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1. Introduction

Hydrology is a quantitative geoscience that describes and seeks to predict the distribution, spatio-temporal variability and circulation of water. Hydrology was born from the need to answer practical questions about water management and water-related hazards. Hydrology has existed for thousands of years as early civilizations of the Indus in Pakistan, the Tigris and Euphrates in Mesopotamia, the Hwang Ho in China and the Nile in Egypt were building hydraulic structures like canals, levees and dams.

2. Conservation Equations

A model of a **system** is a conceptually defined region that receives **inputs** of a conservative quantity and discharges **outputs** of that quantity. The system may store some amount of the quantity. We define a conservative quantity as one that cannot be created or destroyed within the system. Mass $[M]$, momentum $[MLT^{-1}]$ and energy $[ML^2T^{-2}]$ are all conservative quantities.

The basic conservation equation states that the amount of the conservative quantity entering a control volume, minus the amount leaving the volume during the time period, equals the change in the amount of the quantity stored during the time period.

$$\text{Amount In - Amount Out = Change in Storage} \tag{1}$$

Another way to state this is:

$$\frac{I}{\Delta t} - \frac{Q}{\Delta t} = m_I - m_Q = \frac{\Delta S}{\Delta t} \tag{2}$$

Where I is the amount of a conservative quantity entering a region in time period Δt and Q is the amount of a conservative quantity leaving a region in time period Δt and ΔS is the change in storage. By taking the limit as Δt tends to zero $i = lim_{\Delta t \to 0} \frac{I}{\Delta t}$, $q = lim_{\Delta t \to 0} \frac{Q}{\Delta t}$

$$i(t) - q(t) = \frac{dS}{dt} \tag{3}$$

All these conservation equations are the **water balance equations** and they can be applied to conservative quantities through various portions of the hydrologic cycle, from pore to global.

2a. *Example of a linear reservoir*

In a linear reservoir, discharge is proportional to the storage $q(t) = KS(t)$ where K is a proportionality constant that doesn't depend on time.

$$i - q = i - KS = \frac{dS}{dt} \tag{4}$$

we multiply by e^{Kt}

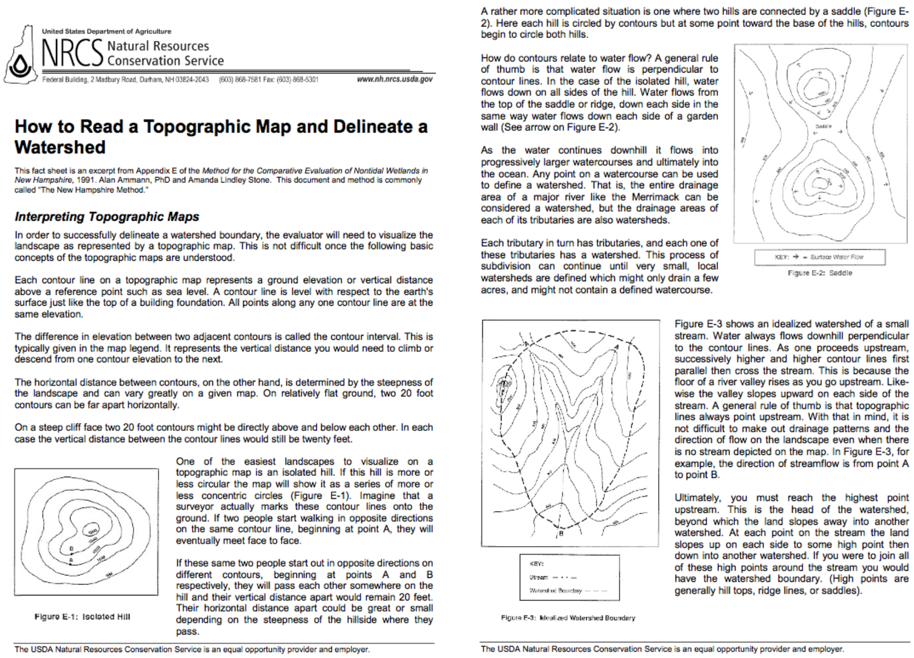
$$\begin{aligned}
e^{Kt}\frac{dS}{dt} + e^{Kt}KS &= ie^{Kt} && (5)\\
\frac{d(Se^{Kt})}{dt} &= ie^{Kt} && (6)\\
\int_0^t d(Se^{Kt}) &= \int_0^t ie^{Kt}dt && (7)\\
Se^{Kt} - S_0 &= \frac{i}{K}(e^{Kt} - 1) && (8)\\
S &= S_0e^{-Kt} + \frac{i}{K}(1 - e^{-Kt}) && (9)
\end{aligned}$$

