# CIVE 6361 – ENGINEERING HYDROLOGY
Fall 2004

Water and the Hydrologic Cycle

The hydrologic cycle is a concept central to hydrology. It is conceptualized as a continuous process, without start or finish. It is shown schematically in Figure 2.

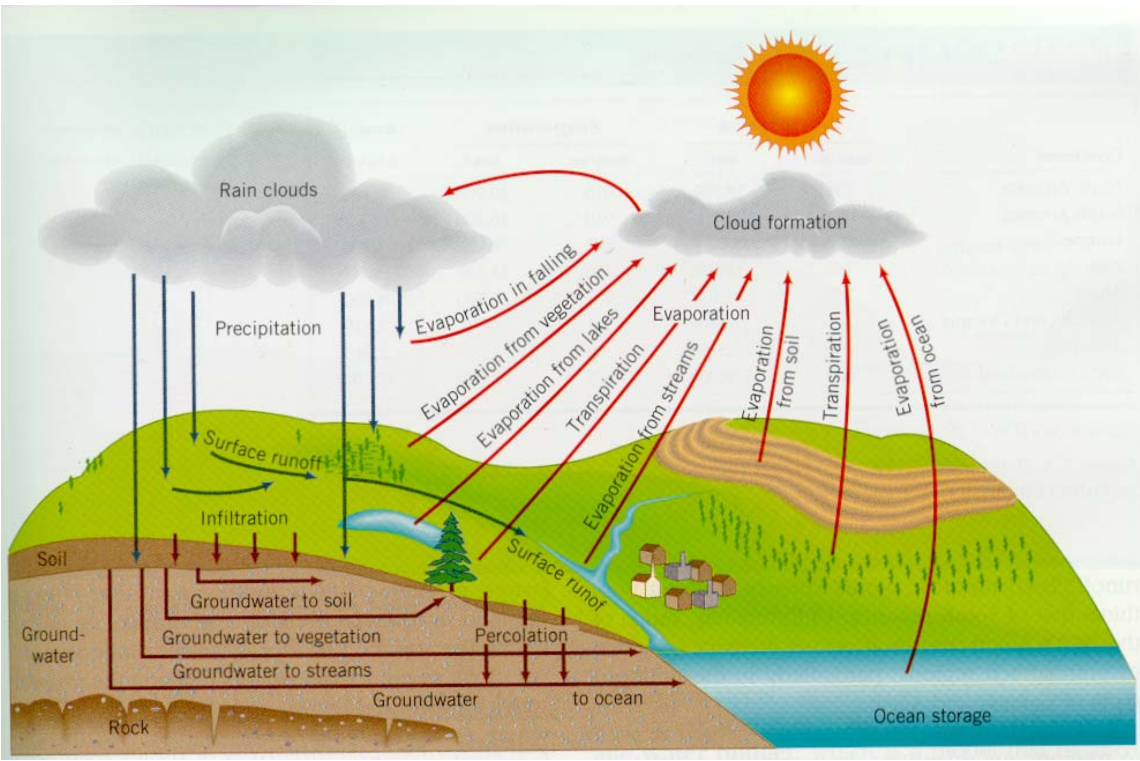


Figure 1. Hydrologic Cycle Schematic
From: Botkin and Keller, 1998. Envrionmental Science, J. Wiley & Sons, New York.

Water evaporates from the ocean and other water bodies, and transpires through vegetation. Collectively these processes are called evapo-transpiration. The water vapor rises into the atmosphere until it condenses and precipitates mostly as rainfall, but also as snow, sleet, hail, etc. Over land, roughly 40% of precipitation becomes runoff, while the remainder returns to the atmosphere. Hydrologic cycle is the name given to the dynamic process where water is transported from the subsurface to the surface to the atmosphere and back again. The concept of the hydrologic cycle is central to an understanding of the occurrence of water and the development and management of water supplies.

Although the hydrologic cycle has neither a beginning nor an end, it is convenient to discuss its principal features by starting with evaporation from vegetation, from exposed moist surfaces including the land surface, and from the ocean. This moisture forms clouds, which return the water to the land surface or oceans in the form of precipitation.

Precipitation occurs in several forms, including rain, snow, and hail, but only rain is considered in this discussion. The first rain wets vegetation and other surfaces and then begins to infiltrate into the ground. Infiltration rates vary widely, depending on land use, the character and moisture content of the soil, and the intensity and duration of precipitation, from possibly as much as 25 mm/hr in mature forests on sandy soils to a few millimeters per hour in clayey and silty soils to zero in paved areas. When and if the rate of precipitation exceeds the rate of infiltration, overland flow occurs.

The first infiltration replaces soil moisture, and, thereafter, the excess percolates slowly across the intermediate zone to the zone of saturation. Water in the zone of saturation downward and laterally to sites of ground-water discharge such as springs on hillsides or seeps in the bottoms of streams and lakes or beneath the ocean.

Water reaching streams, both by overland flow and from ground-water discharge, moves to the sea, where it is again evaporated to perpetuate the cycle.

Movement is the key element in the concept of the hydrologic cycle.

Climates

Weather
Tropical
Arid
Sub-tropical
Continental
Polar
Highlands

Important Climatic Episodes/Events

ENSO (El Nino Southern Oscillation)
Catastrophic Flooding (www.tsarp.org)
Droughts

Atmospheric Process

Humidity

- Absolute humidity is ratio of water vapor mass to air volume.
- Specific humidity is ratio of water vapor mass to air mass.
- Mixing ratio is ratio of water vapor mass to dry air mass.
- Relative humidity is ratio of actual vapor pressure to saturation vapor pressure expressed in percent.
- Dew point is the temperature air would have to be cooled with no change in pressure or moisture content for saturation (condensation) to occur.

Precipitation and Watersheds.

Precipitation in the form of rain, hail, snow is a fundamental input to the hydrologic cycle. It occurs when air rises, expands and cools and the water vapor. In the air condenses. The condensed drops must fall through the sky and not evaporate before they reach the ground. The drops increase in size by coalescence (liquid-liquid) producing rain or snow. Rainfall has large spatial variability with storms covering From less than a few square kilometers to hundreds of thousands of square kilometers.

Precipitation Measurement

- Point gages.
- Radar reflectivity (i.e. NEXRAD & Doppler)
- Satellite remote sensing.

Point Gages

Point gages are still the primary tool, but radar is becoming more reliable. Point gages measure precipitation at a single location, usually using a tipping-bucket device and radio telemetry or a data logger.

**Figure 2**

Typical permanent monitoring station. Rain gage is located inside of cylinder.

**Figure 3**

Typical temporary monitoring station. Rain gage is small cylinder located in lower right of picture. Rain gage normally would be placed on the central mast.

**Figure 4**

**Figure 5**

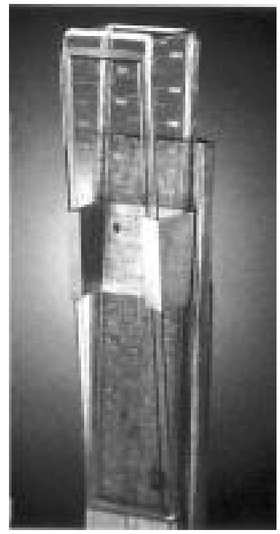

**Figure 6**

Cumulative rain gages. Require site visit to record depths. Right-most picture is "fence-post" and not typically used in hydrologic work.

Rain gage networks are used for flood analysis. The HCOEM network in Harris Co.,Tx is an example of such a network.

