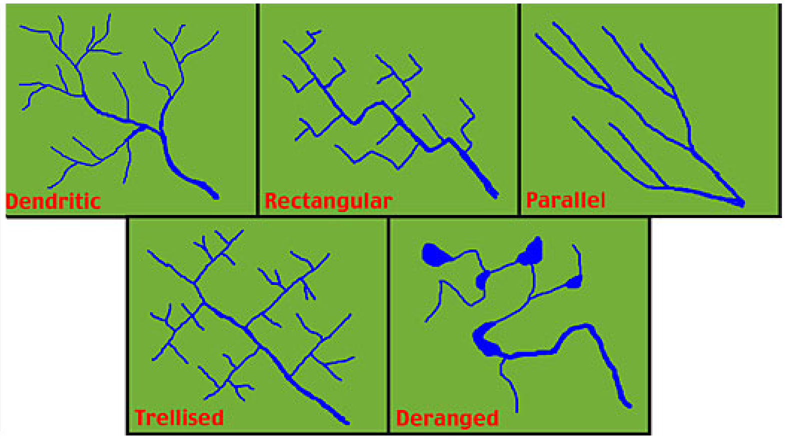
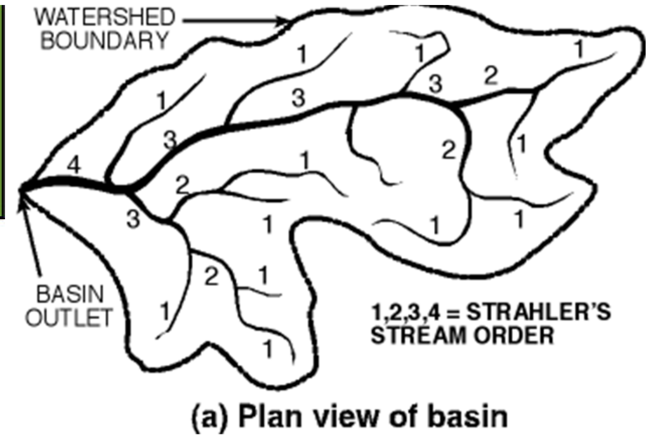
http://www.reddit.com/r/MapPorn/comments/18k4cx/huge_map_of_north_america_and_drainage_basins/



http://www.physicalgeography.net/fundamentals/10aa.html

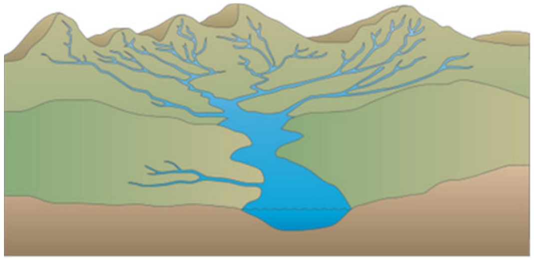


http://ohiodnr.com/water/pubs/fs_st/stfs03/tabid/4159/Default.aspx

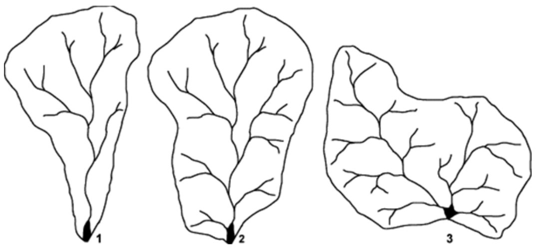
Env E 320: Environmental Hydrology

TOPIC 1: WATERSHEDS

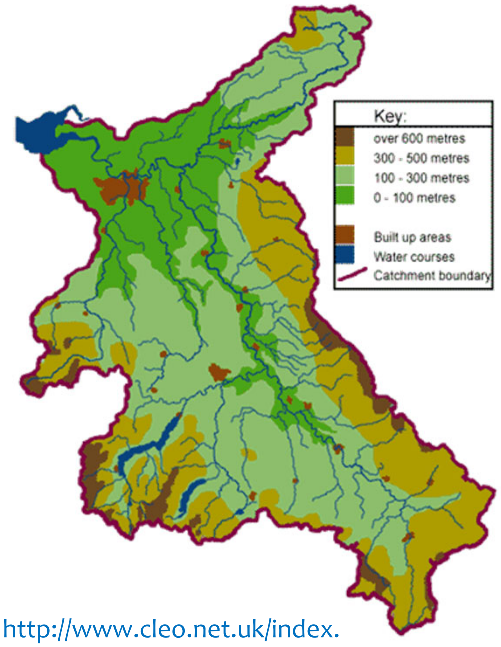
Information in Topic 1 is from pages 2-3 *and* 37-43 *of* ***Bedient et al. (2019)*** *and from* ***Ponce (1989)***