3. The Watershed

We often use the conservation equation above to describe the hydrologic characteristics of a geographical region. Most commonly, this is a watershed (drainage basin, river basin or catchment). Defined as ”the topographically-defined area that contributes all the water that passes through a given cross section of a stream. This is a natural unit for water-resource and land-use planning. Hydrologists usually delineate watersheds above stream-gaging stations or other important points (reservoirs etc.) There are infiniete number of watersheds can be drawn for a stream. Currently, topographic information is becoming available via digital elevation models (DEMs) and computer programs can delineate watersheds.

- A watershed is divided from other watersheds through a **watershed divide**.

- The **watershed surface** has 3-D topogrphy drained by a **stream network**.
- **Contour lines** are typically used to represent lines of constant elevation. A stream is perpendicular to the contour lines.



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How to Read a Topographic Map and Delineate a Watershed

This fact sheet is an excerpt from Appendix E of the *Method for the Comparative Evaluation of Nontidal Wetlands in New Hampshire*, 1991. Alan Ammann, PhD and Amanda Lindley Stone. This document and method is commonly called "The New Hampshire Method."

Interpreting Topographic Maps

In order to successfully delineate a watershed boundary, the evaluator will need to visualize the landscape as represented by a topographic map. This is not difficult once the following basic concepts of the topographic maps are understood.

Each contour line on a topographic map represents a ground elevation or vertical distance above a reference point such as sea level. A contour line is level with respect to the earth's surface just like the top of a building foundation. All points along any one contour line are at the same elevation.

The difference in elevation between two adjacent contours is called the contour interval. This is typically given in the map legend. It represents the vertical distance you would need to climb or descend from one contour elevation to the next.

The horizontal distance between contours, on the other hand, is determined by the steepness of the landscape and can vary greatly on a given map. On relatively flat ground, two 20 foot contours can be far apart horizontally.

On a steep cliff face two 20 foot contours might be directly above and below each other. In each case the vertical distance between the contour lines would still be twenty feet.

One of the easiest landscapes to visualize on a topographic map is an isolated hill. If this hill is more or less circular the map will show it as a series of more or less concentric circles (Figure E-1). Imagine that a surveyor actually marks these contour lines onto the ground. If two people start walking in opposite directions on the same contour line, beginning at point A, they will eventually meet face to face.

If these same two people start out in opposite directions on different contours, beginning at points A and B respectively, they will pass each other somewhere on the hill and their vertical distance apart would remain 20 feet. Their horizontal distance apart could be great or small depending on the steepness of the hillside where they pass.

Figure E-1: Isolated Hill

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A rather more complicated situation is one where two hills are connected by a saddle (Figure E-2). Here each hill is circled by contours but at some point toward the base of the hills, contours begin to circle both hills.

How do contours relate to water flow? A general rule of thumb is that water flow is perpendicular to contour lines. In the case of the isolated hill, water flows down on all sides of the hill. Water flows from the top of the saddle or ridge, down each side in the same way water flows down each side of a garden wall (See arrow on Figure E-2).

As the water continues downhill it flows into progressively larger watercourses and ultimately into the ocean. Any point on a watercourse can be used to define a watershed. That is, the entire drainage area of a major river like the Merrimack can be considered a watershed, but the drainage areas of each of its tributaries are also watersheds.

Each tributary in turn has tributaries, and each one of these tributaries has a watershed. This process of subdivision can continue until very small, local watersheds are defined which might only drain a few acres, and might not contain a defined watercourse.

KEY: → = Surface Water Flow

Figure E-2: Saddle

Figure E-3 shows an idealized watershed of a small stream. Water always flows downhill perpendicular to the contour lines. As one proceeds upstream, successively higher and higher contour lines first parallel then cross the stream. This is because the floor of a river valley rises as you go upstream. Likewise the valley slopes upward on each side of the stream. A general rule of thumb is that topographic lines always point upstream. With that in mind, it is not difficult to make out drainage patterns and the direction of flow on the landscape even when there is no stream depicted on the map. In Figure E-3, for example, the direction of streamflow is from point A to point B.

