DAVID FORD MEMORIAL LECTURE IN HYDROLOGY

A REVIEW OF HYDROLOGY

Or: Understanding Hydrology When Working With Technical Professionals

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West Yost

SEPTEMBER| FMA 2025 CONFERENCE

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David T. Ford, Ph.D., P.E., D.WRE

(1950-2020)

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Agenda

1. Goals
2. What is hydrology?
3. History
4. How do we measure hydrology?
5. Hydrologic cycle
6. What is a watershed?
7. Characteristics of watersheds
8. Many words about loss
9. Precipitation
10. Frequency analysis
11. Peak discharge estimation
12. Curve numbers
13. Unit hydrograph
14. Questions

What Is <u>Not</u> In This Course

- Math (OK, just a little where ***absolutely*** necessary)
- Flow in pipes & pressure flow
- Hydrogeology
- Snow fall and snow melt runoff
- Reservoirs
- Water quality
- Evaporation
- Erosion & sediment transport
- Post-fire hydrology

$$\frac{\partial(\rho\eta)}{\partial t} + \frac{\partial(\rho\eta u)}{\partial x} + \frac{\partial(\rho\eta v)}{\partial y} = 0,$$

$$\frac{\partial(\rho\eta u)}{\partial t} + \frac{\partial}{\partial x}\left(\rho\eta u^2 + \frac{1}{2}\rho g\eta^2\right) + \frac{\partial(\rho\eta uv)}{\partial y} = 0,$$

$$\frac{\partial(\rho\eta v)}{\partial t} + \frac{\partial}{\partial y}\left(\rho\eta v^2 + \frac{1}{2}\rho g\eta^2\right) + \frac{\partial(\rho\eta uv)}{\partial x} = 0.$$

Conservative form of the shallow water equations. Note: we aren't discussing these today!

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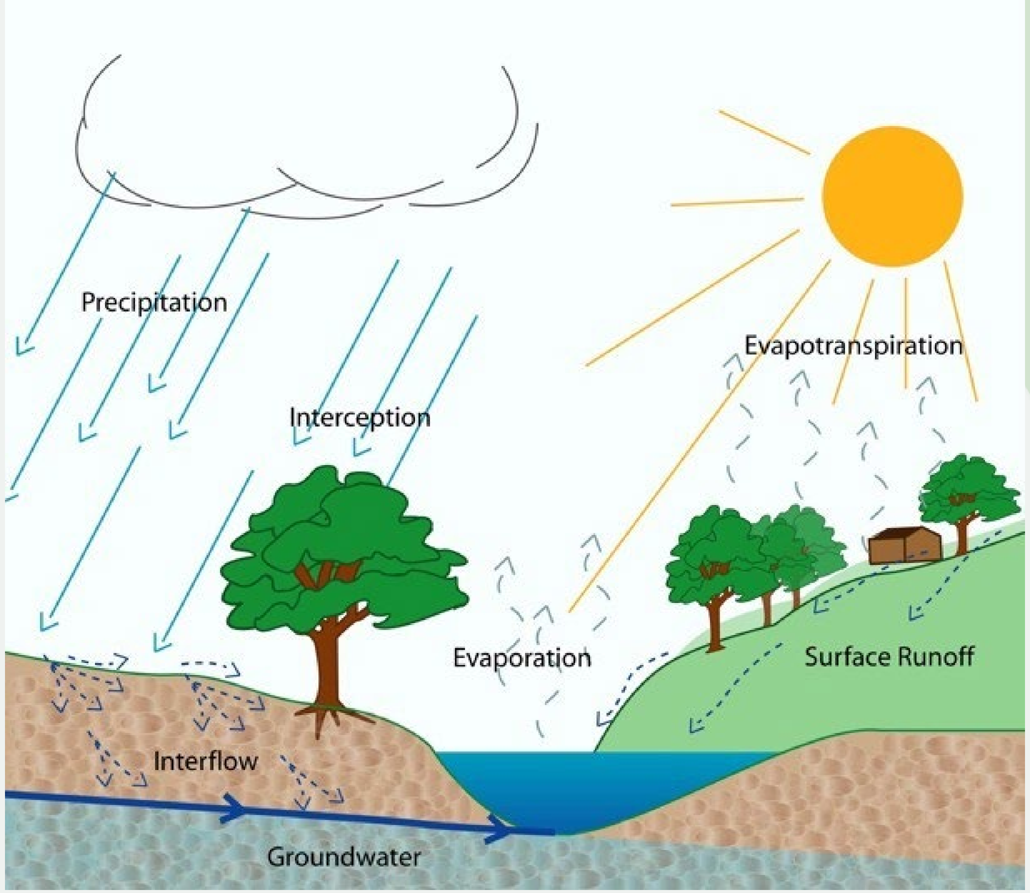
Where to find today's course

Download the full slide deck at West Yost's website using the QR code, below:

Goals, or what are the most important things you can get in exchange for one hour of your time?

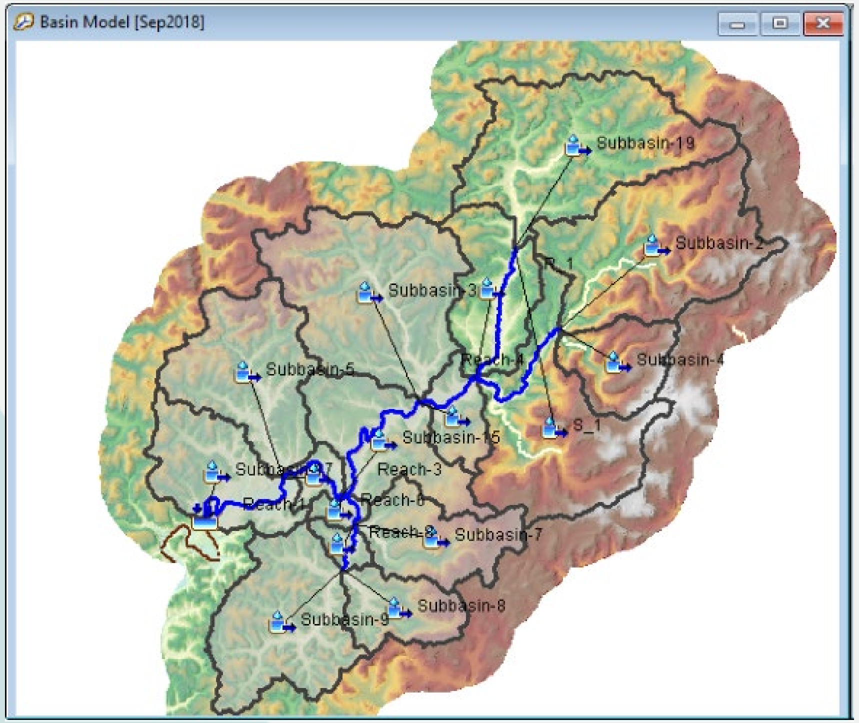
1. Learn a few ***concepts*** that will allow you to understand and follow technical discussions and writing in hydrology.
2. Learn the fundamental ***technical vocabulary*** that will allow you to understand and participate in technical discussions and writing in hydrology.

KEY TAKEAWAY: the ***technical vocabulary*** expresses ***concepts*** that are used to share information in discussions and writing of hydrology.

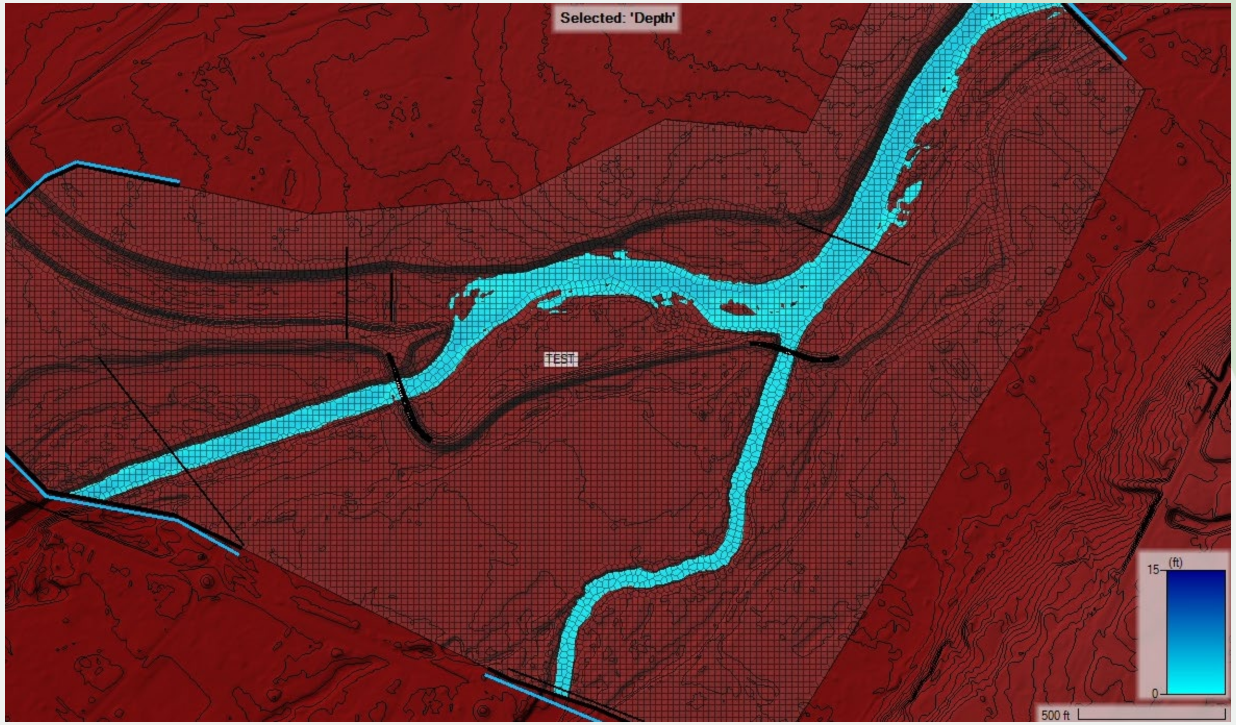


Source: D. Beyerlein, Clear Creek Solutions, LinkedIn. Note: The point in Doug's original article, in part, was that we have more sophisticated tools at our disposal than the simple hydrologic methods we're discussing here. Still, I liked the graphic for today's discussion.