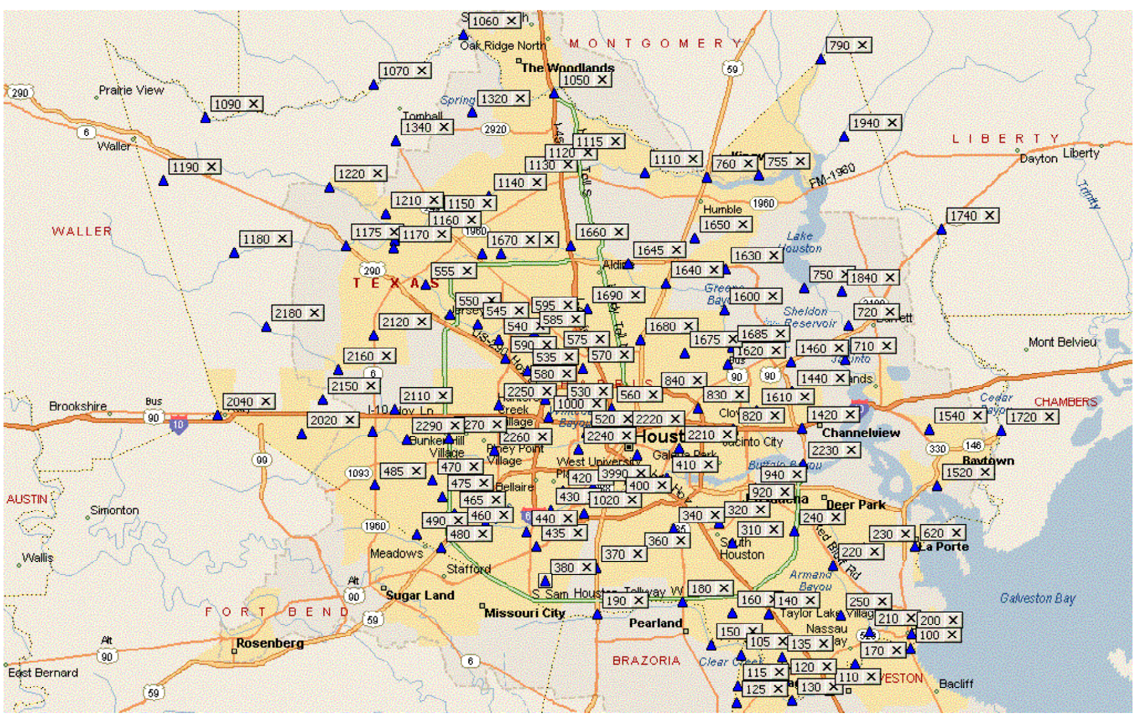


**Figure 7. Rain gage network map for Harris Co.**

The networks consist of several permanent-monitoring stations like Figure 1 (or Figure 2) located over a geographical area

Ideally, all gages can be queried in real-time and simultaneously so that rainfall contours can be produced. Rain gage networks are critical for ground truth of radar data. A rain gage is a point measure of precipitation at a location. Two gages a few km apart may record very different values during a thunderstorm, but similar values during a meso-scale storm. Figure 7 is a picture of the Harris Co. network depths on Sep. 3, 2003 (24 hour cumulative).

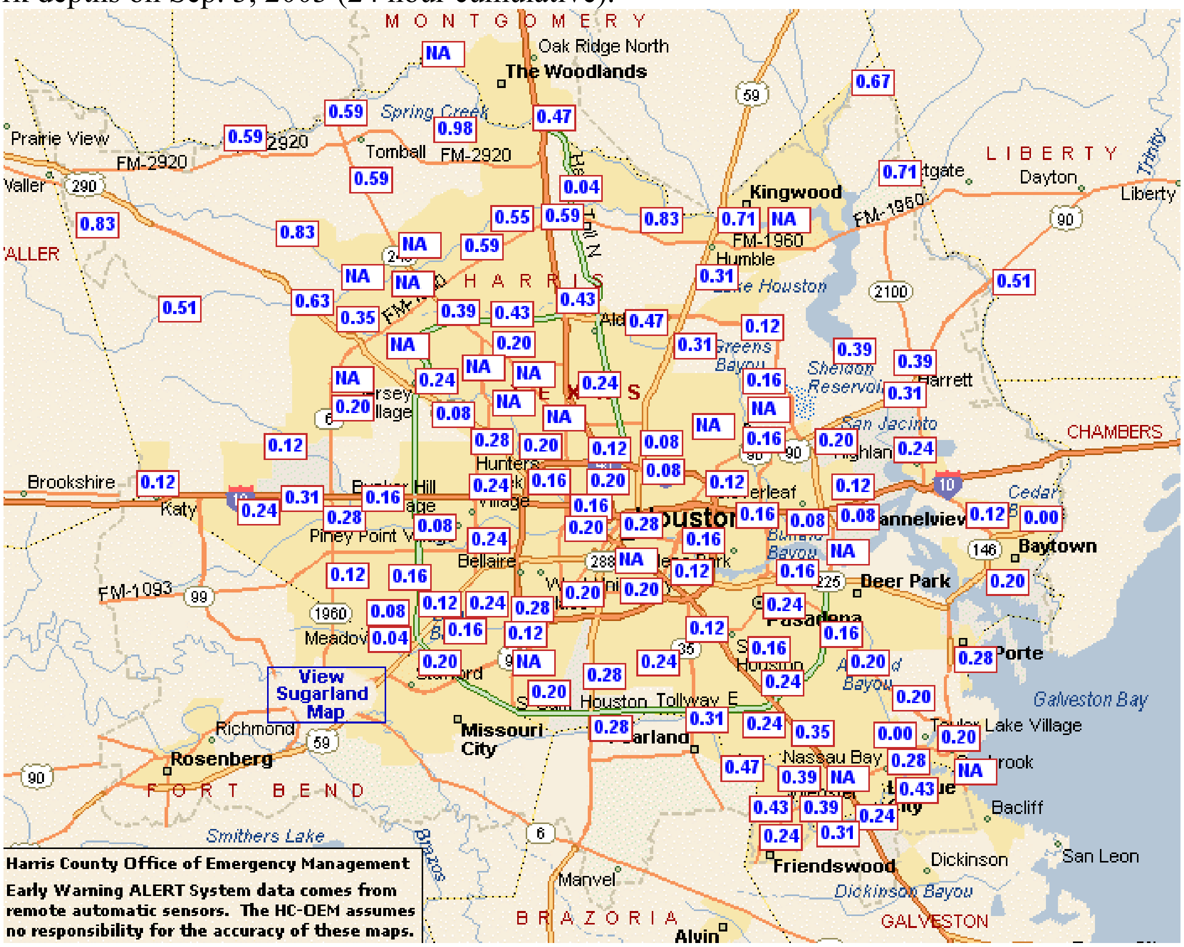


**Figure 8. Rain gage 24-hour cumulative depths for Harris Co., Sep 3, 2003.**

## Radar Reflectivity

Radar imaging is used to supplement gage data for large areas. Radar does not determine rainfall depths. Comparing the Radar returns (intensities) with actual depth measurements (or historical measurements) is how radar data are converted into depths for hydrologic analysis – hence the need for point gages remains. Generally the reflectivity is used in a correlation equation to produce estimates of depth per unit time.

The next figures are typical radar images: Note the similarity in all three kinds of images, also note that even the commercial image does not report depths, just regions of light and heavy rainfall. This limited information is typical of Radar data. Research to determine reliable methods to directly convert such images into rainfall depth maps (in near- real time) is in progress. For the time being, only gage data are useful for hydrologic analysis from an engineering design perspective, although the Radar images are valuable for contouring the observed depths.