Ultimately, you must reach the highest point upstream. This is the head of the watershed, beyond which the land slopes away into another watershed. At each point on the stream the land slopes up on each side to some high point then down into another watershed. If you were to join all of these high points around the stream you would have the watershed boundary. (High points are generally hill tops, ridge lines, or saddles).

KEY:
Stream — · · —
Watershed Boundary — — —

Figure E-3: Idealized Watershed Boundary

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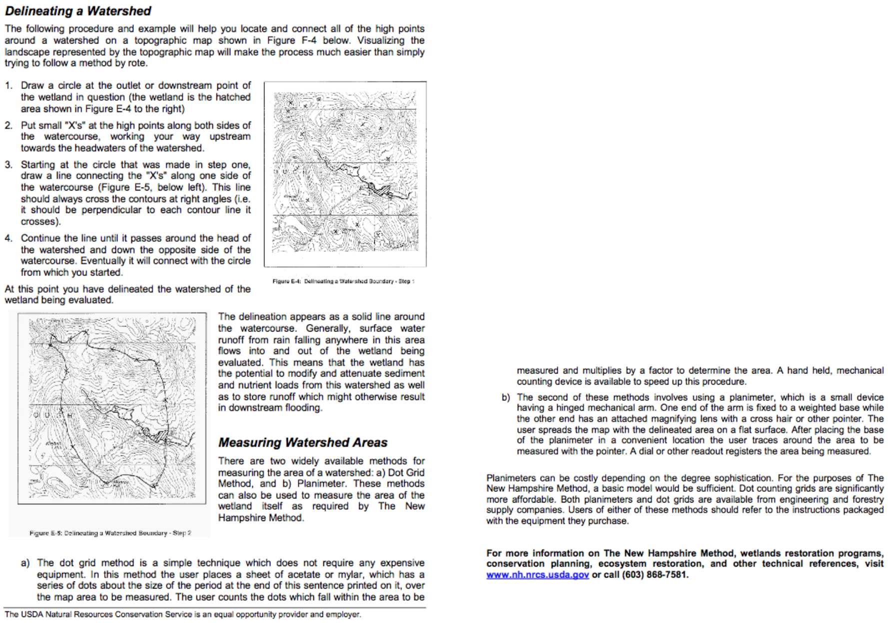
Figure 1: Delineating a Watershed 1

We are part of the Colorado River Basin, which begins in the high mountains of the Rockies in Colorado and Wyoming, and flows to the Gulf of California in the Colorado River delta in Mexico. 75% of the river's flow is supplied by mountain headwaters but most of the basin is in the semiarid desert and at a mean discharge of 40 m^3/s is one of the driest in he world (compare to the 18,400 m^3/s in the Lower Mississippi). Nearly all tributaries in the lower basin are intermittent, Tucson lies in the Santa Cruz river basin which is part of the Gila river basin.



Delineating a Watershed

The following procedure and example will help you locate and connect all of the high points around a watershed on a topographic map shown in Figure F-4 below. Visualizing the landscape represented by the topographic map will make the process much easier than simply trying to follow a method by rote.

1. Draw a circle at the outlet or downstream point of the wetland in question (the wetland is the hatched area shown in Figure E-4 to the right)
2. Put small "X's" at the high points along both sides of the watercourse, working your way upstream towards the headwaters of the watershed.
3. Starting at the circle that was made in step one, draw a line connecting the "X's" along one side of the watercourse (Figure E-5, below left). This line should always cross the contours at right angles (i.e. it should be perpendicular to each contour line it crosses).
4. Continue the line until it passes around the head of the watershed and down the opposite side of the watercourse. Eventually it will connect with the circle from which you started.

Figure E-4: Delineating a Watershed Boundary - Step 1

At this point you have delineated the watershed of the wetland being evaluated.

Figure E-5: Delineating a Watershed Boundary - Step 2

The delineation appears as a solid line around the watercourse. Generally, surface water runoff from rain falling anywhere in this area flows into and out of the wetland being evaluated. This means that the wetland has the potential to modify and attenuate sediment and nutrient loads from this watershed as well as to store runoff which might otherwise result in downstream flooding.