What is hydrology? Or, what is the difference between hydrology and hydraulics?



Source: HEC-HMS Users Manual. Note: Image illustrates hydrologic numerical model with watershed and sub-watersheds delineated.



Source: West Yost. Note: Image illustrates two-dimensional hydraulic numerical model of a flow split. Flow direction is to the southwest (bottom left).

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Definitions

- *Simplified* definitions for the purposes of this course:

(Surface water) Hydrology: the science of water's movement through the atmosphere [precipitation], on the surface of the earth [runoff], (in ground water,) and back to the atmosphere [evaporation/evapotranspiration].

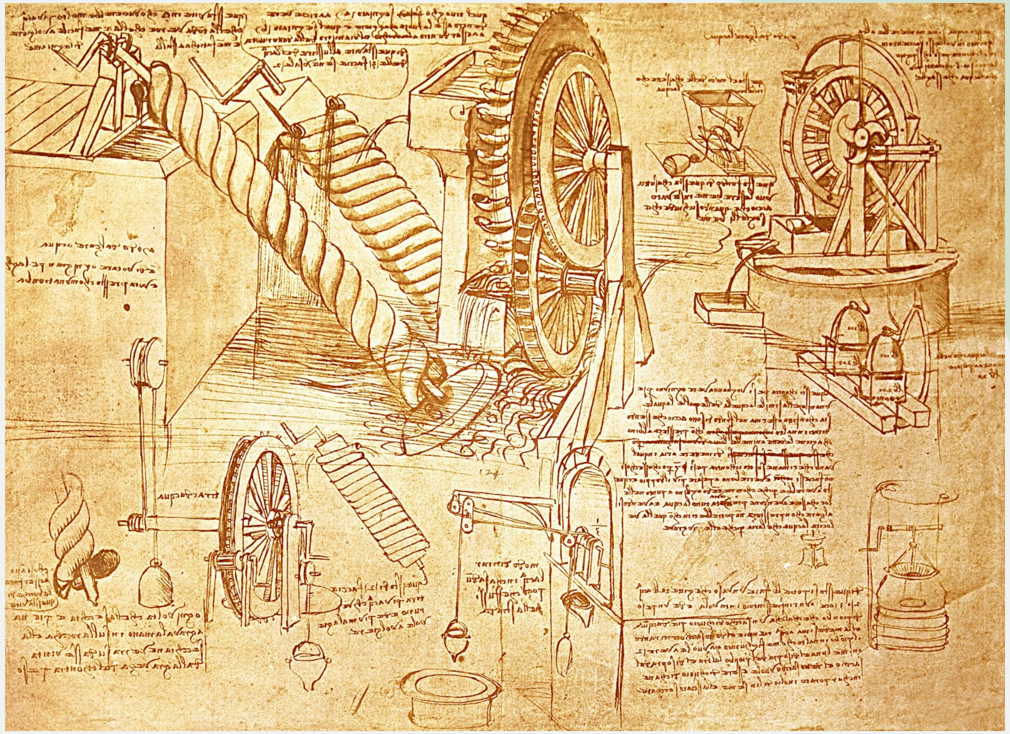
(Surface water) Hydraulics: the science of fluids [water] in motion (usually) in conduits.

A very quick history of hydrology

- **Ancient** – Agricultural irrigation, Sumer (Iraq), 6000-1500 BCE; Nile River Dam, Egypt, 4000 BCE; Du Jiang Yan (都江堰), Sichuan (China), 250 BCE; Stream flow measurements, Rome, 100 CE.
- **Middle** – Relationship between area, velocity and flow rate (da Vinci), Italy, 1500 CE; Rainfall and surface flow measurements (Perrault), France, 1700 CE; Evaporation rate (Halley), England/France, 1700 CE.
- **Modern** – Darcy's Law, France, 1770 CE ; Manning's Equation, Ireland, 1890 CE, ; Unit hydrograph (Sherman), USA, 1932; Statistical hydrology (Gumbel), USA, 1958; Stanford watershed [computer] model, USA, 1966; HEC-1/HEC-2 (USACE), USA, 1966.

Some pretty pictures on the history of hydrology

Source: ischoolconnect.com. Note: Chand Baori Stepwell, India.



Source: artlovescience.wordpress.com. Note: da Vinci’s water wheel.

How do we measure hydrology?

<u>A very incomplete list:</u>

- **Rainfall** – inches [length]
- **Return period/recurrence interval** – years/percent [time/dimensionless]
- **Watershed size** – acres or square miles [area]
- **Storage** – acre-feet [volume]
- **Infiltration** – inches per hour [length per time]
- **Flow rate** – cubic feet per second [volume per time]

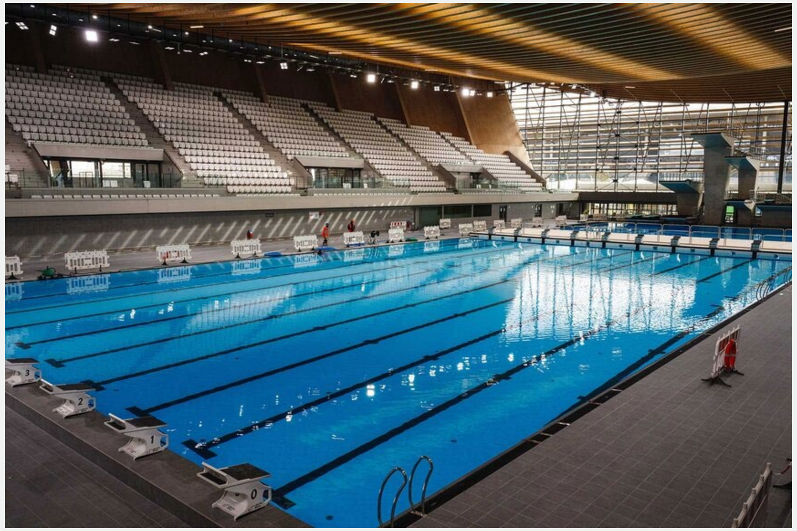
Source: weather.gov. Note: rain gage.

Source: ysi.com. Note: Stream gage.

Takeaway: Understanding the [units] of measurement is key to understanding elements of the hydrologic process.

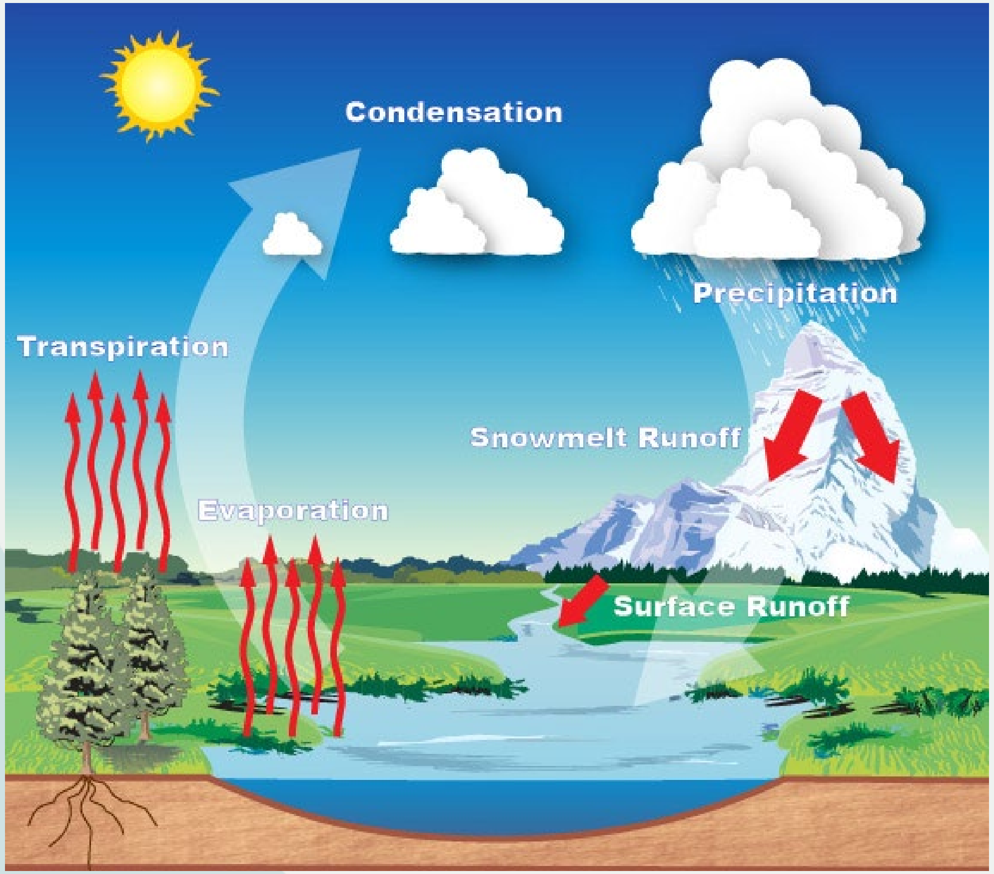
Measurement visualization Exercise

- One Home Depot bucket = 5 gallons.
- One cubic foot per second (CFS) = 7.5 gallons per second, or 1.5 Home Depot buckets per second.
- One Olympic swimming pool = 660,000 gallons, or 132,000 Home Depot buckets.
- 100-year discharge on Sacramento River at I street = 110,000 CFS, or 1.25 Olympic swimming pools per second, or 165,000 Home Depot buckets per second.