http://ian.umces.edu/imagelibrary/albums/userpics/10002/normal_ian-symbol-river-3d-catchment.png



http://www.sciencedirect.com/science/article/pii/S0022169404004081



http://www.cleo.net.uk/index.php?category_id=390

Section overview

1. Engineering Hydrology
2. The Hydrological Cycle
3. Watersheds
4. Watershed Response and the Water Balance

1. ENGINEERING HYDROLOGY

- **Hydrology** studies the waters of the earth…

- The study of hydrology includes,
  - The distribution and movement of water **on and under** land surfaces, and exchanges with the **atmosphere**
  - **Physical** and **chemical** interactions with earth materials
  - **Biological processes** and **human activities** that affect its movement, distribution, and quality

- Hydrology encompasses both **surface water hydrology** and **groundwater hydrology**
  - Groundwater hydrology is considered a subject in itself

- Related earth sciences: climatology, meteorology, geology, geomorphology, sedimentology, geography, and oceanography

- Note: *Hydrology is not an exact science*

Hydrologists

- Study aspects of the hydrological cycle
  - e.g. rainfall, runoff, snow, groundwater
- Predict the magnitude of floods
- Study the effect of weather (climate change) on water quantity
  - e.g. drought on the Prairies

The 1996 flood in Chicoutimi, QC

The 2013 Alberta flood (Canmore)

Engineering Hydrology

- Engineering hydrology is an applied earth science
- It uses **hydrological principles** to solve **engineering problems,** particularly in terms of managing water resources for various engineering purposes:

I.e. it "...includes those segments of the field pertinent to planning, design and operation of engineering projects for the control and use of water"
(Linsley, Kohler and Paulhus, 1982)

- Practical applications of hydrology
  - Flood and drought control and management
    - Planning, design and control of hydraulic structures such as dams, levees, and diversions to control river flows
    - Floodplain delineations and emergency responses
  - Municipal water systems
    - Water supply and treatment
    - Stormwater management and wastewater treatment
  - Irrigation and agriculture
    - Reservoirs, river diversions, canal and pipe systems
  - Hydropower generation, navigation and transportation
  - Ecosystem management, conservation, pollution abatement
    - Fish and wildlife protection
    - Preservation and construction of wetlands and other habitats
  - Climate change adaptation

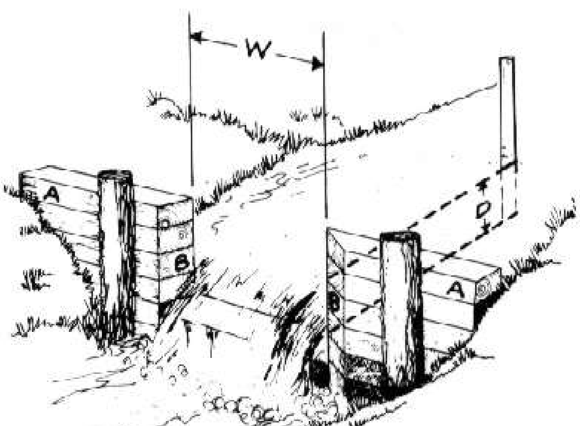


Fig. 1 Weir

http://www.waterwheelfactory.com/weir.htm

History of hydrology

- Egyptians built a dam across the Nile as early as 2950 BC (Sadd-el-kafara dam)
- Sumerians and Egyptians irrigated crops more than 4000 years ago
- Greek philosophers were "first serious students of hydrology"
- Romans built 11 major aqueducts and attempted streamflow measurements as early as 97 AD

http://en.wikipedia.org/wiki/Aqueduct_%28bridge%29

Bedient et al. (2019)

Early history

- **Leonardo da Vinci** discovered relationship between area, velocity and flow ($Q = AV$)
- **Perrault** conducted first measurement of rainfall and surface flow in 17th c. → Seine R.
- **Bernoulli**'s theorem (early 18th c.)
- **Darcy**'s Law for flow in porous media (19th c.)
- **Darcy-Weisbach** equation (1850s)
- Discharge measurements on Rhine (1867)
- USGS set up systematic flow measurements on Mississippi (1888)

Bedient et al. (2019)

