not so obvious. In all parts of the hydrologic cycle, though, the flow processes are difficult to model accurately and are the subjects of continuing research.

Basic processes and principles

Precipitation

Rainfall depth and **intensity**
Actual storms and **design storms**

Characterizing storms

- **Hyetograph**
- **Volume-Duration-Frequency**
- **Intensity-Duration-Frequency**—IDF curves available for most locations
  See attached curves for Fort Collins.

Exceedence probability –probability that a storm of a given magnitude and duration will be exceeded at a given location in a given year.

Return period= 1/Exceedence probability. Discuss public's failure to understand the concept of a 100-year storm.

Go through an example of how to calculate return periods given a set of annual maximum 1-hr or 24-hr rainfall data.
Procedure:

1. Rank the data from largest to smallest--largest gets rank 1, smallest rank N.
2. Compute the exceedence probability for each rank P = rank/(N+1).
3. Return period = 1/ P.

Return Period Calculation Example

Given 10 years of annual maximum 1-hour rainfall, find the 2 and 10-year design storms.

Year	**Maximum 1-hr Rainfall** (cm)	**Rank**	**Exceedence P=rank/(N+1)**	**Return Period (1/P)** (years)
1991	5.4	1	0.09	11.00
1994	5.2	2	0.18	5.50
1996	5.1	3	0.27	3.67
1992	4.8	4	0.36	2.75
1999	4.8	5	0.45	2.20
1998	4.7	6	0.55	1.83
1993	4.4	7	0.64	1.57

1997	4.3	8	0.73	1.38
2000	4.1	9	0.82	1.22
1995	4	10	0.91	1.10

To find the 2-year storm, interpolate between the storms for 1.83 and 2.20 years, or approximately 4.75 cm.
The 10 year storm is interpolated between values for 5.50 and 11.0 years, or about 5.36 cm.

Characterizing pollutant loadings

Water pollution requires both a source of a contaminant and moving water to transport the contaminant. The moving water can be either surface water or ground water or both.

To characterize pollutant loadings from a given source, both surface runoff and percolation to ground water must be estimated.

Mass load per time = (concentration) x (flow rate)

Generally, flows are estimated using a **mass balance** for a defined **system** or **control volume,** for example a watershed, aquifer, agricultural field, mine, parking lot, or any region with carefully defined system boundaries.

Δ storage = inflow - outflow

Observe the schematic representation of watershed hydrology on page 200. Many possible systems of interest can be defined. The relative importance of the various processes often depends on the size of the time scale of interest, as we shall see.

Write mass balance equations for **runoff**, **interflow**, and **ground water flow**. Often a block diagram of the processes and storage components, as shown in Figure 4.12 can be helpful in formulating and understanding the mass balance.

Note that evapotranspiration, ET, does not appear in a mass balance for event scale surface runoff, but does appear in a mass balance for interflow. Why?

How might you calculate ET for a field or watershed using a mass balance?

Another way to write a mass balance for runoff is:
Runoff = rainfall – initial abstractions – infiltration

Initial abstractions include both **depression storage** and **interception**.

Soil moisture storage—not well covered in the text.

Soil moisture storage is most often expressed on a volume basis.
Soil water content, θ= cm of water/ cm of soil
Soil water storage as a depth of water or volume/unit area = θD,
where D is the depth of soil of interest, often the root depth