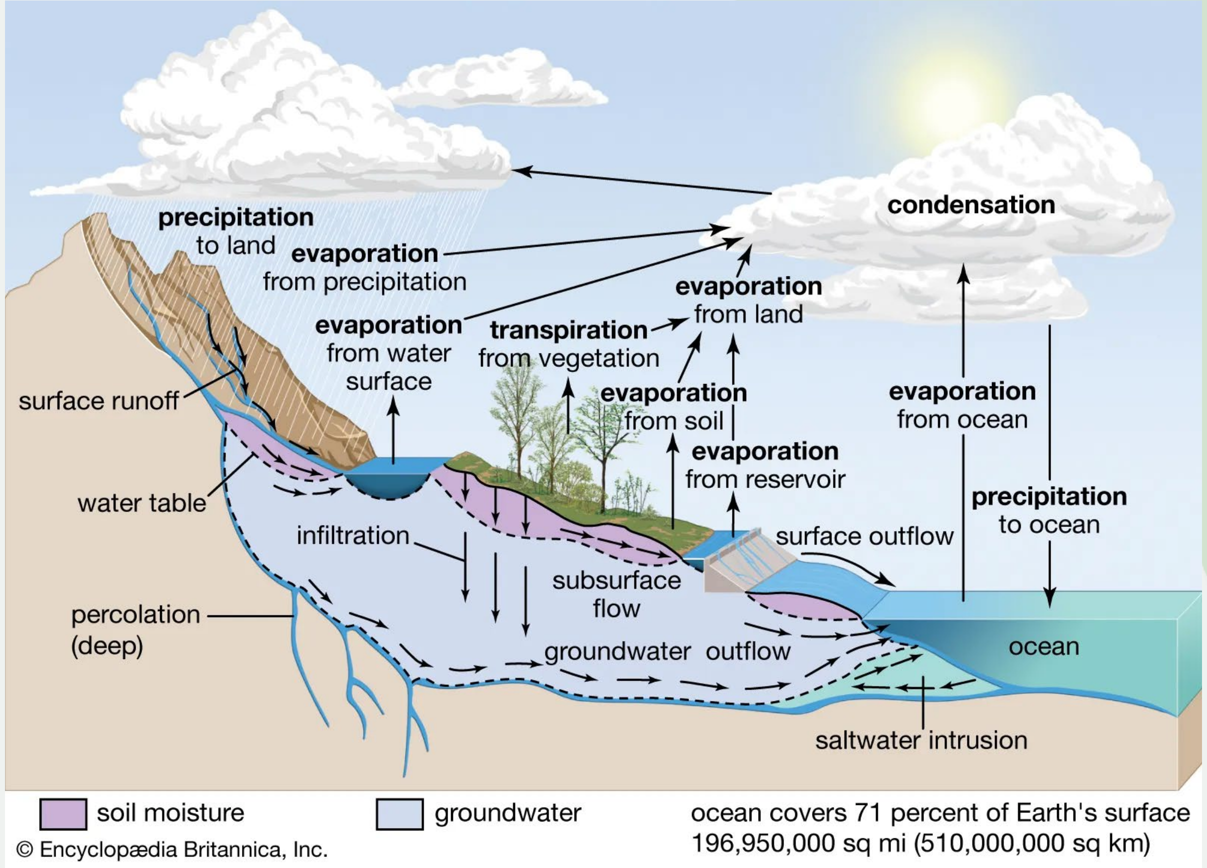


Source: Home Depot (above), NBC News (2024 Paris Olympics Aquatics Center, below)

Hydrologic cycle



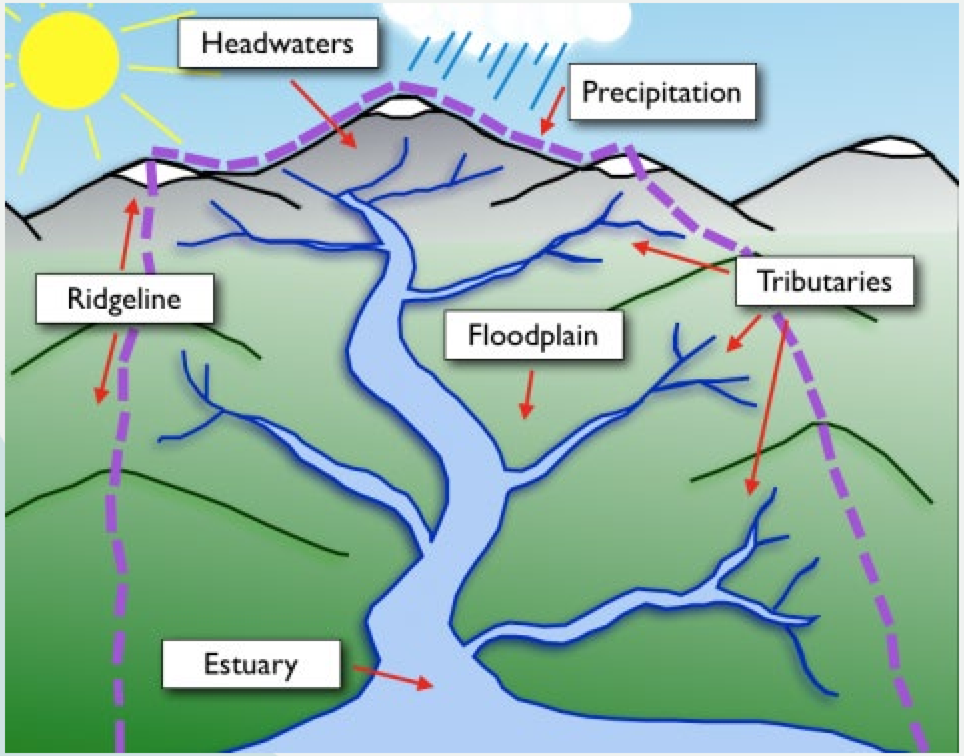
Source: NOAA



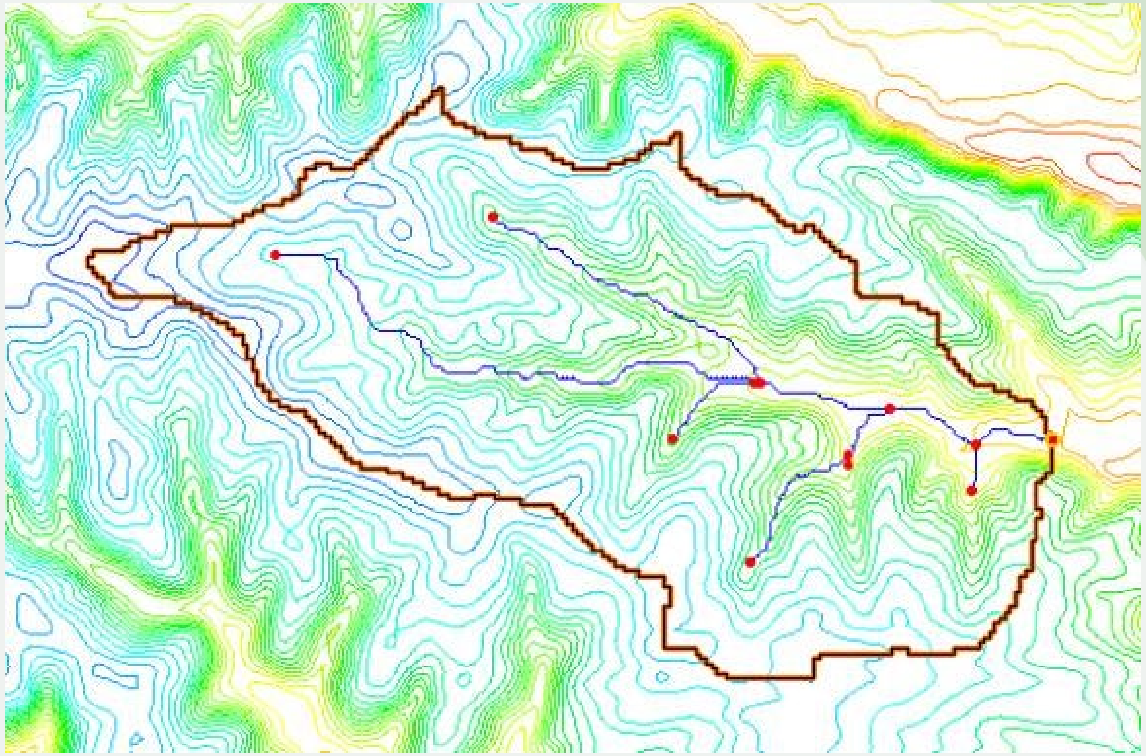
Source: Britannica

What is a watershed?

- Watershed: a contained area of land that drains to a single outlet.