Measuring Watershed Areas

There are two widely available methods for measuring the area of a watershed: a) Dot Grid Method, and b) Planimeter. These methods can also be used to measure the area of the wetland itself as required by The New Hampshire Method.

a) The dot grid method is a simple technique which does not require any expensive equipment. In this method the user places a sheet of acetate or mylar, which has a series of dots about the size of the period at the end of this sentence printed on it, over the map area to be measured. The user counts the dots which fall within the area to be measured and multiplies by a factor to determine the area. A hand held, mechanical counting device is available to speed up this procedure.

b) The second of these methods involves using a planimeter, which is a small device having a hinged mechanical arm. One end of the arm is fixed to a weighted base while the other end has an attached magnifying lens with a cross hair or other pointer. The user spreads the map with the delineated area on a flat surface. After placing the base of the planimeter in a convenient location the user traces around the area to be measured with the pointer. A dial or other readout registers the area being measured.

Planimeters can be costly depending on the degree sophistication. For the purposes of The New Hampshire Method, a basic model would be sufficient. Dot counting grids are significantly more affordable. Both planimeters and dot grids are available from engineering and forestry supply companies. Users of either of these methods should refer to the instructions packaged with the equipment they purchase.

For more information on The New Hampshire Method, wetlands restoration programs, conservation planning, ecosystem restoration, and other technical references, visit www.nh.nrcs.usda.gov or call (603) 868-7581.