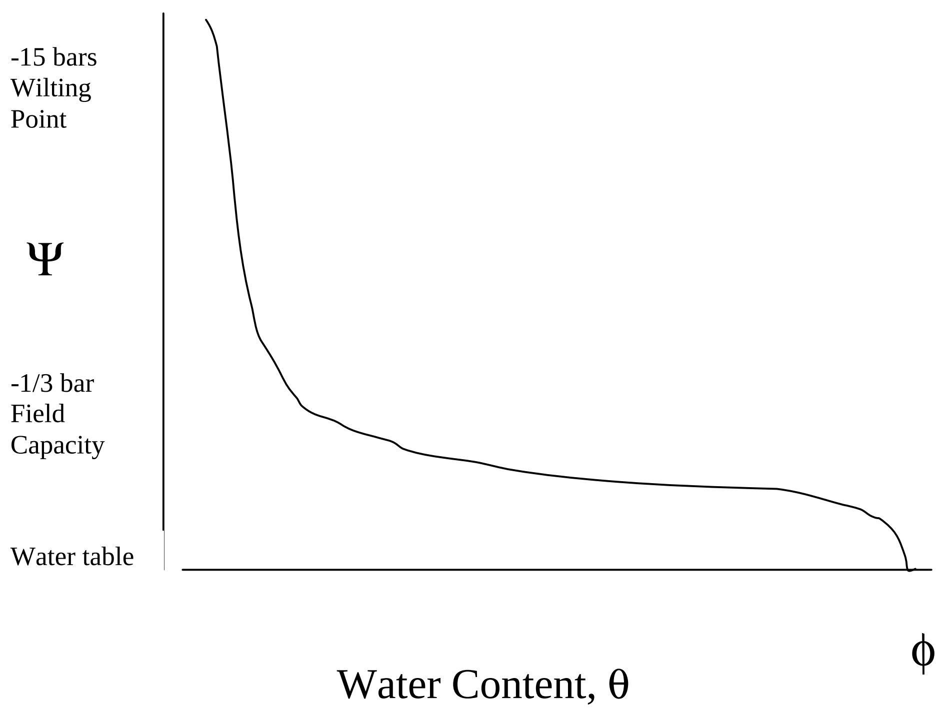
Water is stored in the soil **under tension** or negative pressure. Soils vary in their water holding characteristics which include
Porosity, ϕ**,** or **saturated water content** θ_s .

Field capacity – about 0.3 bars tension / suction

Wilting point – about 15 bars tension / suction

Water contents may be related to tensions (negative pressures) via a **soil-water characteristic curve** for a particular soil, which depends on the soil texture (particle-size distribution).

Imagine a static column of soil and water at equilibrium. The water contents and pressures would look something like this.



One bar = 1 atmosphere

Water holding characteristics for soils over a range of textures are shown in Figure 4.14 on page 152. For a given tension, finer-textured soils hold more water than coarser-textured soils. For very fine soils, a large fraction of the water in storage is held at high tensions, above the wilting point, and is thus not available for plant uptake (page 152).

Infiltration Capacity

Limited by either **rainfall rate** or the **infiltration capacity** of the soil, that is the ability of the soil to transmit water (**permeability**) under the available energy (pressure) **gradient**.

Thus, infiltration into coarse soils and dry soils can occur more rapidly than into fine soils and wet soils.

Runoff Potential

Since permeability and infiltration capacity are directly related, permeability and runoff potential are inversely related. See the SCS Hydrologic Groups (A, B, C, D) on page 150-151, Table 4.2. Which represents the highest runoff potential? Highest infiltration capacity? Soil Surveys classify most of the soils in the U.S. (4000 soils in Colorado alone.)

Variation of infiltration rate with time

Ponding occurs when the rainfall rate exceed the infiltration capacity of the soil Under non-ponded conditions infiltration rates vary with the rainfall rates. Under ponded conditions infiltration rates decrease with time because the energy gradient decreases as the soil gets wet.

Under ponded conditions and long times, the infiltration rate approaches **the saturated hydraulic conductivity, K_{sat}** of the soil because the gradient in Darcy's Law approaches one.

Alternative Mathematical Models for Infiltration Capacity

Horton, Holtan, Phillips, Green-Ampt equations, pages 152-156. There are several others including the Kostiakov equation. All show an exponential decay with time, see Fig 4.15 on page 153. Let's focus on a few examples.

Horton equation

Phillip's equation

Green-Ampt

Note the *parameters* in each of these equations. How would you obtain values for these parameters? What is the effect of initial soil moisture content?

Given the above equations, how would you estimate the total infiltration which had occurred up to a certain time? What if the soil were not ponded the entire time?

Evapotranspiration

Evaporation is an important component of the overall hydrologic budget. Evaporation estimates are especially important in estimating annual water yield from watersheds, losses from lakes and reservoirs, and irrigation demands of crops. In Colorado, irrigation is by far the largest use of water, accounting for 80-90% of the total.

At times it is important to distinguish between **evaporation** from a water or wet soil surface and **transpiration** from plants. However, the two are often lumped together as **evapotranspiration (ET or Et).** The physics of evaporation are the same whether or not plants are involved. However, plants add a resistance to water flow which can make estimates a bit more complicated.

Evaporation and Et can be measured indirectly using a water balance or budget and can be estimated using predictive equations which have the factors affecting evaporation as inputs. These equations can be empirical, physically based, or a combination of the two. Physically based models are based on an energy budget.