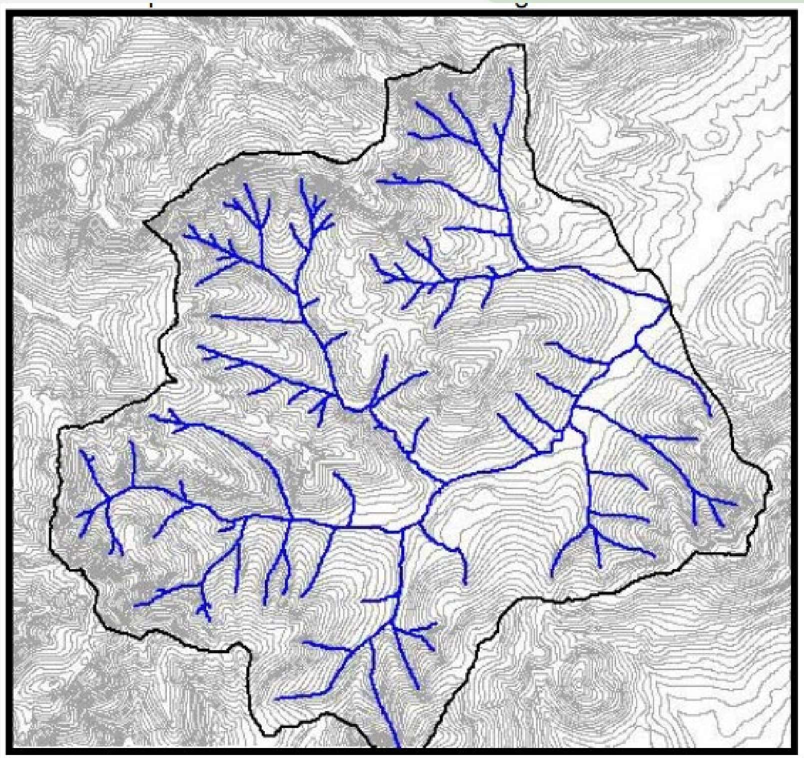
Source: NOAA



Source: gsshawiki.com Note: GSSHA is a 2D model for combined hydraulics, hydrology, groundwater and water quality analysis..

How to delineate a watershed

1. Find the **single** outlet.
2. Identify the ridgelines and connect them. Note: **ridgelines are contours that point down-slope**. The ridgelines should connect to form a **closed** watershed.
3. Identify the streamlines and connect them. Note: **streamlines are contours that point up-slope**. Streamlines should all merge at the single outlet.
4. Revise as needed.

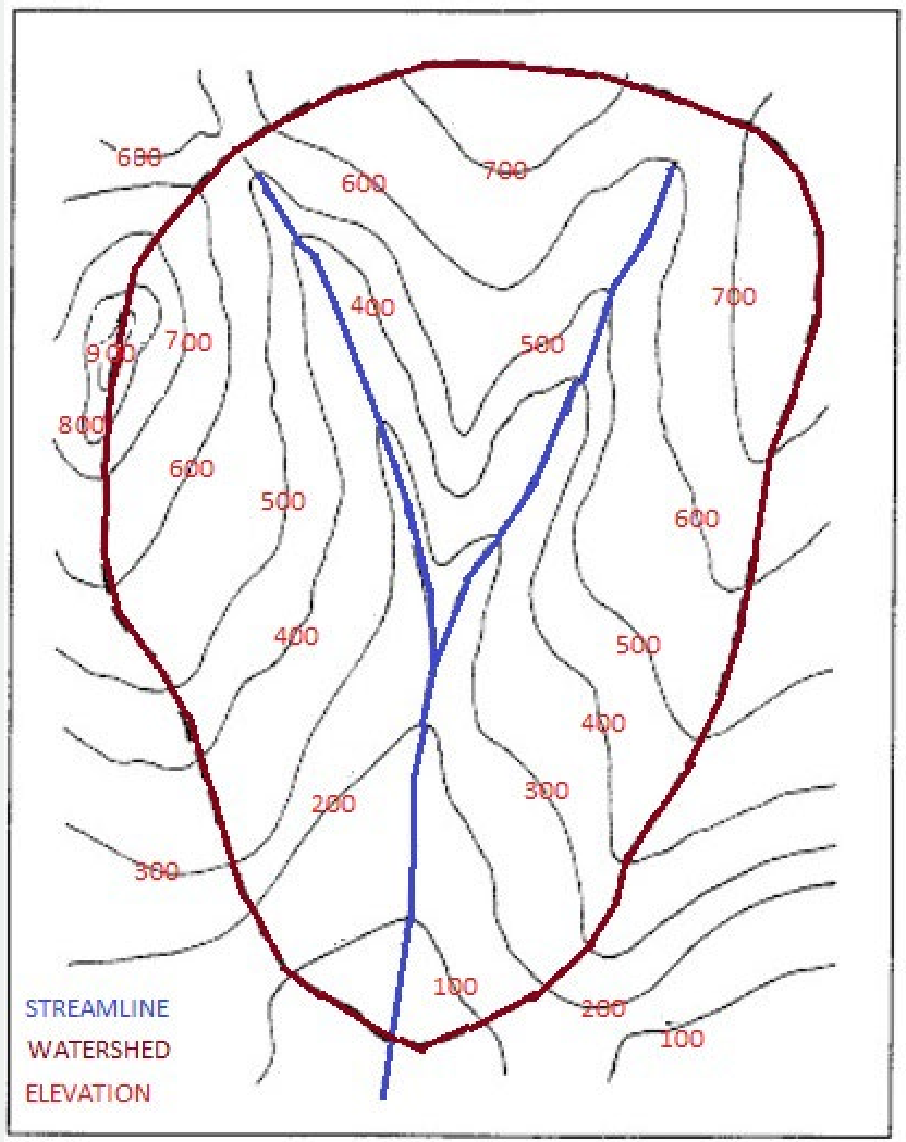


Source: https://people.wou.edu/~taylors/g302/watershed_delineation_drainage_area_exercise.pdf

A few watershed delineation rules

- Ridgelines or streamlines should be perpendicular to contour lines where they intersect.
- Ridgelines and streamlines do not cross.
- Ridgelines connect high points and streamlines connect low points.

- Can you see where the image violates these rules?



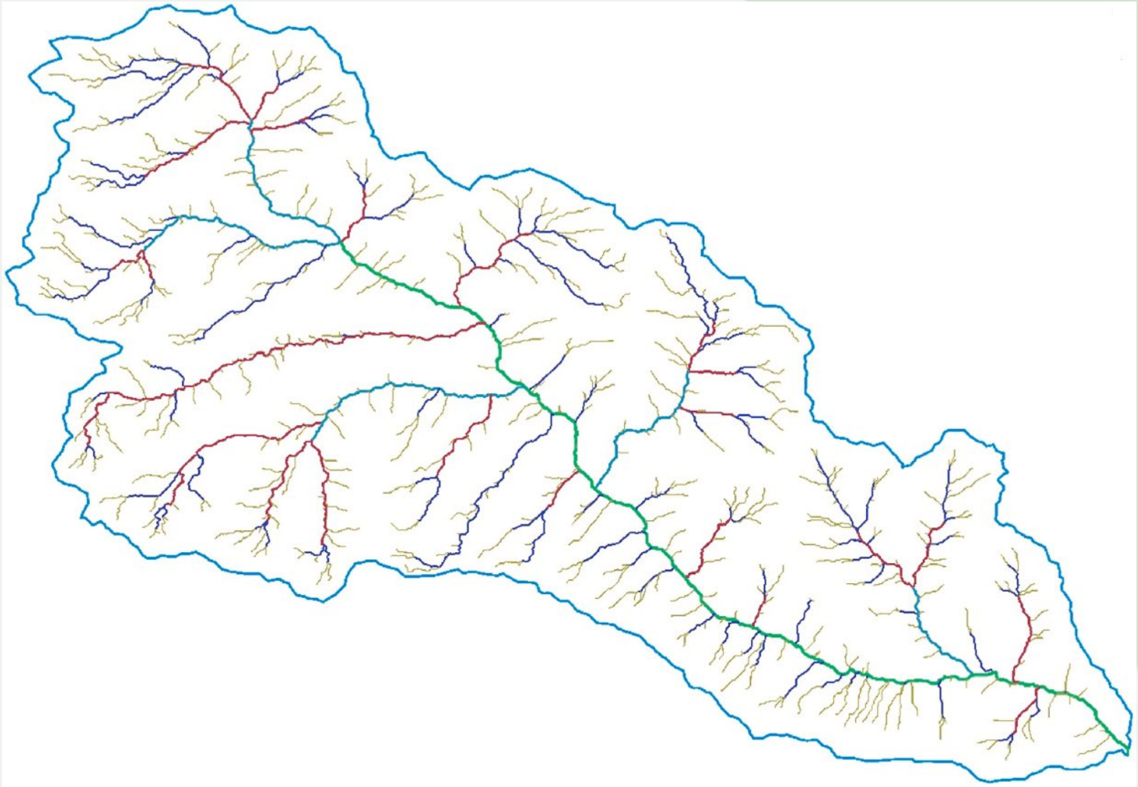
Source: Wikipedia Note: the image has been heavily edited for the course.

Watershed delineation exercise homework

- An example watershed is provided as a supplement to the presentation as contour maps. There is one provided contour map that does not include a delineation and another contour map of the same watershed that includes a suggested delineation. The latter is provided to check your work.
- If you need assistance with your homework you can reach me at djaffe@westyost.com
- In case you missed it the first time, the link to the presentation (and your homework) is provided in the QR code to the right.