Figure 2: Delineating a Watershed 2

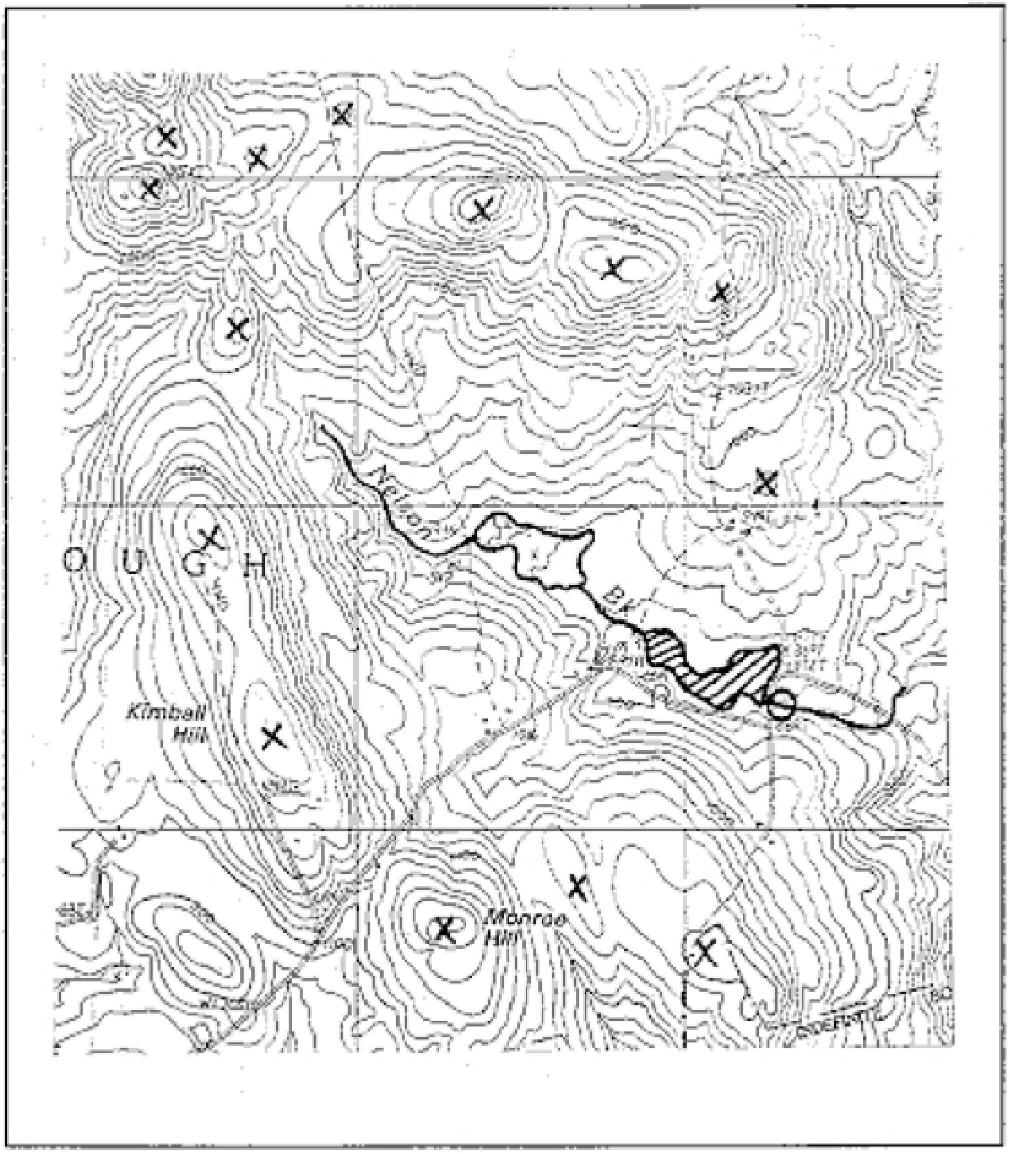


Figure E-4: Delineating a Watershed Boundary - Step 1

Figure 3: Example Watershed Delineation

Figure 4: Colorado and Gila River Basin

4. Application of the Water-Balance Equation to the Watershed

Figure 5: Figure 2-3 of Dingman

When looking at a time period of length Δt, we can write the water balance equation as:

$$P + G_{in} - (Q + ET + G_{out}) = \Delta S \tag{10}$$

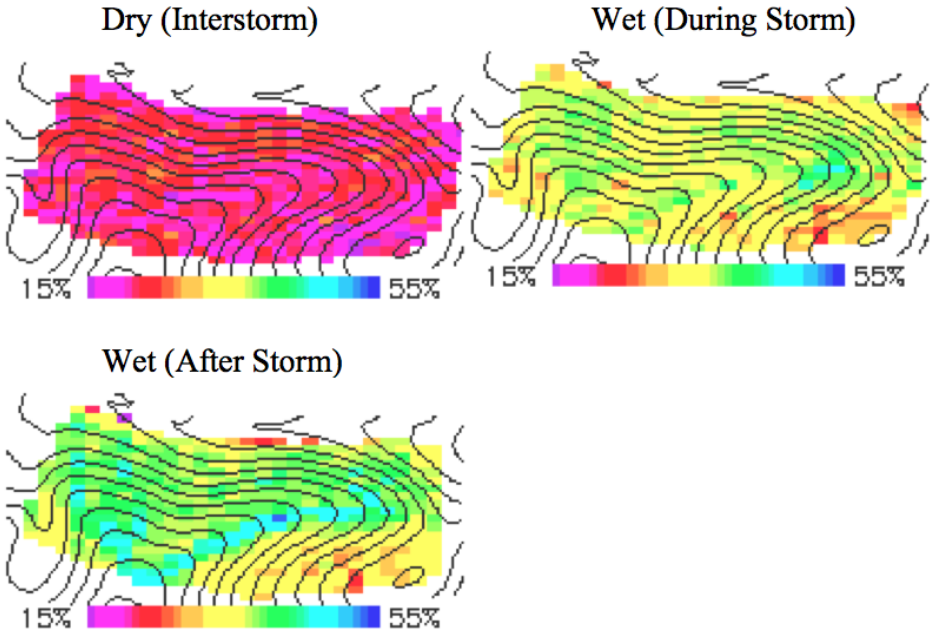
Where P is precipitation, G_{in} is ground-water inflow, Q is stream outflow, ET is evapotranspiration, G_{out} is ground-water outflow, and ΔS is the change in all forms of storage over the time period. All dimensions are $[L^3]$. Averaged over many years the net change in storage is 0.The total amount of liquid water leaving the region is called **runoff**. $RO = Q + G_{out}$, and it represents the water that is available for human use and management. Closing the water balance entails measurements of all the components in 10. It is difficult because we must:

- Define the control volume boundaries
- Estimate fluxes at the boundaries over space and time
- Know the system storage capacity
- Know the internal redistribution within the control volume

5. Spatio-Temporal Variability

Rates of input and output of hydrologic variables vary spatially and temporally. As an example, topography and soil characteristics influence soil moisture distribution. In particular during wet events (during or after storms).

In addition, S(x,t), I(x,t), Q(x,t) are functions of both space and time. For example look at the rainfall (I) and discharge (Q) measurements in a research watershed in North Carolina over 1983.