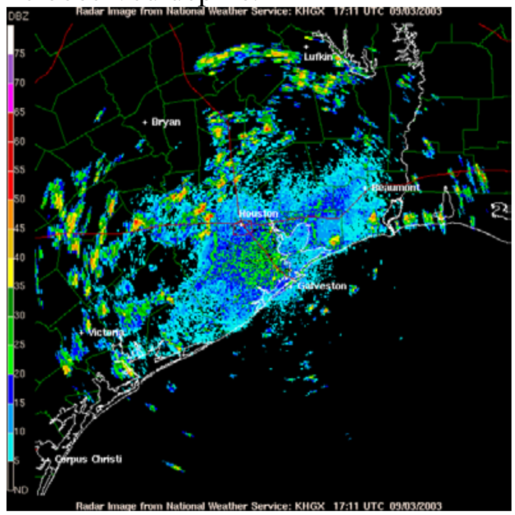


**Figure 9 Radar image - color is proportional to reflected energy.**

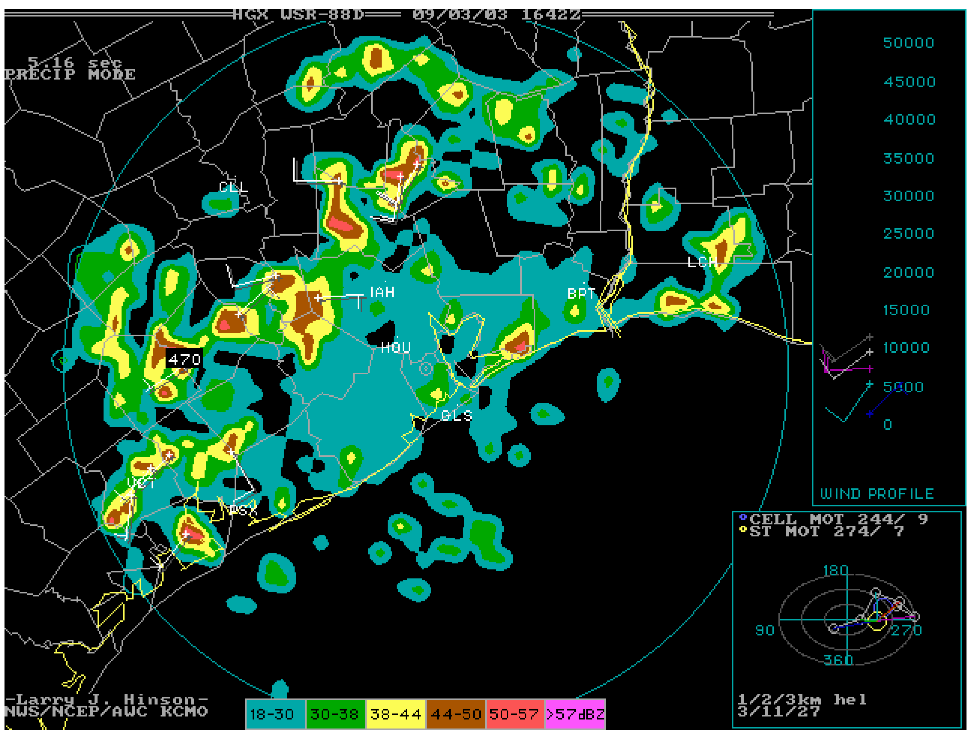


**Figure 10. Radar image - Color is proportional to reflected energy. Radar is in precip mode (i.e. rainfall is probably occurring). This image is the kind of data that is used to generate the pictures we see on the evening news.**

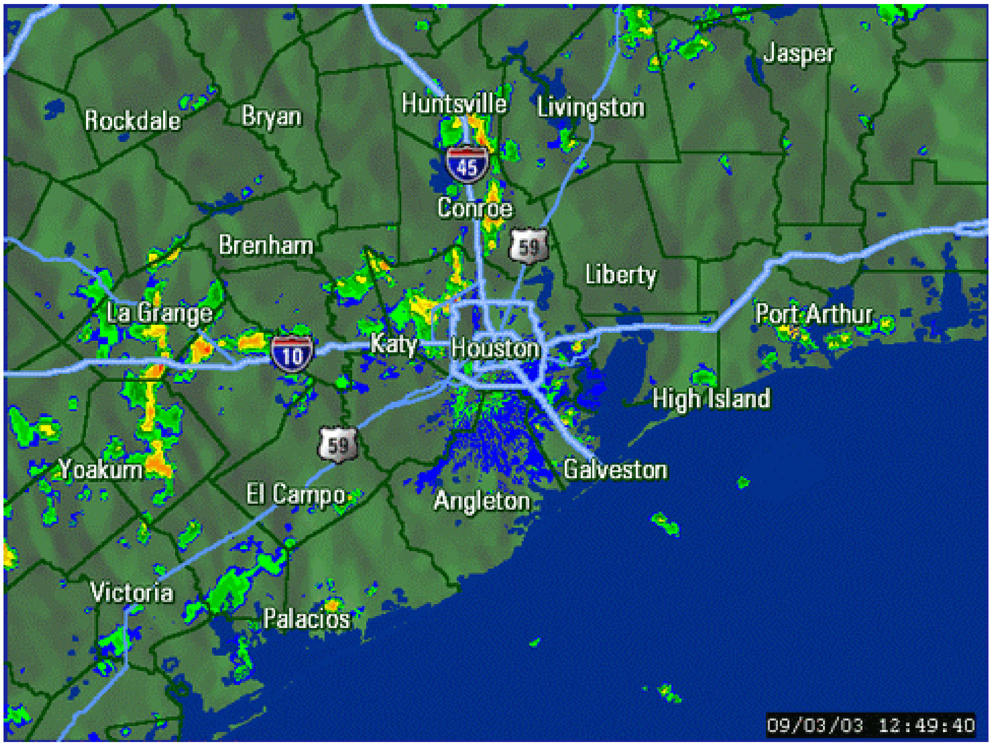


**Figure 11. Same "image" after commercial interpretation (Channel 13 news)**

Remote Sensing

Satellite imagery is used for larger scale determination of precipitation, again with the caveat on ground truth. Different wavelengths of energy can be detected, certain wavelengths are very sensitive to water vapor and can determine where water is located in the atmosphere. The presumption is that regions with water will experience precipitation and remote sensing tries to relate these vapor regions to precipitation depths by ground truth or flat out guessing. The next few images illustrate the kind of data that can be obtained. In most cases we can get the raw data if we wish, but this is often useless in many engineering studies.

The next figures are a visible and infrared. Interpreting IR images is sometimes confusing as heat is usually images as light colors (in monochrome) and cool as dark areas. In some other kinds of imaging the opposite intensity scheme is used. Like Radar, satellite imaging cannot determine depths of precipitation (at least not yet), but with a ground based network, the images can be calibrated against measured depths and on an event-by-event basis depths can be realistically estimated.