Characteristics of watersheds: a few words about watershed morphology

- **Area** – units of acres, square miles, etc. Area is the most important watershed characteristic. Runoff volume is proportional to watershed area.
- **Length** – units of feet, miles, etc. (Hydrologic) Length is the along-stream distance of the main channel. Used to measure the travel time (the time for a drop of water to travel from the most remote part of the watershed to its outlet.
- **Slope** – unitless (i.e., S_o = feet/feet). Hydraulic length divided by the difference in elevation along the length. Used to determine the momentum of runoff.
- **Land cover, land use and roughness** – Three physical characteristics that influence runoff and runoff loss. More about these below.



Source: Mishra et al. (2003) Quaternary Science Advances. V. 11, 100096

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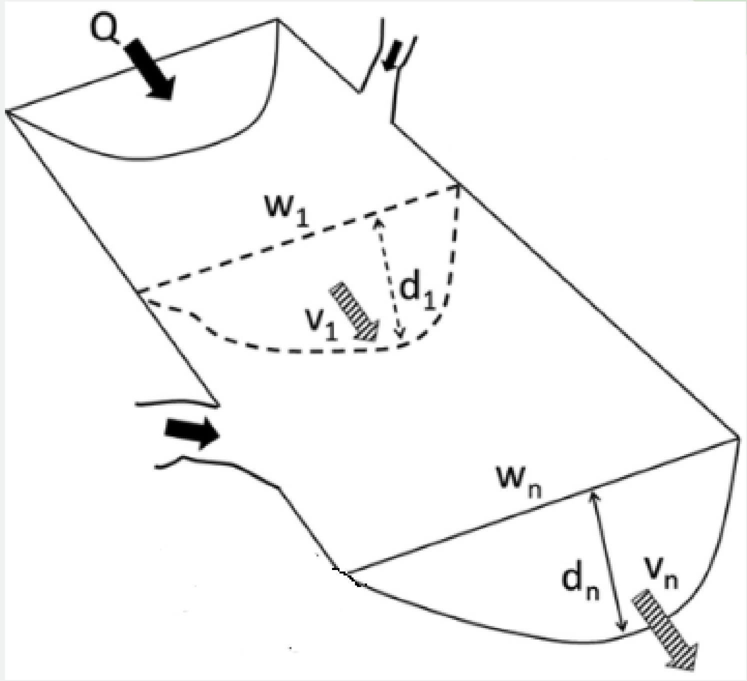
Characteristics of watersheds: a few words about channels

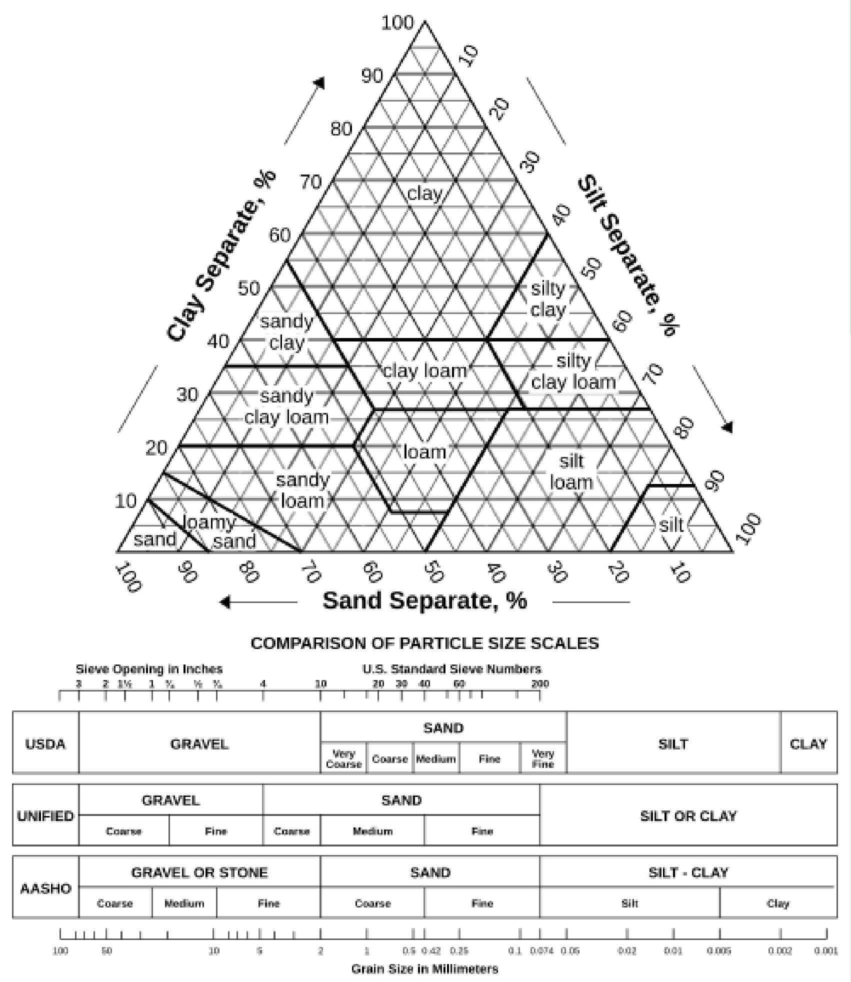
- **Horton's Law** – First order is unbranched tributary, second order is stream formed by two or more first order streams, … etc. Order of watershed is the order of the principal stream.
- **Channel parameters** – Length, slope, top width, area, wetted perimeter.
- **Roughness** – Like sandpaper in reverse. Greater roughness retards flow, increases potential for infiltration, reduces erosion.



Source: https://doi.org/10.1177/03091333145675

Characteristics of watersheds: a few words about soils

- Soil properties vary spatially and with depth.
- **Soil texture** – percentage of sand, silt and clay in a soil. Important factor for infiltration capacity of a soil. More sand = higher infiltration rate.
- **Soil moisture** – water content of the soil. Can be saturated during runoff events. High soil moisture reduces or prevents runoff from being lost to the soil.
- **Hydrologic Soil Group** – a method for characterizing infiltration rate based on soil texture ranging from A (sandy) to D (clayey).



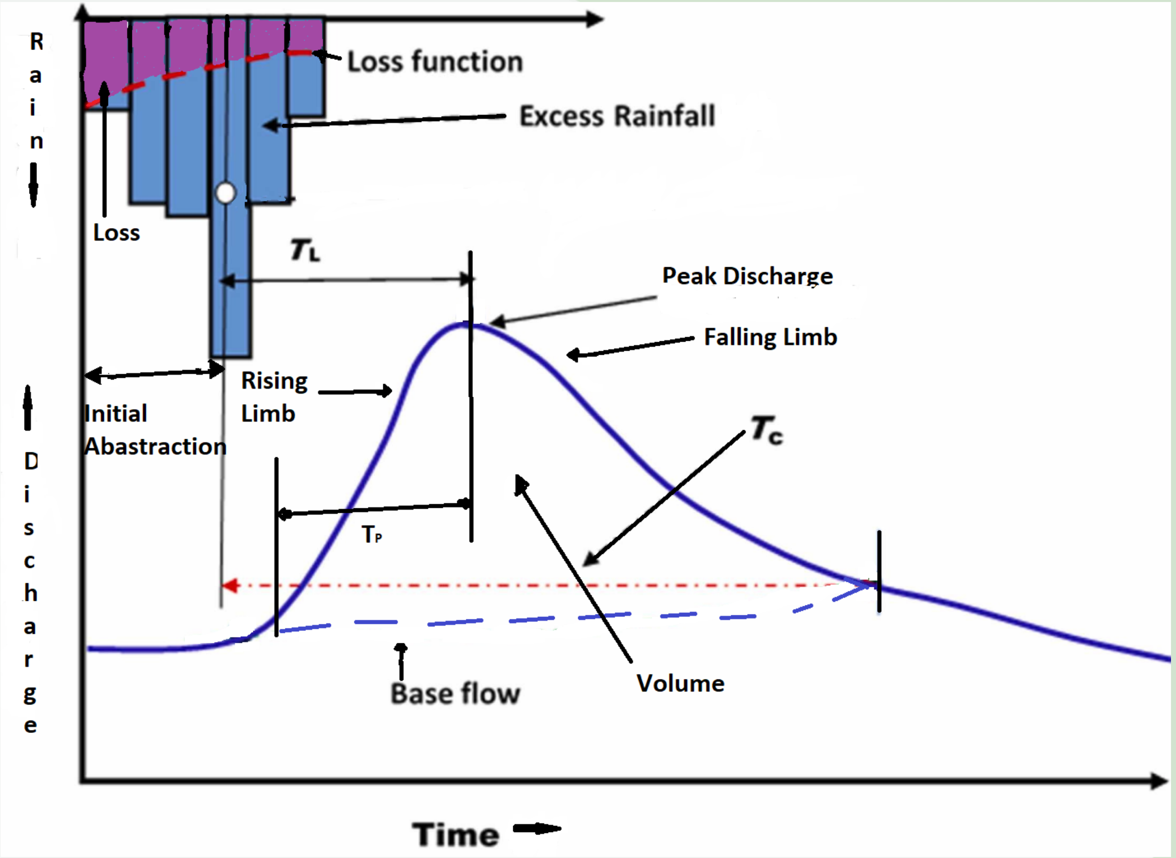
Source: Wikipedia

Characteristics of watersheds: many words about time

- **Travel time** – Units of time. Ratio of flow length [L] to flow velocity [L]/[t] or $T_t = L/v$ for a segment of stream. Time it takes for water to move between two points in a watershed.
- **Time of concentration** – Units of time. Sum of travel time for consecutive segments of stream. The longest travel time in a watershed, or the time it takes to travel from the most distant part of a watershed to its outlet.