Predictive equations may be designed to estimate evaporation from a free-water surface or from a well-watered reference crop such as clipped grass or alfalfa. The latter is called **reference Et**. It is important to make sure that the equation you are using is predicting what you think it is. Evaporation from a free-water surface, grass reference Et, and alfalfa reference Et are all different. **Actual Et** from a crop or native vegetation will be different as well and will depend on the type of crop or plant cover, the stage of growth or canopy density, and the availability of soil water. Generally reference Et is the starting point for estimating plant water use with adjustments for the other factors.

Factors affecting evaporation

- Temperature
- Vapor pressure or relative humidity--Relative humidity is the ratio of actual vapor pressure to saturation vapor pressure at that temperature. Saturation vapor pressures are given by Table 4.1 on page 136.
- Solar radiation – incoming short wave minus reflected short wave and re-radiated long wave
- Wind speed—a function of height and generally measured at a height of 2 meters
- Soil moisture if soil is dry

Water Budget

Evaporation is often estimated using a water budget or mass balance, especially for ponds, lakes, and reservoirs.

Predictive Equations

There are many predictive equations for evapotranspirations for a wide variety of conditions and uses. Several (probably not most as Novotny suggests) have a form similar to 4.8 on page 157.

The Penman Equation

The Penman Equation, along with its variations, is a physically based and potentially highly accurate method of estimating evaporation and/or Et using measurements of weather variables. Even though the method is based on an energy balance, there are still model parameters which required local calibration for best results. The Penman Equation is often used for time steps of one day, and is sometimes used for time periods of less than one day. Generally as the time period increases, the accuracy of estimation increases as well.

There are several forms of the Penman Equation. Generally they are very similar to equation 4.8 with the addition of a net radiation term, ($R_{net}/L\rho$) missing from 4.8, plus weighting factors for the two terms. The required input weather variables are **temperature, solar radiation, relative humidity and wind speed**. The equation has two main terms or components. The missing term represents the <u>energy input from net radiation</u>, and the second term (equation 4.8) represents the <u>evaporative capacity of unsaturated air</u>. The second term increases with increasing wind speed and is zero if the air is saturated, but is not zero if the wind speed is zero. It is interesting to note that the first term is not zero if the air is saturated. How can evaporation occur into saturated air?

Note that the **latent heat of vaporization of water**, L, which relates the net energy flux to the evaporation rate is a function of temperature and is given by an equation on page 157.

Simpler empirical equations

For evapotranspiration (reference Et) estimates, the Jensen-Haise equation, using solar radiation and temperature is often used in the western US to provide estimates of alfalfa reference Et. The Jensen-Haise method should be used for weekly or longer time intervals. The Blaney-Criddle equation, based on temperature only, is used world-wide to provide seasonal Et estimates for specific crops and should be used for time intervals no shorter than one month.

Evaporation Pans

Evaporation may be measured directly using an evaporation pan, the most common of which is a U.S. Weather Bureau Class A pan. However, evaporation from pans is greater than that from a free water surface or a well-watered reference crop. Thus pan evaporation must be adjusted by means of a pan coefficient to obtain lake or crop Et. Pan coefficients are presented in the reference cited below and are specific to the type of pan, the type of Et to be predicted (free-water, alfalfa, or grass reference), and the local conditions surrounding the pan.

Actual Evapotranspiration for a particular crop or vegetative cover can be estimated by multiplying a crop coefficient time the reference Et (see page 158). However, the appropriate coefficient to use depends on the method used to obtain the reference value. Tables of crop coefficients will work only for specific intended applications, and exist for adjusting Penman Et, Jensen-Haise Et, etc. in addition to pan or lake evaporation to obtain actual Et

[**Reference**: Jensen, M.E., R. D. Burman, and R. G. Allen, editors, 1990. Evapotranspiration and Crop Water Requirements, ASCE Manuals and Reports on Engineering Practice No. 70., 332 p.]

Snowmelt

Predictions of snowmelt can be either physically based, purely empirical , or some combination of the two. Physically based models base predictions on the energy available for snowmelt compared to the energy required. Energy can be supplied by solar radiation or by heat transfer from the air, soil, or precipitation. The energy requirement is the latent heat of fusion of water. What is the numerical value of the latent heat of fusion of water?