Dry (Interstorm)

Wet (During Storm)

Wet (After Storm)

Figure 6: Soil moisture measurements in a small basin in Tarrawarra, Australia (From E. Vivoni)

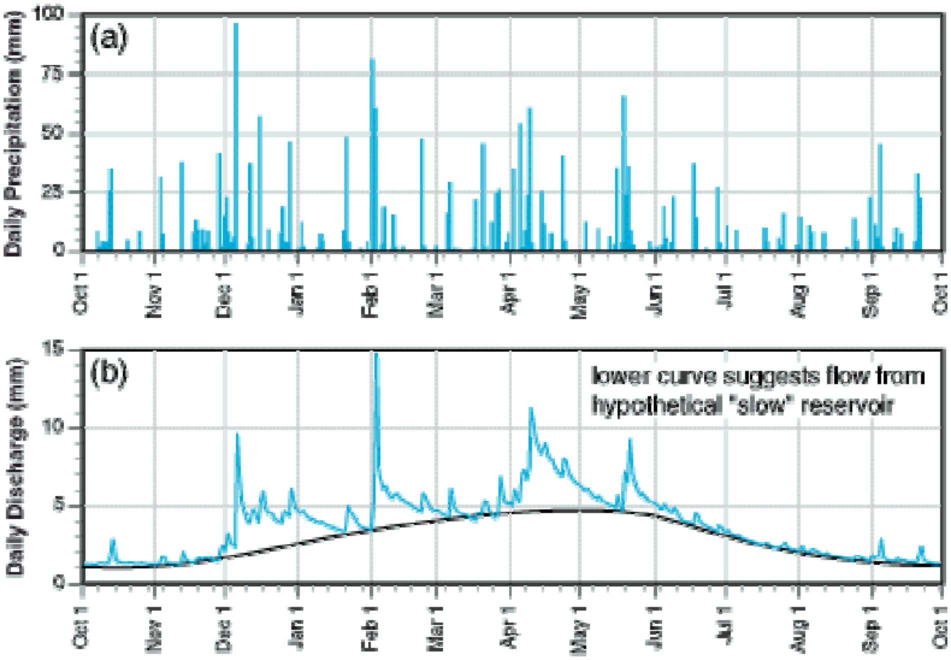


Figure 7: Temporal variability on hydrologic inputs and outputs for the Coweeta Laboratory, basin W34 (From E. Vivoni)

The temporal variability in the inputs and outputs is represented through a time series. Notice that the amount of discharge leaving is not always the same proportion to the rainfall received. The runoff coefficient is defined as:

$$r = \frac{\overline{Q}}{\overline{I}} \tag{11}$$

Where the overbar implies a temporal average over a specified period. Notice that the rainfall-runoff coefficient is also a timeseries, and that the transformation is nonlinear implying that a unit amount of rainfall does not necessarily produce a unit amount of discharge (linear reservoir approximation is limited. The importance of time variability is evident when we think of streamflow available for humans. We cannot rely on the mean flow to be available most of the time, so we must know what streamflow rate is available a large percentage of the time. The variability is related to seasonal and interannual variability and inversely proportional to storage (variability is measured through the coefficient of variation or ratio between quartiles). Storage also increases the persistence, or the tendency for high values of a time-distributed variable to be followed by high values and low values by low values (measured by autocorrelation coefficient).Humans increase water availability by building storage reservoirs.

We can use the concept of **residence time** to understand these relations. Residence time is a relative measure of the storage effect of a reservoir, equal to the average length of time that a "parcel" of water spends in the reservoir. We calculate the residence time by calculating the average mass of a substance of interest in the reservoir by the average rate of outflow (Q or I). $T_R = S/Q = S/I$ For linear reservoirs:

Figure 8: Figure 2-8 Dingman

6. Hydrologic Modeling

- The goal is to predict, forecast and gain understanding of processes. It emphasizes features appropriate for its purpose while omitting other features.
- Represents a portion of the world. Simplified for a specific purpose

- Produces an output from an input
- It is constructed at a particular scale.

There are many different types of models and different ways to classify them. We can divide them according to the way they represent the physical processes:

1. Physically based
2. Conceptual
3. Empirical/Regression
4. Stochastic time series

We can also classify them according to their spatial representation:

1. Lumped
2. Distributed
3. Coordinate System