Travel time and time of concentration are used in predicting peak discharge from hypothetical floods.

- **Time to peak** – Units of time. Time for a stream to reach highest discharge from the beginning of rainfall excess at a specific location.
- **Lag time** – Units of time. Time between peak precipitation intensity and peak stream flow at a specific location.



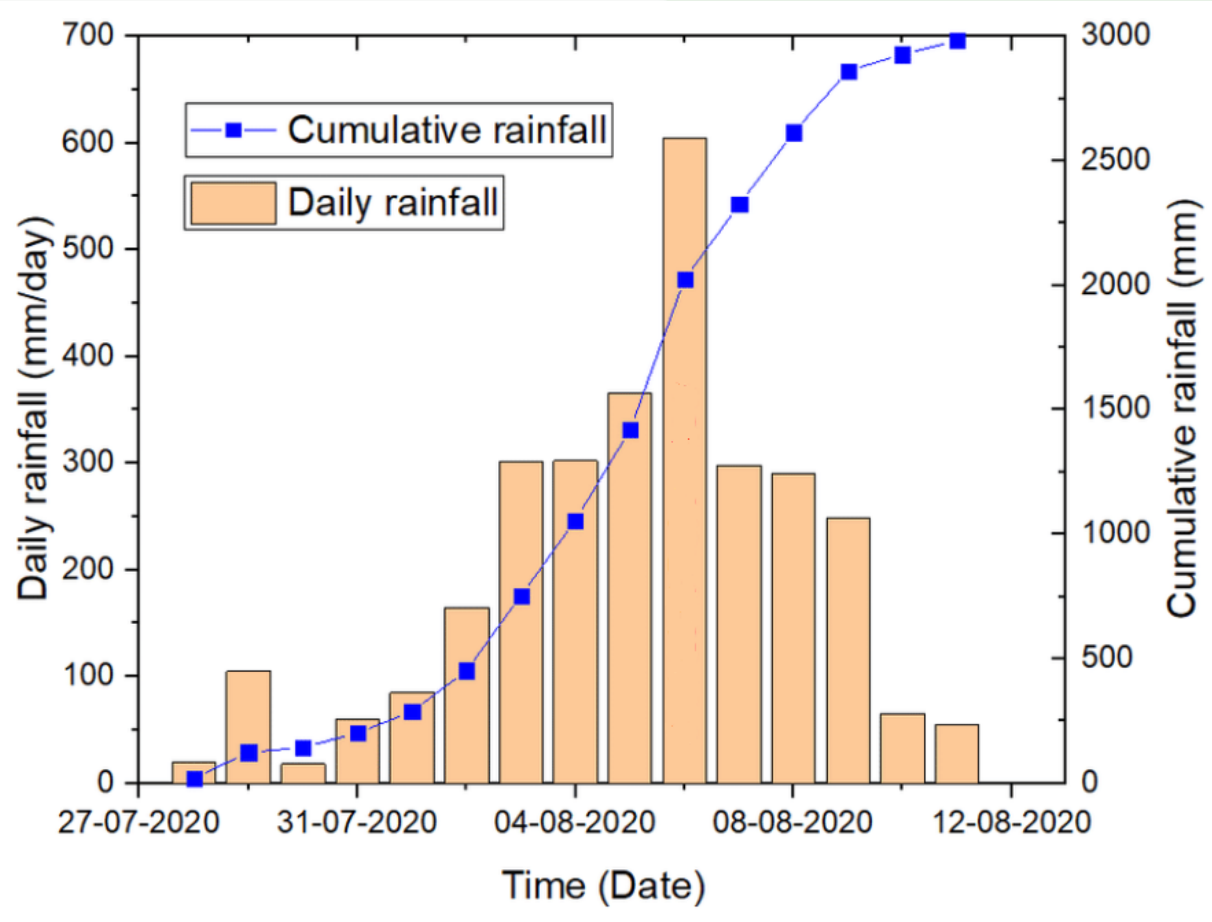
Source: Modified after https://doi.org/10.1016/j.ejrh.2022.101025

Characteristics of watersheds: many words about loss

- Runoff = Precipitation – Initial abstraction – Losses
- **Initial abstraction** – all rainfall that occurs prior to direct runoff.
- **Losses** – the mechanisms in a watershed that result in precipitation storage instead of runoff. Loss is the portion of precipitation that doesn't contribute to runoff.
- Most common losses are **infiltration** (into the ground), **depression storage** (irregularities in the ground surface), and **interception** (capture by vegetation).
- **Hydromodification** – (one definition is…) anthropogenic changes to a watershed that reduce loss.
- Examples of watershed characteristics that influence loss: slope, soil type, vegetative cover, land use, soil moisture.

Precipitation, Part 1

- Many kinds of precipitation – rain, snow, sleet, hail, etc. – here we focus on rain.
- Hydrologic planning and design require **both rainfall volume and rainfall time distribution**.
- Storm events are either **actual storms** or **design storms**. Rainfall analysis is based on actual storms, but design can be based on either actual or design storms.
- Time distribution of rain is shown graphically on a **hyetograph** (hi-uh-to-graph)



Source: Subramanian et al. (2021) doi.org/10.21203/rs.3.rs-941010/v1

Precipitation, Part 2

Rainfall characteristics:

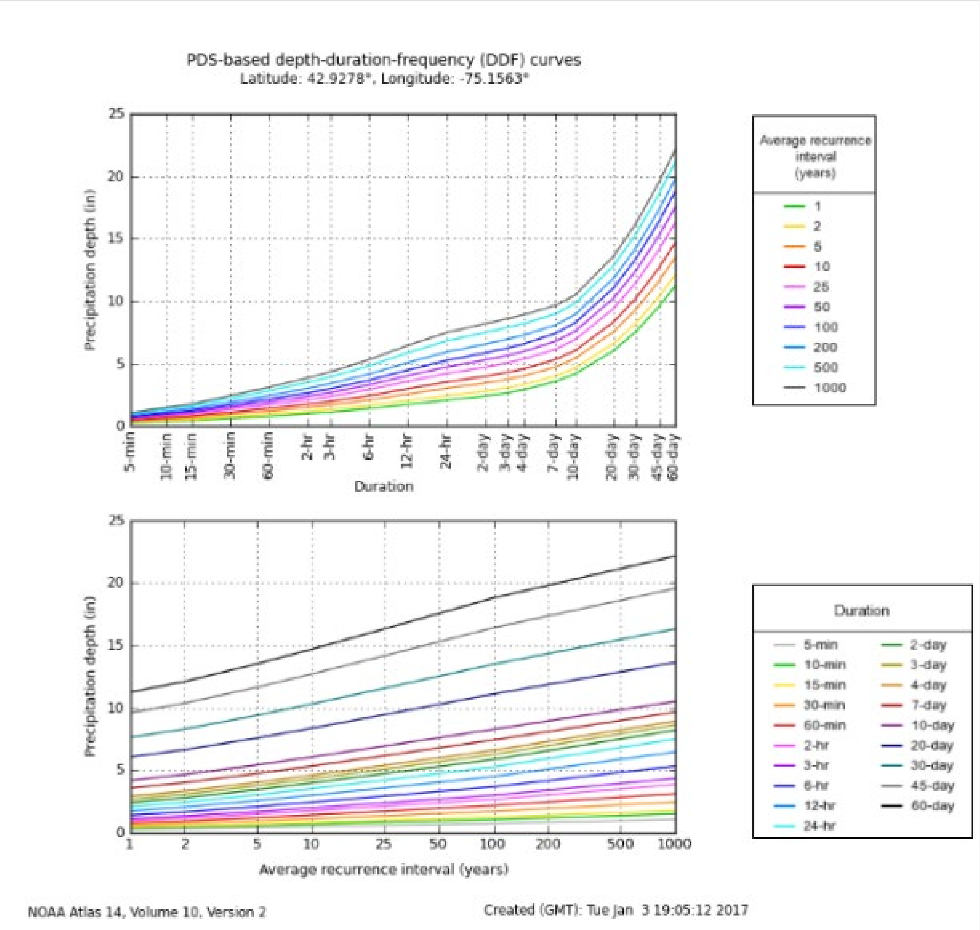
- **Duration** – units of time. Length of time of precipitation.
- **Volume** – units of depth. Amount of precipitation during the storm's duration.
- **Frequency** - frequency of occurrence of precipitation with the same duration and volume).
- Assumption alert #1! Rainfall volume is assumed to occur uniformly over the entire watershed! When this is true, **volume of rainfall = depth x watershed area**
- <u>Example</u>: If a 6-hour duration storm occurred over a 100-acre area watershed with a volume of 3-inches, then the total rainfall volume in the watershed is 300 acre-inches, and the rainfall **intensity** (the rate of rainfall) is 0.5 inches per hour.
- Assumption alert #2! A reported rainfall depth occurs over a combination of intensities with shorter durations.