Degree-day methods relate snowmelt to temperature. These methods assume that snowmelt starts at base value of mean daily temperature, usually 0 deg C. and increases linearly thereafter (eqn 4.10). The slope, CD, can be estimated by regression or taken from Figure 3.12 or other literature values.

Energy –balance methods are based on equations of the form 4.12 on page 160, similar in concept to a Penman equation for evaporation.

Runoff and Peak Discharge: Analysis and Design

Possible design requirements—

1. Total runoff volume
2. Peak runoff rate
3. Runoff rate as a function of time

The NRCS Curve Number Equation –for total runoff volume, page 162

Assumes that a rainfall event may be separated into an initial abstraction, actual retention, and direct runoff.

The actual retention will be somewhat less than the potential maximum retention, denoted as S. S should be a function of land use, interception, infiltration, depression storage, and antecedent moisture.
The overall equation is

$Q = (P - 0.2\,S)^2/(P + 0.8S)$ (eqns 4.16 and 4.17)

If $P < 0.2\,S$, then assume that $Q = 0.0$.

This equation gives the runoff depth in terms of the rainfall depth P and one unknown, S. Runoff volume is simply the depth of runoff times the watershed area. S is found from the SCS (NRCS) curve number, CN, which is an index representing the combination of soil hydrologic group (A-D), cover complex (good, fair, poor), and antecedent moisture conditions. Hydrologic group can be found in soil surveys or field tests of the minimum (long-term) infiltration rate, see table 4.5.

S is related to the CN as follows

$S = (25{,}400/CN) - 254$ (eq 4.20)

Curve numbers are tabulated in table 3.9, and adjustments for antecedent moisture condition are in tables 3.10 and 3.11. Weighted curve numbers can be used for urban areas with given fraction of impervious surface.

Study Boxes 4.4 and 4.5.

Peak discharge: The rational method—Q=CiA (eq 4.22)

Define the variables in this equation. What is a reasonable choice for duration of the design storm?

Define time of concentration, t_c. See page 171.

Weighted average C values for nonhomogeneous watersheds, see (eq 4.23)
Be sure to read the footnote in Table 4.8, pg 172 on calculating
C values for rural watersheds! Don't just use the value in the right column.

Study Box 4.6 on page 174-175

Distribution of runoff with time

from a

1. **rainfall hyetograph**, we wish to construct an
2. **excess rainfall hydrograph** and to then convert this into a
3. **direct runoff hydrograph**.

Construction of excess rainfall hyetographs from rainfall hyetographs—infiltration losses and surface storage losses are removed.

For any storm, the volume of excess rainfall must equal the volume of direct runoff. If we are analyzing a measured event in order to evaluate watershed response (unit hydrograph), we will have measurements of discharge at some stream gage location.

If runoff is observed in addition to rainfall, then the difference between the runoff and the rainfall is equal to the infiltration plus surface storage losses. These losses can be distributed over time in a variety of ways, the simplest of which is to assume a uniform loss rate. *When the losses are subtracted from the rainfall hydrograph, what is left is the excess rainfall hydrograph.*

Construction of direct runoff hydrographs from streamflow measurements--

Often the available measurements are of streamflow rather than runoff directly. Thus, there may be flow present even when it has not recently rained.

Baseflow separation--To extract direct runoff only from an observed discharge hydrograph, it is necessary to remove baseflow or ground-water flow. Several methods for accomplishing this are available. All are somewhat subjective. The simplest is a “straight-line” method. *When the baseflow has been removed from a streamflow hydrograph following a storm event, what is left is the direct runoff hydrograph.*

When runoff is not observed, the infiltration losses can be estimated by one of the infiltration capacity equations we have seen earlier.

Infiltration capacity

Infiltration capacity can be estimated by Horton’s, Holtan, or Phillip’s equations, and other similar exponential decay equations (Kostiakov, Green-Ampt) with parameters which can be locally calibrated or roughly approximated using tables, NRCS soil surveys, etc. If the rainfall rate exceeds the infiltration capacity, then the difference will be the excess rainfall. If the rainfall rate is less than the infiltration capacity, the excess rainfall is zero.

For cases in which the rainfall rate does not initially exceed the infiltration capacity, the infiltration capacity will not decay as fast as the Horton equation predicts. There are several options and much debate about how to proceed. The simplest approach is to ignore the problem, realizing that you will underpredict infiltration and overpredict excess rainfall as a result.