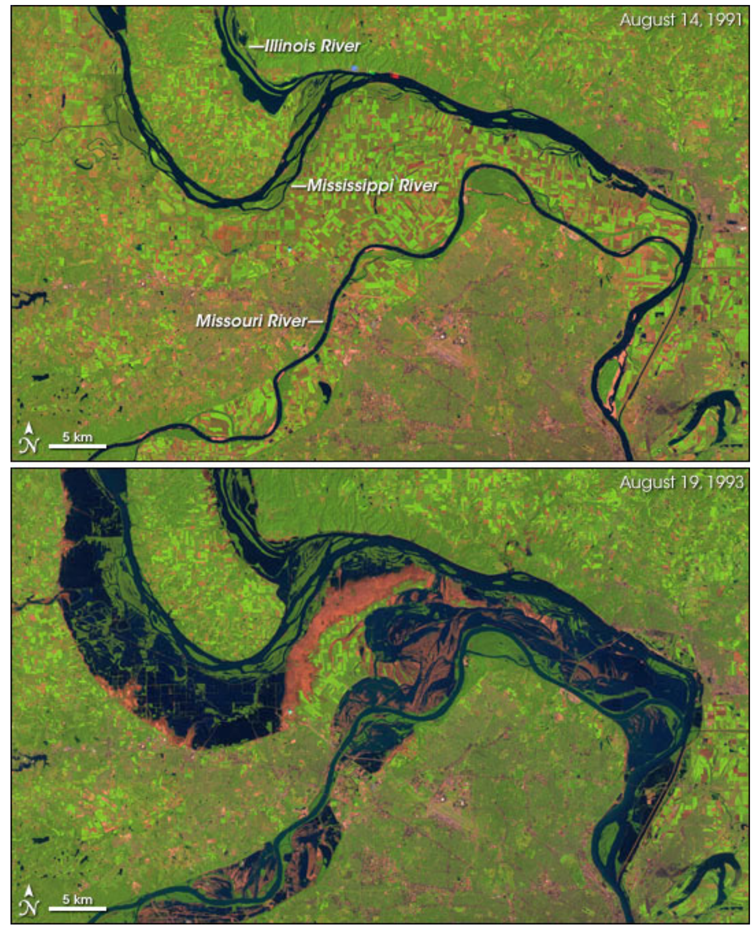
1930s-1950s

- Government agencies set up programs of hydrological research → "Period of rationalization" (**Chow**, 1964)
- **Horton**'s infiltration, **Sherman**'s unit hydrograph, Theis' non-equilibrium equation, **Gumbel** extreme-value distributions
- US Army Corps of Engineers and USGS gauge networks, advances in hydrological theory, flood control, reservoir development, etc.
- Many results still used today for prediction of runoff, infiltration, evaporation

Bedient et al. (2019)

1950s-now

- 1950-1960s: Major **urbanization** required better understanding of flooding, drought
  - Predicting flood peak flows
  - Managing storage reservoirs
- 1970s-1980s: floodplain boundary delineation (FEMA)
  - Massive floods in 1993 (Mississippi) and hurricanes in 2000s
- More recently (1993-): shift from purely structural flood control methods



http://earthobservatory.nasa.gov/IOTD/view.php?id=5422

Bedient et al. (2019)

Computer advances

- Introduction of computers in 1960s-1970s
- Large computer models to match historical data, answer difficult questions, project effects into future
- Understanding of hydrological systems greatly advanced:
  - Urban stormwater, floodplain hydrology, drainage design, reservoir design and operation, flood frequency analysis, large river basin management

Bedient et al. (2019)

2. THE HYDROLOGICAL CYCLE

Exchanges between atmosphere and surface

- The **hydrological cycle** continuously moves water from one "reservoir" to another through,
  - **Precipitation:** rainfall or snowfall
  - **Evaporation:** conversion of water to water vapour
  - **Transpiration:** loss of water vapour from leaves, plant tissue
    - Often combined as "evapotranspiration" (ET)
  - **Interception:** precipitation on vegetation canopy

Processes at surface

  - **Infiltration:** entry of surface water into soil
  - **Runoff:** water flows over land surface