Precipitation, Part 3

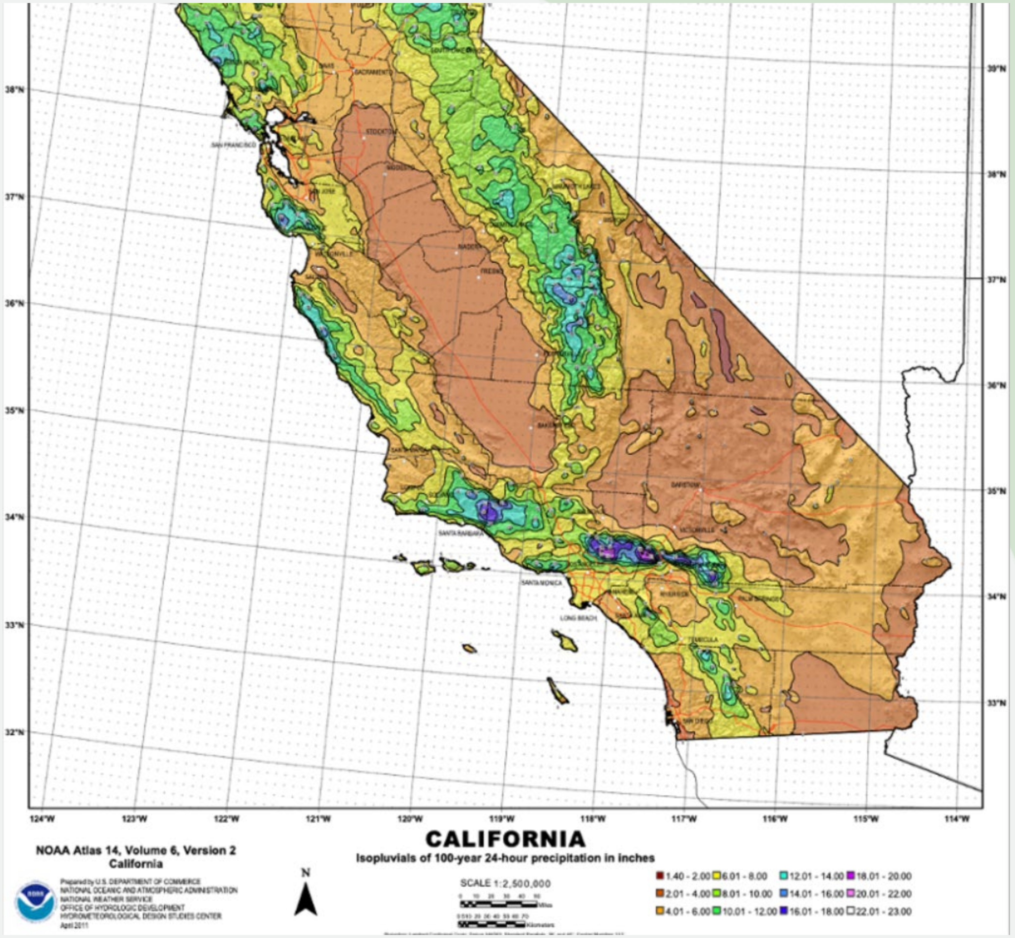
Let's talk about frequency, or what is a 100-year storm?

- **Exceedance Probability** (P) – dimensionless, expressed as a percent. The probability of an event of specific depth and duration will be exceeded in a given year.
- **Return Period** (t) – units of time. The average length of time between events with specific depth and duration .
- **P = 1/t**
- Return period is one of the most misunderstood concepts in hydrology. Rainfall events are independent. A 100-year event can occur in consecutive years, or not in 200 years!
- **Depth, duration and frequency are independent variables!** As is location.

Mapping precipitation



Source: NOAA



Source: NOAA

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Precipitation, Part 4

- **Depth-Area adjustments** – For watersheds greater that about 10 square miles rainfall depth needs to be adjusted *down*. Isohyetal plots represent maximum rainfall depths, while only at storm centers will rainfall depths reach the maximum.
- **Probable Maximum Precipitation** is the greatest depth of precipitation for a given duration meteorologically possible for a design watershed or a given storm area at a particular location at a particular time of year (WMO). PMP is a storm-based approach unlike a point-based approach. Typically used for dams.

Frequency analysis, or why the 2-year storm doesn't produce the 2-year runoff

- Rainfall and runoff are correlated.
- Many watershed characteristics control the transformation from rainfall to runoff: soil moisture, plant cover, etc.
- Which 2-year rainfall? There are many 2-year rainfalls, each with different duration, intensity, and volume.
- The most common statistical distribution in the United States is **Log-Pearson Type III, or LP3**. For a description of developing an LP3 analysis see Bulletin 17C: https://pubs.usgs.gov/publication/tm4B5 and HEC-SSP User's Manual: https://www.hec.usace.army.mil/software/hec-ssp/

Peak discharge estimation

- **Index-Flood method** is a method for estimating runoff when the runoff from one return period is know or estimated. Index-Flood provides the ratio between the known or estimated return period runoff and other return periods. This method is based on the analysis of stream gage data.
- The most common method to estimate peak discharge in the United States is the **Rational Method**.
- Q = CIA
- Q – Discharge, units of volume per time, usually CFS.
- A – Drainage area, units of area, usually acres.
- I – Rainfall intensity, units of depth per time, usually inches per hour.
- C – Runoff coefficient, units of inverse time, representation of loss.

Curve numbers

Rational Method Runoff C Coefficients

Type of Cover	Soil Type	Flat	Rolling 2% to 10%	Mountains over 10%
Buildings and roofs		0.90	0.90	0.90
Concrete pavedsurfaces		0.80	0.90	0.95
Asphalt pavedsurfaces		0.70	0.80	0.90
Earth embankments	bare & compacted	0.60	0.60	0.60
Gravel road shoulders		0.50	0.55	0.60
Sidewalks		0.80	0.82	0.85
Grassed areas	sandy	0.10	0.15	0.20
Grassed areas	clay	0.15	0.20	0.30
Farmed land	sand & gravel	0.25	0.30	0.35
Farmed land	clay & loam	0.50	0.55	0.60
steppe forest	sandy	0.10	0.15	0.20
semi desert land	bare & loose	0.10	0.20	0.30

Source: USACE

Table 5.3. Runoff coefficients, C, for use in the Rational Equation (Erie and Niagara Counties Regional Planning Board, 1981).

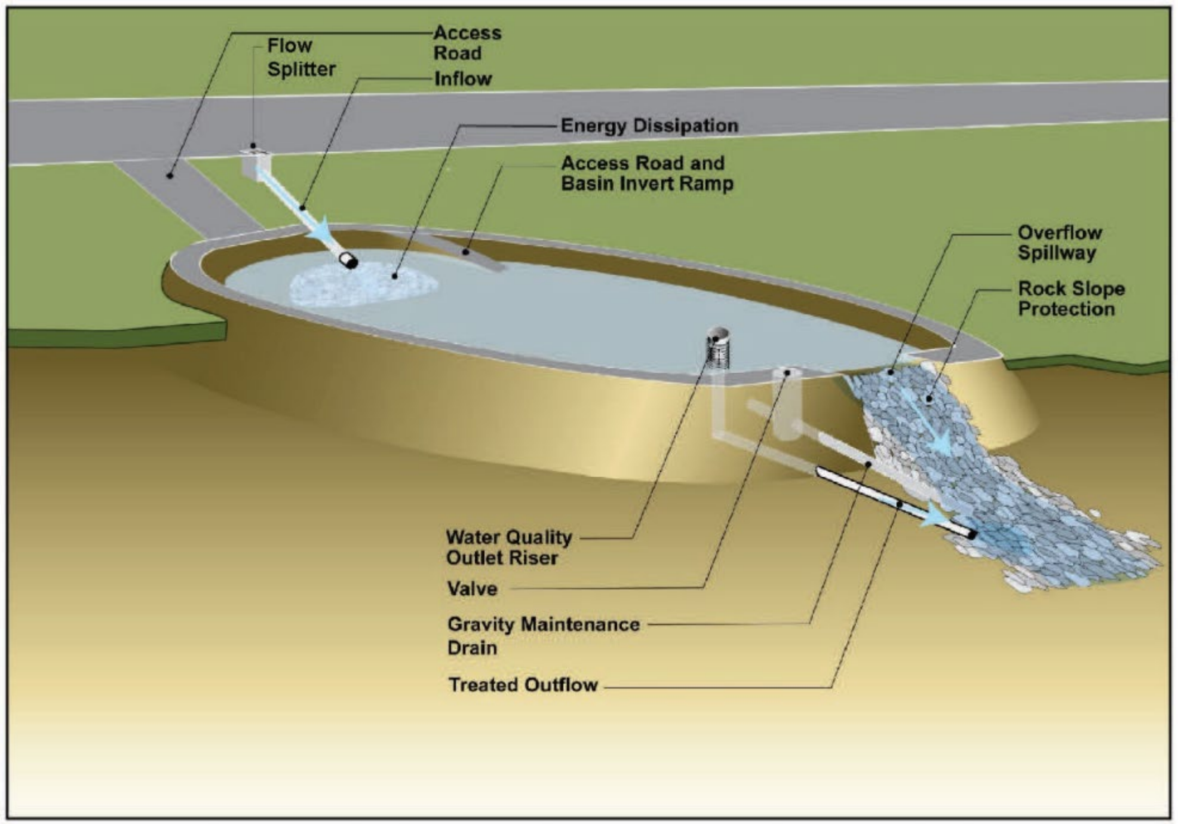
Land Use	Hydrologic Soil Group and Slope Range											
	A			B			C			D		
	0-2%	2-6%	6%+	0-2%	2-6%	6%+	0-2%	2-6%	6%+	0-2%	2-6%	6%+
Industrial	0.67[1] 0.85[2]	0.68 0.85	0.68 0.86	0.68 0.85	0.68 0.86	0.69 0.86	0.68 0.86	0.69 0.86	0.69 0.87	0.69 0.86	0.69 0.86	0.70 0.88
Commercial	0.71 0.88	0.71 0.89	0.72 0.89	0.71 0.89	0.72 0.89	0.72 0.89	0.72 0.89	0.72 0.89	0.72 0.90	0.72 0.89	0.72 0.89	0.72 0.90
High Density[3] Residential	0.47 0.58	0.49 0.60	0.50 0.61	0.48 0.59	0.50 0.61	0.52 0.64	0.49 0.60	0.51 0.62	0.54 0.66	0.51 0.62	0.53 0.64	0.56 0.69
Medium Density[4] Residential	0.25 0.33	0.28 0.37	0.31 0.40	0.27 0.35	0.30 0.39	0.35 0.44	0.30 0.38	0.33 0.42	0.38 0.49	0.33 0.41	0.36 0.45	0.42 0.54
Low Density[5] Residential	0.14 0.22	0.19 0.26	0.22 0.29	0.17 0.24	0.21 0.28	0.26 0.34	0.20 0.28	0.25 0.32	0.31 0.40	0.24 0.31	0.28 0.35	0.35 0.46
Agricultural	0.08 0.14	0.13 0.18	0.16 0.22	0.11 0.16	0.15 0.21	0.21 0.28	0.14 0.20	0.19 0.25	0.26 0.34	0.18 0.24	0.23 0.29	0.31 0.41
Open Space[6] (Grass/Forest)	0.05 0.11	0.10 0.16	0.14 0.20	0.08 0.14	0.13 0.19	0.19 0.26	0.12 0.18	0.17 0.23	0.24 0.32	0.16 0.22	0.21 0.27	0.28 0.39
Freeways and Expressways	0.57 0.70	0.59 0.71	0.60 0.72	0.58 0.71	0.60 0.72	0.61 0.74	0.59 0.72	0.61 0.73	0.63 0.76	0.60 0.73	0.62 0.75	0.64 0.78