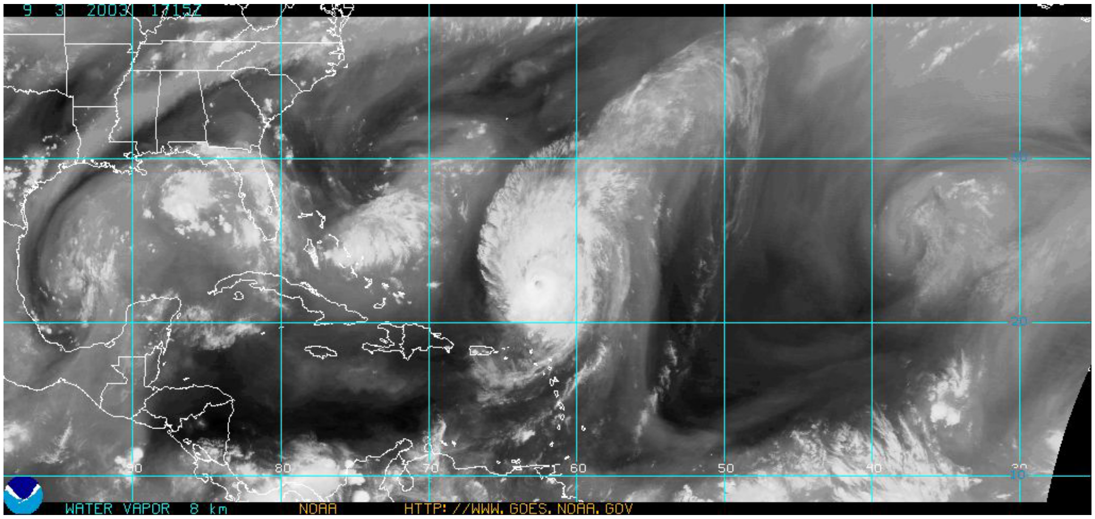


**Figure 12. GEOS Water Vapor Image**

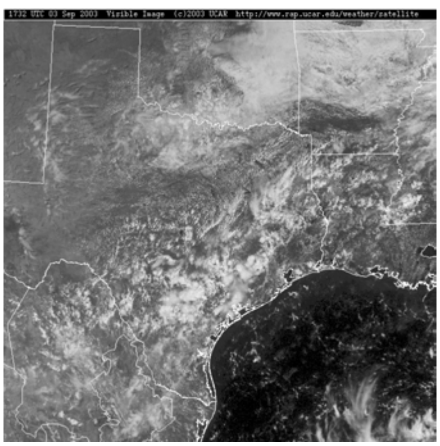

**Figure 13. Visible Satellite**

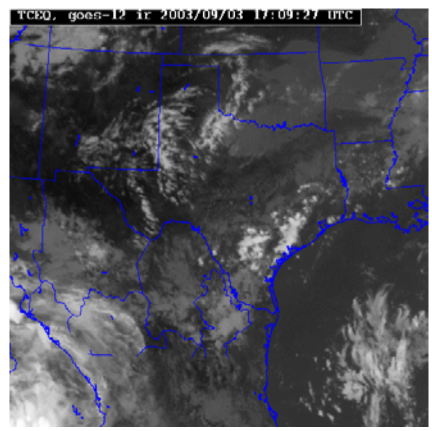


**Figure 14. IR Satellite**

Precipitation analysis.

Because precipitation is the input source for water in hydrologic systems of interest to engineers, one must be able to quantify precipitation in a few different ways for practical application.

Determination of Distributed Precipitation Data from Point Gage Data

A watershed is the area of land where all of the water that is under it or drains off of it goes into the same place. First consider a location where streamflow can be observed, call this location the outlet. Precipitation falls upstream of this location and is the source of runoff past the outlet. If a unit of precipitation falls upstream of the outlet and eventually drains past the outlet, the area defined by all such locations is called the drainage area to the outlet, and this area is the watershed. The concept also applies in groundwater with the area called a basin, or capture zone, depending on context.

In water budget studies and in unit hydrograph analysis the volume of precipitation is as important as the rate and spatial distribution. Missing data are often a problem and either kriging or simple arithmetic interpolation is used to supply estimates of rainfall at a gage location that has missing data. Kriging is probably a more defendable approach but is probably too complicated for manual or small project application.

The entire volume of rainfall applied to an entire basin is called the precipitation volume. If the basin area normalizes this volume the resulting value is called the effective uniform depth (EUD). There are several methods to compute EUD: arithmetic mean, theissen polygon network, iso-heyetal method. Mean area precipitation and effective uniform depth are for all practical purposes the same concept.

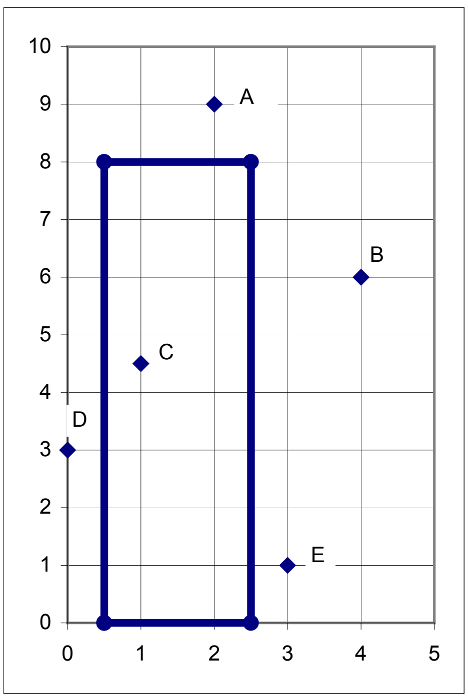


**Figure 15. Hypothetical Watershed and Rain Gages**

| Rain Gage Name | X (km) | Y(km) | Z(mm) |
|---|---|---|---|
| A | 2 | 9 | 99.1 |
| B | 4 | 6 | 85.1 |
| C | 1 | 4.5 | 90.2 |
| D | 0 | 3 | 88.9 |
| E | 3 | 1 | 78.7 |

**Figure 16. Rain Gage Locations and Depths**

1) Arithmetic mean, and distance weighted mean methods.

The arithmetic mean method simply computes the mean value of all the rain gage catches (depths) and assigns this value as the average uniform depth over the watershed. To determine rainfall volume, multiply this depth by the area.

The formula for average depth (precipitation) is simply,

$$\overline{P} = \frac{1}{n}\sum_{i=1}^{n} P_i$$

In this example the result is 88.4 mm over the entire watershed.

| | A | B | C | D |
|---|---|---|---|---|
| 1 | Rain Gage | | | |
| 2 | Name | X (km) | Y(km) | Z(mm) |
| 3 | A | 2 | 9 | 99.06 |
| 4 | B | 4 | 6 | 85.09 |
| 5 | C | 1 | 4.5 | 90.17 |
| 6 | D | 0 | 3 | 88.9 |
| 7 | E | 3 | 1 | 78.74 |
| 8 | | | | |
| 9 | =(1/5)*SUM(D3:D7) | | | 88.4 |
| 10 | | | | |

**Figure 17. Calculation of average depth.**

The total volume in cubic meters is the product of the average depth and the watershed area converted into cubic meters. The watershed area is 16 km$^2$. Thus the total volume of precipitation over the watershed is 1.41x10$^6$ m$^3$. We will compare this volume to the other ways of estimated distributed rainfall depths.

2) Polygon weighted methods.

The polygon methods divide the watershed into subareas and assign depths at gages to each sub area, compute the total volume (sum of all sub-area volumes), then divide by the watershed area to determine an area-weighted average. Thiessen polygons (nearest neighbor approach) are the most common division scheme. Thiessen weights are reported in most USGS data.

To determine Thiessen polygons we first draw segments joining each gage.

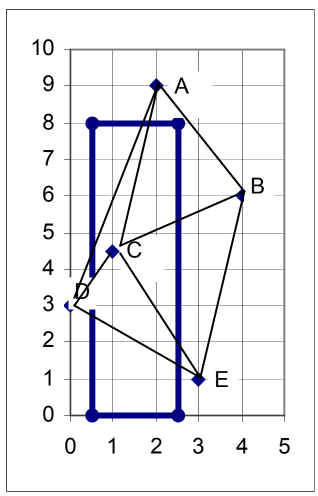


**Figure 18. Watershed and gage network with gages joined**

Now locate bisectors along each segment.

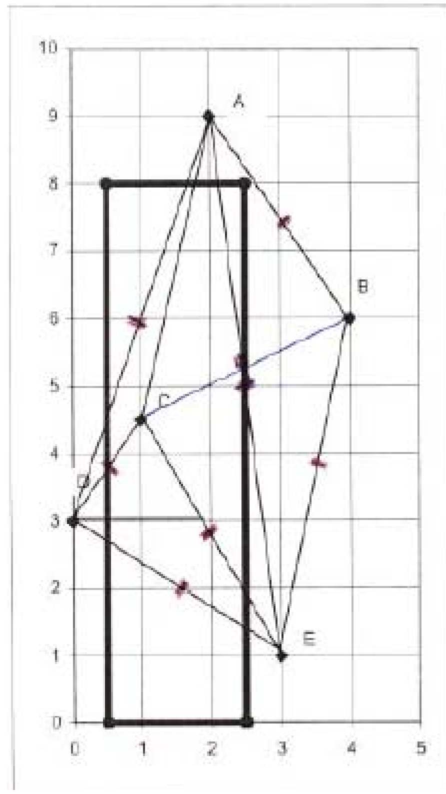


**Figure 19. Bisection locations marked**

Draw perpendicular bisectors at each location, mark each side with nearest gage name.