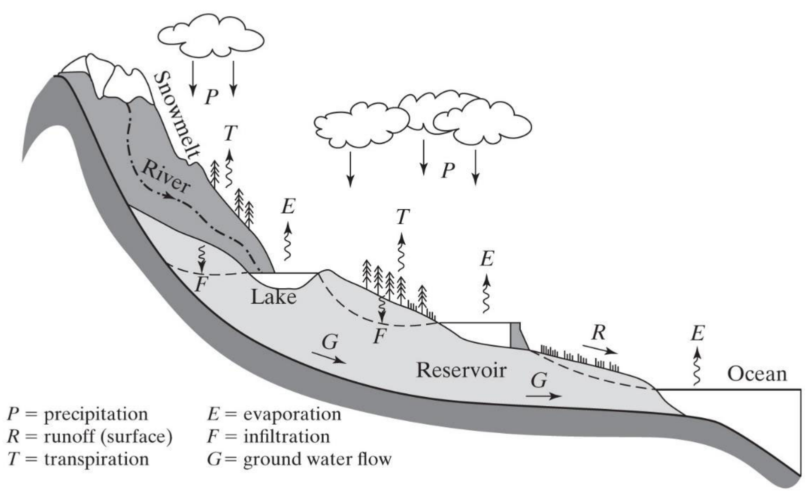


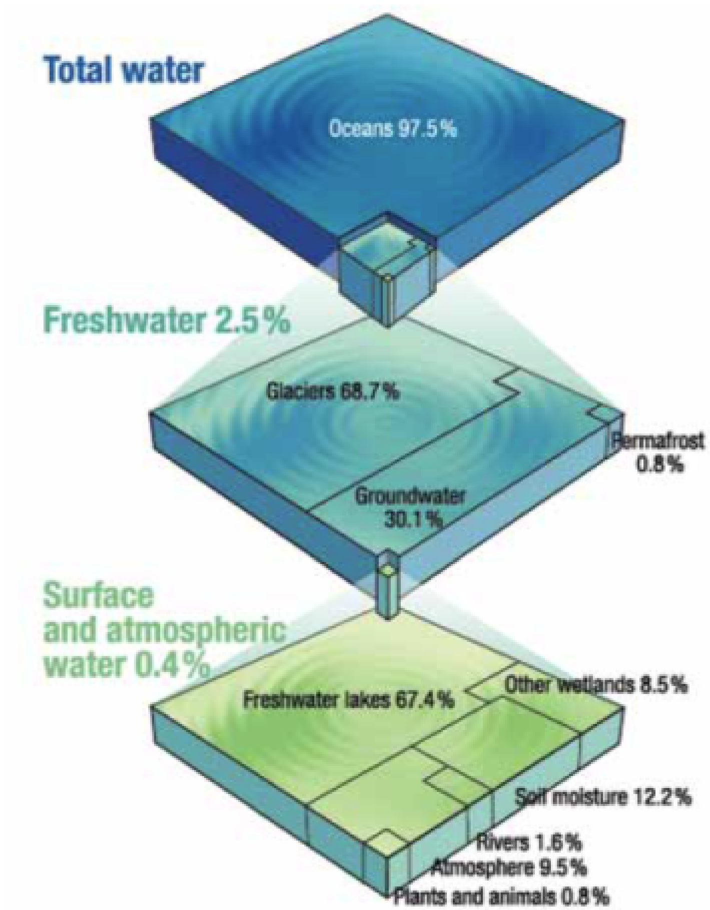
Fig. 1-1a in Bedient et al. (2019)

The three phases of water

- **Vapour Phase**
  - Evaporation, Evapotranspiration
  - Sublimation, Vapour diffusion
- **Liquid Phase**
  - Rainfall
  - Snowmelt
  - Surface runoff, interflow
  - Infiltration, exfiltration & percolation
  - Groundwater
  - Capillary rise
- **Solid Phase**
  - Snowfall, snowpack, hail, glaciers
  - River ice, sea ice

How much water is there?