1. Lower runoff coefficients for use with storm recurrence intervals less than 25 years.
2. Higher runoff coefficients for use with storm recurrence intervals of 25 years or more.
3. High density residential areas have more than 15 dwelling units per acre.
4. Medium density residential areas have 4 to 15 dwelling units per acre.
5. Low density residential areas have 1 to 4 dwelling units per acre.
6. For pastures and forests we recommend using the lower runoff coefficients which are listed for open spaces (our addition to original source).

Source: Erie and Niagra Regional Planning Board

A few introductory thoughts on runoff analysis

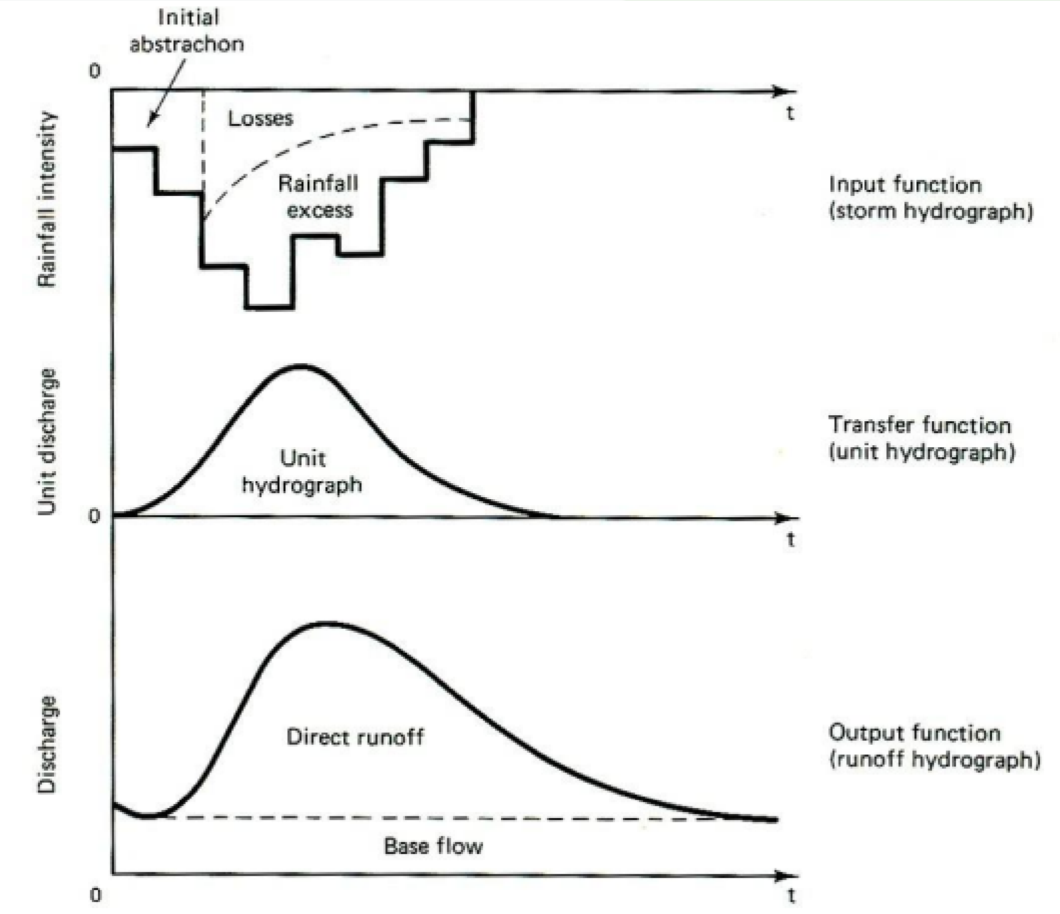
- Two kinds of hydrographs: **observed** (stream gage) and **synthetic** (estimated mathematically).
- Why is this important: when designing for runoff events the historical record may be limited (i.e., relatively short historical record) or non-existent data (i.e., no stream gage).
- Design is typically for specific events (i.e., 85th percentile, 100-year, etc.) that are not present in the historical record.
- Design applications of hydrographs include pipelines (peak discharge), basins (hydrograph volume), and effects of land use changes (peak discharge and volume).



Source: Caltrans

Unit hydrograph

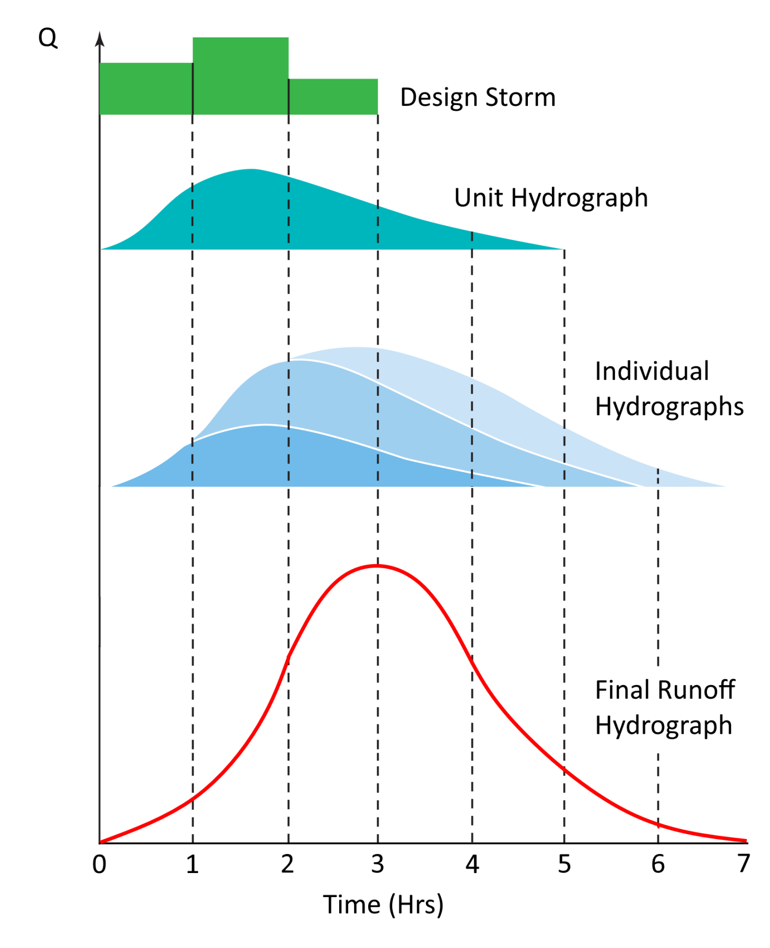
- The hydrograph that results from 1 inch of (1) **rainfall excess** generated from a (2) **uniform spatial rainfall distribution** over a watershed at a **(3) uniform rate of excess** over (4) a **specific duration**.
- Why do we care: the unit hydrograph is the tool used to develop a runoff hydrograph from rainfall hyetograph.
- Once a watershed response to a storm is known, the unit hydrograph can be used to predict the response to other rainfall events.



Source: McCuen 1998

Example process to set up a unit hydrograph, skipping the math

- Select a design storm (i.e., 100-year, 24-hour)
- Develop a unit hydrograph based on the watershed's unique characteristics (i.e., C, Tc, etc.) of a specific duration
- Excess runoff from the design storm hyetograph ordinate is multiplied by the unit hydrograph ordinate to create a **series of individual hydrographs** for specific intervals
- Individual hydrographs are summed to create the final hydrograph



Source: Hydrology Studio

Select references

- Bedient, P., and W. Huber (1992) Hydrology and Floodplain Analysis. Addison Wesley.
- McCuen, R. (1998) Hydrologic Analysis and Design. Prentice Hall.
- Thompson, S. (1999) Water Use, Management, and Planning in the United States. Academic Press.

THANK YOU

David Jaffe LinkedIn