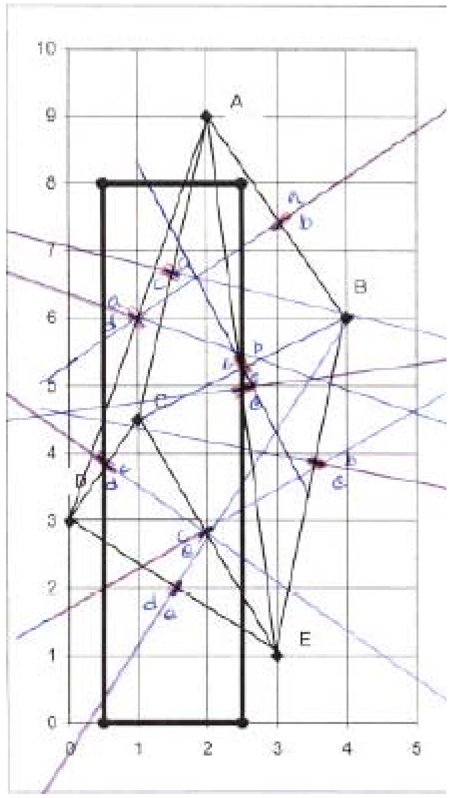


**Figure 20. Bisectors drawn**

Locate intersections of nearest neighbor boundaries, and mark interfaces.

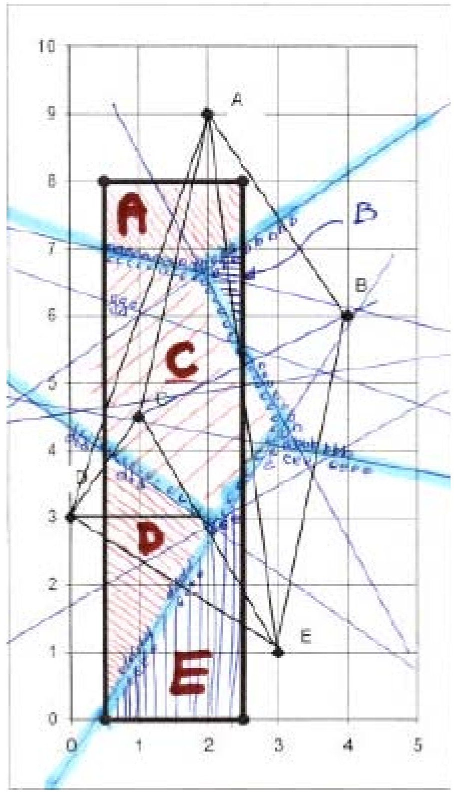

**Figure 21. Areas nearest each gage demarked**

Measure areas within watershed assigned to each gage. The Theissen weight is the ratio of the gage assigned area and the watershed area. Once either the watershed areas are known, or the Theissen weights are known the uniform precipitation depth can be computed as

$$\overline{P} = \sum_{i=1}^{n} \frac{A_i}{A} P_i = \frac{1}{A} \sum_{i=1}^{n} A_i P_i$$

For this example the result is 87 mm of depth.

3) Isoheyetal methods. Involve rainfall contour maps.

The isoheyetal method requires the analyst to contour the rainfall, either manually (examples) or using a contouring package. Several are available in the public domain or proprietary programs can be used. Once the rainfall is contoured, the contour map is overlain on the watershed. Reasonable contour intervals are selected and the area between panels is determined. In the example we select 5 panels, each representing a change in 5 mm of depth. The contouring was manual (and somewhat by eyeball).

| | A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|---|
| 1 | Rain Gage | | | | | | |
| 2 | Name | X (km) | Y(km) | Z(mm) | Gage Area | Theissen Weight | Weighted Precip (mm) |
| 3 | A | 2 | 9 | 99.06 | 2.20 | 0.138 | 13.6 |
| 4 | B | 4 | 6 | 85.09 | 0.45 | 0.028 | 2.4 |
| 5 | C | 1 | 4.5 | 90.17 | 5.73 | 0.358 | 32.3 |
| 6 | D | 0 | 3 | 88.9 | 3.00 | 0.188 | 16.7 |
| 7 | E | 3 | 1 | 78.74 | 4.63 | 0.289 | 22.8 |
| 8 | | | | | | | |
| 9 | =(1/5)*SUM(D3:D7) | | | 88.4 | | | 87.7 |
| 10 | | | | | | | |
| 11 | | | | | | | |

**Figure 22. Depth calculations for Theissen Polygons**

The average depth applied within a panel is the average depth of the bounding contour lines (in this case, take the smaller value and add 2.5 mm).

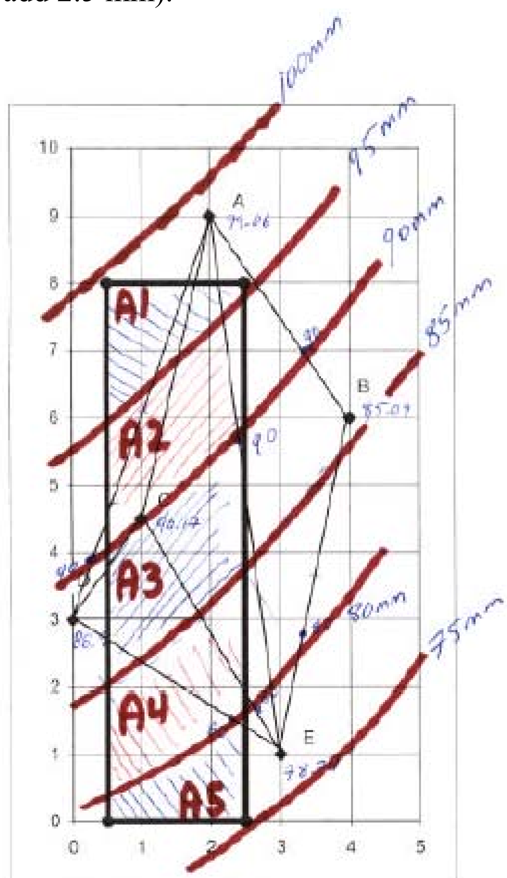


**Figure 23. Isoheyet methods**

Once the areas are determined, isoheyet weights are determined in the same fashion as Theissen weights (the areas used are quite different) and the uniform depth is determined as the weighted sum using the same formula, except the $A_i$ are the panel areas, and $P_i$ are now the assigned panel depths.

| | A | B | C | D | E | F | G | H | I | J | K | L | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Rain Gage | | | | | | | | | | | | |
| 2 | Name | X (km) | Y(km) | Z(mm) | Gage Area | Theissen Weight | Weighted Precip (mm) | | IsoHyetPanel | Area | IsoHyetWeight | Panel Precip | Weighted Precip |
| 3 | A | 2 | 9 | 99.06 | 2.20 | 0.138 | 13.6 | | A1 | 2.30 | 0.144 | 97.5 | 14.0 |
| 4 | B | 4 | 6 | 85.09 | 0.45 | 0.028 | 2.4 | | A2 | 4.16 | 0.260 | 92.5 | 24.0 |
| 5 | C | 1 | 4.5 | 90.17 | 5.73 | 0.358 | 32.3 | | A3 | 4.01 | 0.251 | 87.5 | 22.0 |
| 6 | D | 0 | 3 | 88.9 | 3.00 | 0.188 | 16.7 | | A4 | 3.87 | 0.242 | 82.5 | 20.0 |
| 7 | E | 3 | 1 | 78.74 | 4.63 | 0.289 | 22.8 | | A5 | 1.65 | 0.103 | 77.5 | 8.0 |
| 8 | | | | | | | | | | | | | |
| 9 | =(1/5)*SUM(D3:D7) | | | 88.4 | | | 87.7 | | | | | | 88.0 |
| 10 | | | | | | | | | | | | | |

**Figure 24. Isoheyet calculations**

Complex maps using numerical methods

The same numerical planimetric methods above can be used to determine the total volume of some distributed variable over an area. The isoheyetal method of estimating uniform rainfall depth is a example. First one prepares a contour map of the variable of interest over the area of interest. Next one selects panels of the contour map that will represent sub-areas that have a uniform value of the depth variable.