Now suppose that we have obtained an excess rainfall hydrograph by some method, and we need to convert it into a runoff hydrograph.

Unit Hydrographs

*The transfer function that converts an excess rainfall hydrograph into a runoff hydrograph is the **unit hydrograph**.*

Recall the definition of hydrograph. Remember that volumes and depths are interchangeable. For most analyses, depths are more convenient.

Why are runoff hydrographs needed? Why can't we base designs and management on peak discharges alone?

Definition:
A unit hydrograph is the direct runoff hydrograph which results from a single unit (1 inch or 1 cm) of excess rainfall in a stated time period, T.

Unit hydrographs depend on watershed characteristics and may be obtained by direct observation of rainfall and runoff, or any of several synthetic unit hydrographs may be used (4.31 and 4.32 on page 178 or the NRCS dimensionless unit hydrograph on pages 180-185).

Let's suppose now that we have a workable unit hydrograph. How do we use it?

Using Unit Hydrographs to Predict Runoff from Excess Rainfall

Recall the definition of a unit hydrograph—the direct runoff response or output of a given watershed to a unit input of excess precipitation over a given interval of time, T. The time interval is the effective duration of the unit hydrograph and can be anything, including zero. The response in this extreme case is called the unit impulse hydrograph, instantaneous unit hydrograph (IUH), or the kernel function. The most convenient interval T is the same as that for which we have an excess rainfall hydrograph as we shall see.

Unit hydrographs may be used to determine the watershed response to any time pattern of excess rainfall if we can assume that the system behaves **linearly**. In other words, if we double the input, we double the response, the time pattern of response to a given input does not depend on when the input occurs, and responses to multiple inputs can be added. See the discussion of linearity on page 176.

The relationship between the excess rainfall hydrograph, the instantaneious unit hydrograph, and the runoff hydrograph is given by equation 4.26 on page 176.

We can extend this example to the general case of discrete inputs and unit hydrographs as follows.

$$y(t) = \sum_{j=1}^{t} x(j)U(t-j+1)$$

In this equation, U(), is the discrete unit hydrograph ordinate for time () with an effective duration T equal to the discretization interval for both excess rainfall and runoff, and x () is the excess rainfall for time (). This equation is called a **convolution equation** and the continuous form 3.29 is called the convolution integral.

The use of the convolution equation is illustrated very well in Figure 4.21 on page 176.

Work an example dealing with unit hydrographs.

The SCS (NRCS) Unit Hydrograph—particular shape based on analysis of many data sets.

Both **triangular and curvilinear forms** are available. The triangular form is obviously simpler, and we shall work with it. There is a single parameter of the NRCS unit hydrograph, either the time to peak or time of concentration. Either determines the entire unit hydrograph.

For the triangular form, the time to peak, $\mathbf{t_p}$, **is 2/3** $\mathbf{t_c}$. The **total time of runoff is 8/3** $\mathbf{t_p}$. Thus, the recession limb, $t_r = 5/3\ t_p$ or $10/9\ t_c$.

From geometry, the total runoff volume would be = ½ $q_p\ (t_p + t_r)$. For a unit hydrograph, this volume must = 1.0 so $\mathbf{q_p = 2/(t_p + t_r)}$. (see equation 4.38)

The effective duration of the excess rainfall pulse T, or **D, = 0.133** $\mathbf{t_c}$.

These relationships are portrayed in Figure 4.24 on page 181.

So all you really need to construct the NRCS triangular unit hydrograph for a given watershed is the time of concentration and the above relationships. The rest of the equations are unnecessary. The time base D = 0.133 t_c (eq 4.42a) . All computations are performed using this time interval (or closest rounded value). Thus the excess rainfall hydrograph must be expressed using a discretization interval of T for convolution with the NRCS Unit Hydrograph.

To find the time of concentration for a given watershed, a number of methods can be used. A method suggested in the text is equation 3.42 on page 160 to find a lag time, t_l, which is related to the time of concentration by $t_c = 1.666t_l$. The lag time may be adjusted for urban watersheds using equation 3.43.

Study Box 4.7.

Ground Water Systems

Conceptualization: See Figures 4.30 , 4.31, and 4.32 on pages 197, 198, and 200.

Water balance equations 4.51, 4.52, and 4.53 on page 200.