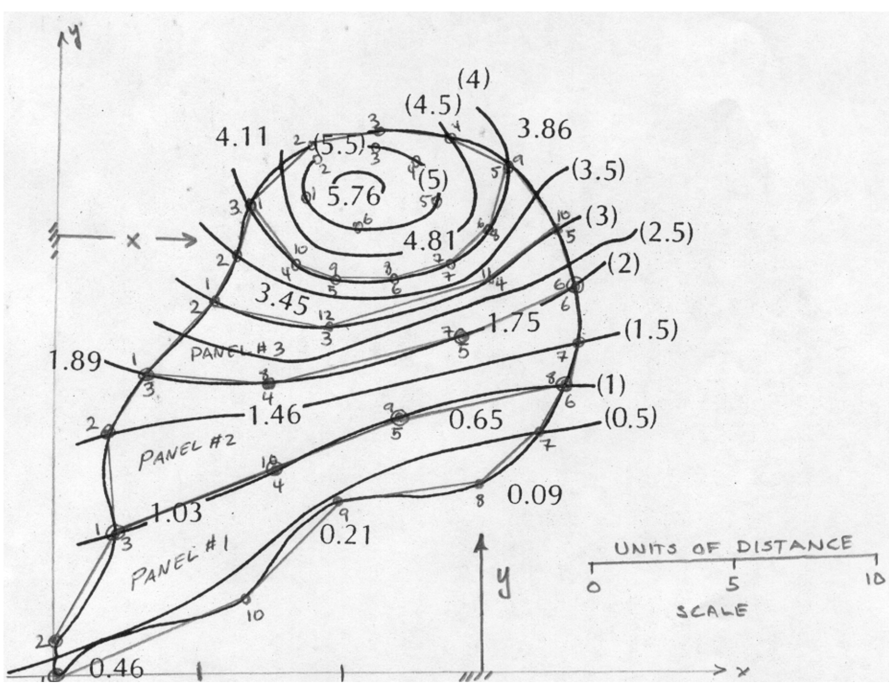


Figure 5. Isoheyetal panels for rainfall volume calculation

Lastly one determines the area of the sub-areas, and computes the volume as the product of the sub-area and the uniform depth value. This technique is illustrated with the map below. The accuracy of the procedure is increased as the panels are made to represent smaller and smaller variations in the depth variable.

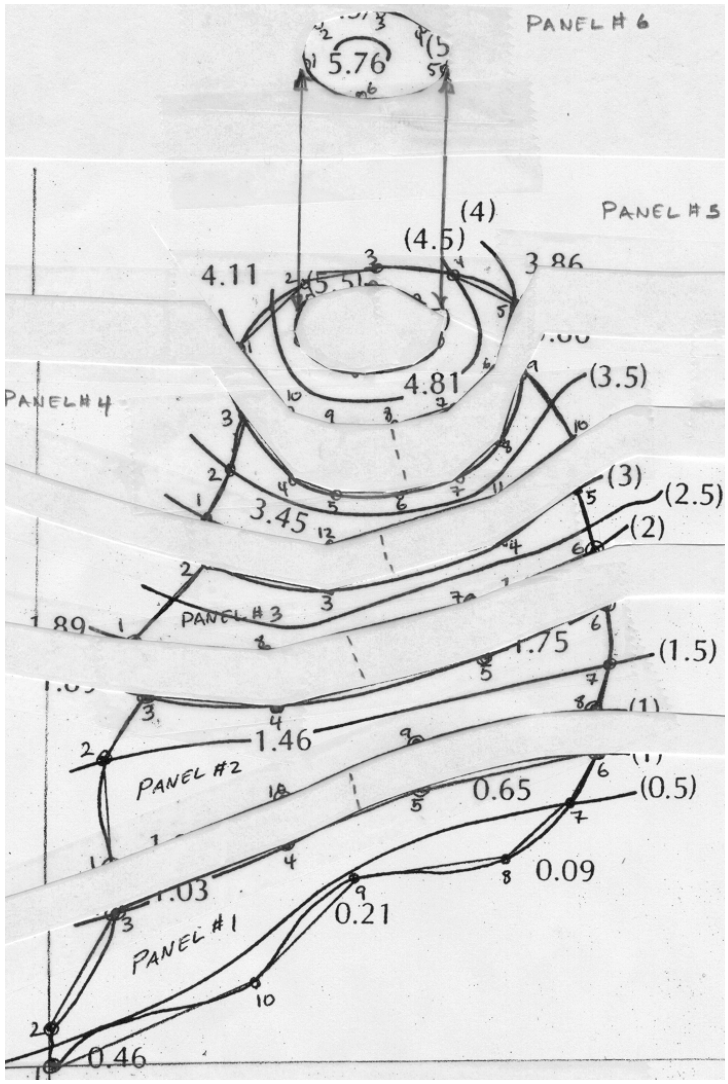


Figure 6. Exploded view of panels.

| | A | B | C | D | E | F | G | H | I | J |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Area Calculations by Polygon Approximation | | | | | | | | | |
| 2 | | | | | | | | | | |
| 3 | Panel #1 | | | | | Panel #2 | | | | |
| 4 | Node # | X | Y | Area | Depth | Node # | X | Y | Area | Depth |
| 5 | 1 | 0 | 0 | | | 1 | 2 | 5 | | |
| 6 | 2 | 0 | 1.2 | 0 | | 2 | 1.9 | 8.4 | -0.67 | |
| 7 | 3 | 2 | 5 | 6.2 | | 3 | 3.1 | 10.7 | 11.46 | |
| 8 | 4 | 7.5 | 7.1 | 33.28 | | 4 | 7.5 | 10.3 | 46.2 | |
| 9 | 5 | 12 | 8.8 | 35.78 | | 5 | 14 | 11.7 | 71.5 | |
| 10 | 6 | 17.8 | 10 | 54.52 | | 6 | 18 | 13.5 | 50.4 | |
| 11 | 7 | 16.9 | 8.4 | -8.28 | | 7 | 18.1 | 11.6 | 1.255 | |
| 12 | 8 | 14.8 | 6.6 | -15.8 | | 8 | 17.8 | 10 | -3.24 | |
| 13 | 9 | 9.8 | 6 | -31.5 | | 9 | 12 | 8.8 | -54.5 | |
| 14 | 10 | 6.5 | 2.5 | -14 | | 10 | 7.5 | 7.1 | -35.8 | |
| 15 | 1 | 0 | 0 | -8.13 | | 1 | 2 | 5 | -33.3 | |
| 25 | Sum | | | 52.09 | 0.5 | Sum | | | 53.34 | 1.5 |
| 29 | Volume | | | 26.05 | | | | | 80 | |
| 31 | Volume all Panels | | | 400.5 | | | | | | |
| 32 | Area all Panels | | | 193 | | | | | | |
| 34 | Effective Uniform Depth | | | | 2.076 | | | | | |

| | K | L | M | N | O | P | Q | R | S | T |
|---|---|---|---|---|---|---|---|---|---|---|
| 3 | Panel #3 | | | | | Panel #4 | | | | |
| 4 | Node # | X | Y | Area | Depth | Node # | X | Y | Area | Depth |
| 5 | 1 | 3.1 | 10.7 | | | 1 | 5.5 | 13 | | |
| 6 | 2 | 5.5 | 13 | 28.44 | | 2 | 6.2 | 14.6 | 9.66 | |
| 7 | 3 | 9.5 | 12 | 50 | | 3 | 6.8 | 16.5 | 9.33 | |
| 8 | 4 | 15.1 | 13.7 | 71.96 | | 4 | 8.3 | 14.2 | 23.03 | |
| 9 | 5 | 17.5 | 15.5 | 35.04 | | 5 | 9.7 | 13.8 | 19.6 | |
| 10 | 6 | 18 | 13.5 | 7.25 | | 6 | 11.7 | 13.8 | 27.6 | |
| 11 | 7 | 14 | 11.7 | -50.4 | | 7 | 13.7 | 14.3 | 28.1 | |
| 12 | 8 | 7.5 | 10.3 | -71.5 | | 8 | 15 | 15.4 | 19.31 | |
| 13 | 1 | 3.1 | 10.7 | -46.2 | | 9 | 15.2 | 17.8 | 3.32 | |
| 14 | | | | | | 10 | 17.5 | 15.5 | 38.3 | |
| 15 | | | | | | 11 | 15.1 | 13.7 | -35 | |
| 16 | | | | | | 12 | 9.5 | 12 | -72 | |
| 17 | | | | | | 1 | 5.5 | 13 | -50 | |
| 25 | Sum | | | 24.59 | 2.5 | Sum | | | 21.24 | 3.5 |
| 29 | | | | 61.48 | | | | | 74.32 | |

| | U | V | W | X | Y | Z | AA | AB | AC | AD |
|---|---|---|---|---|---|---|---|---|---|---|
| 3 | Panel #5 | | | | | Panel #5 | | | | |
| 4 | Node # | X | Y | Area | Depth | Node # | X | Y | Area | Depth |
| 5 | 1 | 6.8 | 16.5 | | | 1 | 8.6 | 16.5 | | |
| 6 | 2 | 8.7 | 18.4 | 33.16 | | 2 | 9 | 17.9 | 6.88 | |
| 7 | 3 | 11.1 | 19 | 44.88 | | 3 | 11 | 18.2 | 36.1 | |
| 8 | 4 | 13.6 | 18.7 | 47.13 | | 4 | 12.4 | 17.8 | 25.2 | |
| 9 | 5 | 15.2 | 17.8 | 29.2 | | 5 | 13.2 | 16.5 | 13.72 | |
| 10 | 6 | 15 | 15.4 | -3.32 | | 6 | 10.5 | 15.5 | -43.2 | |
| 11 | 7 | 13.7 | 14.3 | -19.3 | | 1 | 8.6 | 16.5 | -30.4 | |
| 12 | 8 | 11.7 | 13.8 | -28.1 | | | | | | |
| 13 | 9 | 9.7 | 13.8 | -27.6 | | | | | | |
| 14 | 10 | 8.3 | 14.2 | -19.6 | | | | | | |
| 15 | 1 | 6.8 | 16.5 | -23 | | | | | | |
| 25 | Sum | | | 33.41 | 4.5 | Sum | | | 8.3 | 5.5 |
| 27 | Panel 5 Volume | | | 150.3 | | | | | | |
| 28 | Panel 6 Volume | | | 37.35 | | | | | | |
| 29 | | Volume (5-6) | | 113 | | | | | 45.65 | |

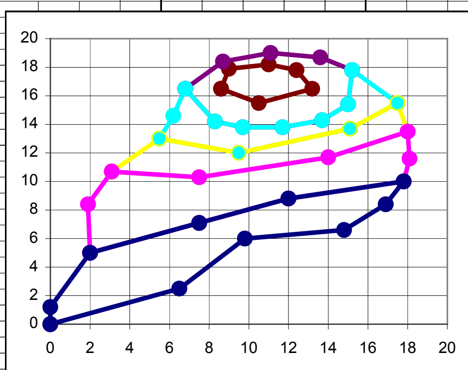


Figure 7. Solution to watershed rainfall example.

For occasional use, the manual methods are adequate. If one needs to make such determinations frequently, say weekly, then a GIS based tool makes a lot of sense.

## Estimating Missing Rainfall Data

[Insert in future notes]
Reasons
Station-Average
Normal-Ratio
Isoheyetal
Quadrant
Gage Consistency (to detect changes in weather or technicians)

Evaporation and Transpiration

Evaporation

The loss of water from a water surface is a function of thermal energy input (sunshine), air and water temperature, wind speed (convection), and the relative humidity at the water surface and overlying air (expressed as vapor pressures). One process relationship attributed to Dalton (yes the same Dalton in Dalton's law) is

$$E = (e_s - e_a)(a + bu)$$

where

$E$ is the evaporation rate in mm/d

$e_s$ is the saturation vapor pressure in kPa (based on water temperature)

$e_a$ is the vapor pressure in the air in kPa (based on air temperature)

$a,b$ are empirical constants

$u$ is windspeed in m/s.

The relationship indicates that high wind speed and low relative humidity (large differences in vapor pressure) result in large rates. The saturation pressure is typically determined from tabulation and is strongly temperature dependent. If you know the dew point of the air, you can use the table to look up the vapor pressure in the air. The ratio of these two pressures is the relative humidity. Likewise, if you know the relative humidity then the product of the relative humidity and saturation pressure is a good estimate for the vapor pressure in the air.

For example, suppose a particular lake has empirical constants of $a = 1 \times 10^{-6}$ and $b = 1.22$. The average wind speed is 4.0 m/s, the average air temperature is 20°C, the average water temperature is 10°C and the average relative humidity is 30%. Then what is the average evaporation rate?

$e_s$ = 1.227 kPa (@ 10°C)

$e_a$ =(0.30)(2.337 kPa(@ 20°C)=0.70 kPa

$u$ = 4.0 m/s.

$E$ = (1.227-0.70)(0.000001+1.22)(4.0) = ~2.57 mm/d

Obviously, you need a tabulation or relationship to relate temperature to vapor pressure. A good approximation to estimate saturation vapor pressure is $e_s = (0.611)(10^{\frac{7.5T}{237.7+T}})$, where $T$ is temperature in degrees Celsius. (http://www.usatoday.com/weather/whumcalc.htm)

The physics behind this process can be explained (at least in-part) as a phase change energy requirement. When matter changes from one state to another (solid-liquid-gas) there is a change in heat energy of the matter. The heat or thermal energy of a substance is measured in calories (cal). One calorie is the amount of energy required to raise the temperature of one gram of pure water at 14.5°C temperature one degree Celsius.

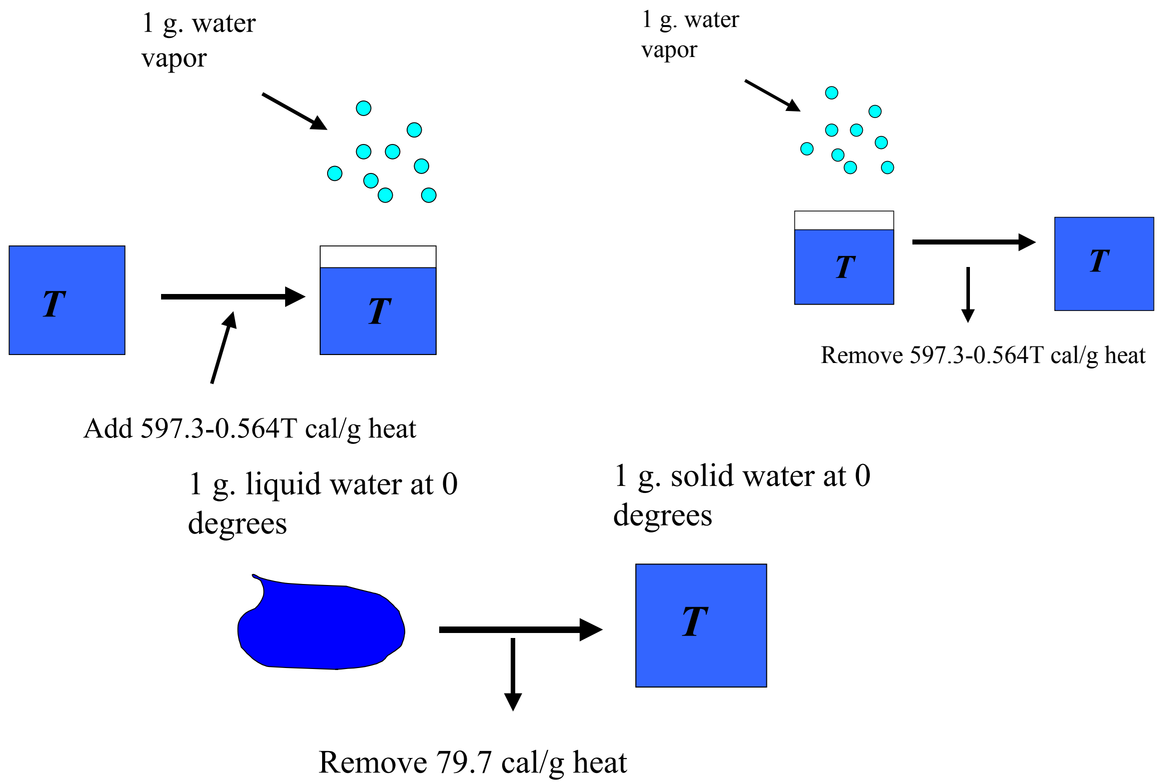


**Figure 25. Phase change energies**

The evaporation of water requires an amount of energy called the latent heat of vaporization. At temperatures encountered in most natural systems this energy requirement is

$$H_v(cal/g) = 597.3 - 0.564T$$

When water condenses, the amount of heat released is called the latent heat of condensation. To freeze water at $0^oC$ 79.7 cal/g of heat must be removed from the water. To melt ice at $0^oC$ 79.7 cal/g of heat must be added to the ice. Dalton's model combines these energy requirements with a flux-law model to account for advection of vapor rich air above the water surface as a function of windspeed.

Transpiration

Units of Measurements

<u>References</u>

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Readings

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Exercises

1) Define:
    a. Interception
    b. Transpiration
    c. Evaporation
    d. Evapotranspiration
    e. Precipitation
    f. Balanced Storm
    g. Intensity-Duration-Frequency
    h. Hyetograph
    i. Effective-Uniform-Depth

2) The mean annual rainfall depth over a 280 $km^2$ watershed is 725mm. What is the mean annual volume of rain falling on the watershed in $m^3$, $ft^3$, gallons, and ac-ft?

3) The mean annual precipitation for a certain 132mi$^2$ watershed is 25 inches. Assume that 20 percent of the annual precipitation reaches the watershed outlet as streamflow. Determine the mean streamflow rate in ac-ft/yr, sfd/yr, ft$^3$/s, and m$^3$/s.

4) The map below shows the location of 8 rain gages and the watershed boundary. The rainfall depths for a certain storm are in the table below. Use the Thiessen polygon method to determine the mean rainfall depth over the watershed for this storm event.

| Gage | Storm Depth (mm) |
|---|---|
| A | 25 |
| B | 18 |
| C | 92 |
| D | 95 |
| E | 192 |
| F | 175 |
| G | 152 |
| H | 168 |

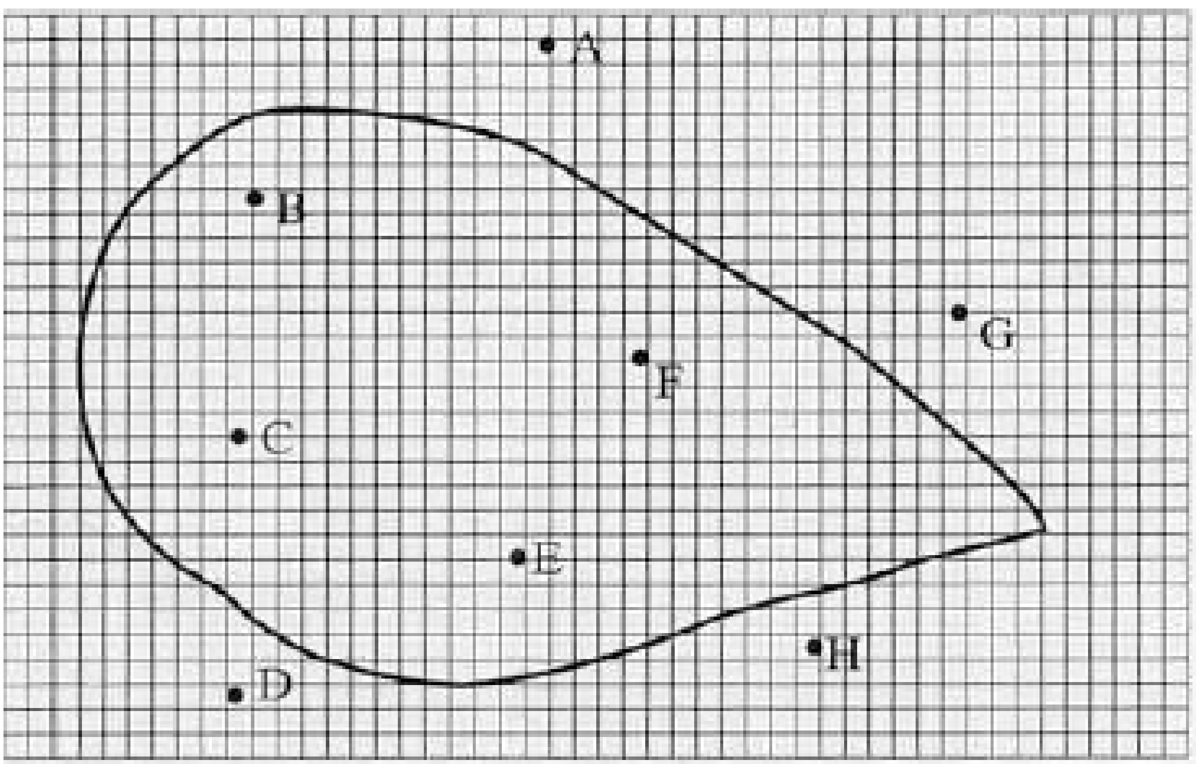


**Figure 26. (Image from pg 103 Textbook)**

5) Use the internet and search for "Palmer Drought Index." Briefly describe for what the drought index is used.

6) Compute the discharge in the stream based on the current meter measurements provided below for different points in the cross section

| Depth and Distances (ft) | | Velocity Measurements (ft/sec) | | |
|---|---|---|---|---|
| Distance (ft) | Depth (ft) | V at 0.2*depth | V at 0.6 depth | V at 0.8 depth |
| 0 | 0.0 | -- | -- | -- |
| 3 | 1.2 | -- | 0.72 | -- |
| 6 | 3.7 | 1.11 | -- | 0.91 |
| 9 | 6.5 | 1.43 | -- | 1.16 |
| 12 | 8.6 | 1.63 | -- | 1.24 |
| 15 | 7.6 | 1.36 | -- | 1.10 |
| 18 | 6.4 | 1.24 | -- | 1.03 |
| 21 | 4.8 | 1.18 | -- | 0.87 |
| 24 | 2.3 | -- | 0.84 | -- |
| 26 | 0.0 | -- | -- | -- |

7) Use the internet to find and print the historical daily flow hydrograph for USGS gaging station #08074000. Write the name of the station and describe both its general location and plot its actual location (latitude-longitude) on a topographical map (use www.topozone.com where you can enter a lat-log and get a target plotted on a map, then print the map).