Figure 4.1: Global distribution of the world's water

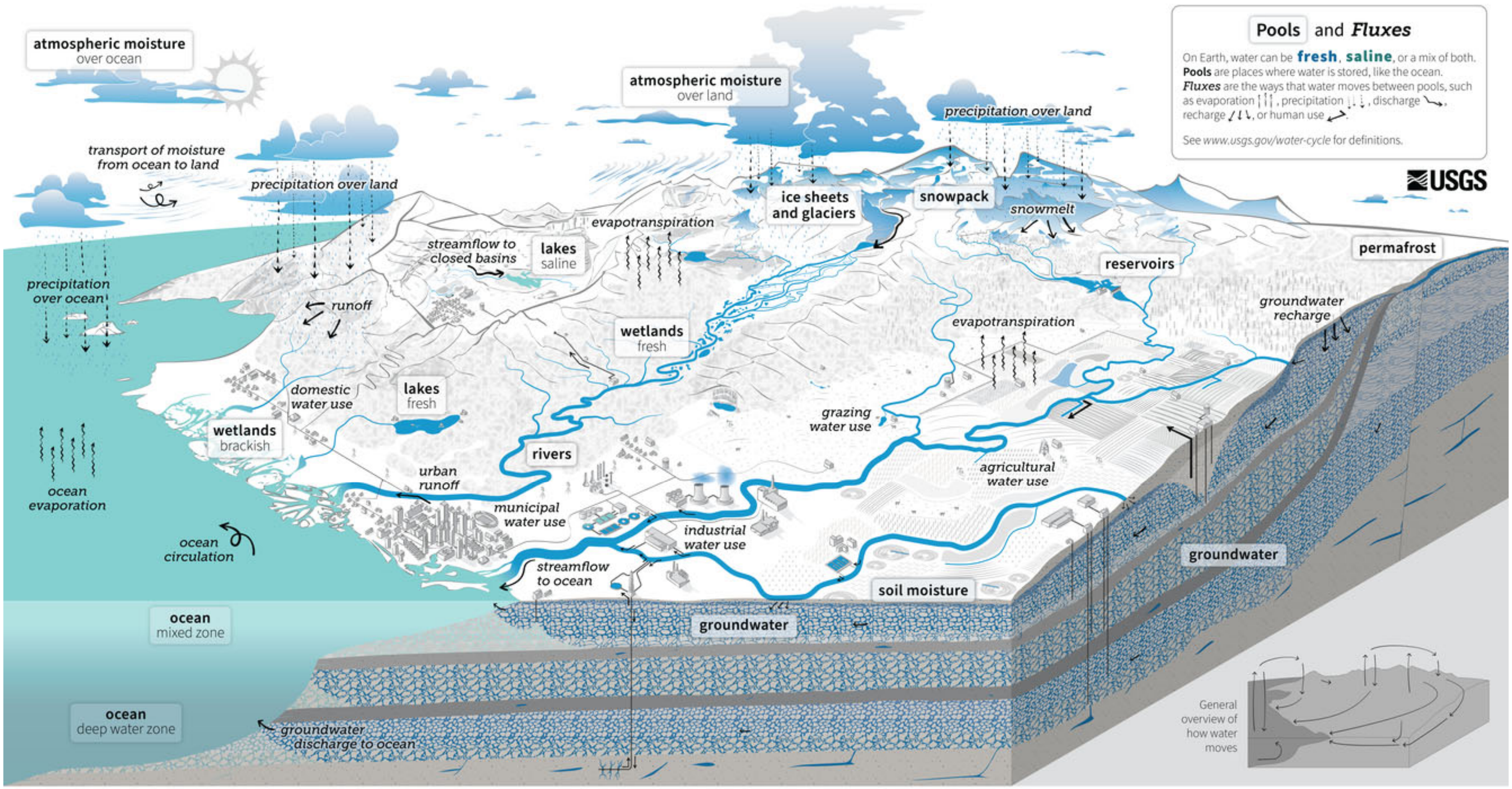


Component	Mean residence time	Total water stored (thousands of cubic kilometres)	Freshwater stored (thousands of cubic kilometres)
Permafrost zone, ground ice	10,000 years	300	300
Polar ice	9,700 years	24,023	24,023
Oceans	2,500 years	1,338,000	na
Mountain glaciers	1,600 years	40.6	40.6
Groundwater (excluding Antarctica)	1,400 years	23,400	10,530
Lakes	17 years	176.4	91.0
Swamps	5 years	11.5	11.5
Soil moisture	1 year	16.5	16.5
Streams	16 days	2.1	2.1
Atmosphere	8 days	12.9	12.9
Biosphere	Several hours	11.2	11.2
Total		1,385,985	35,029

UNESCO, WWDR2, Chapter 4

UNESCO, WWDR3, Chapter 10

Water stocks and flows: the hydrological cycle



The Water Cycle

The water cycle describes where water is found on Earth and how it moves. Water can be stored in the atmosphere, on Earth's surface, or below the ground. It can be in a liquid, solid, or gaseous state. Water moves between the places it is stored at large scales and at very small scales. Water moves naturally and because of human interaction, both of which affect where water is stored, how it moves, and how clean it is.

Liquid water can be fresh, saline (salty), or a mix (brackish). Ninety-six percent of all water is saline and stored in **oceans**. Places like the ocean, where water is stored, are called **pools**. On land, saline water is stored in **saline lakes**, whereas fresh water is stored in liquid form in **freshwater lakes**, artificial **reservoirs**, **rivers**, **wetlands**, and in soil as **soil moisture**. Deeper underground, liquid water is stored as **groundwater** in aquifers, within the cracks and pores of rock. The solid, frozen form of water is stored in **ice sheets**, **glaciers**, and **snowpack** at high elevations or near the Earth's poles. Frozen water is also found in the soil as **permafrost**. Water vapor, the gaseous form of water, is stored as **atmospheric moisture** over the ocean and land.

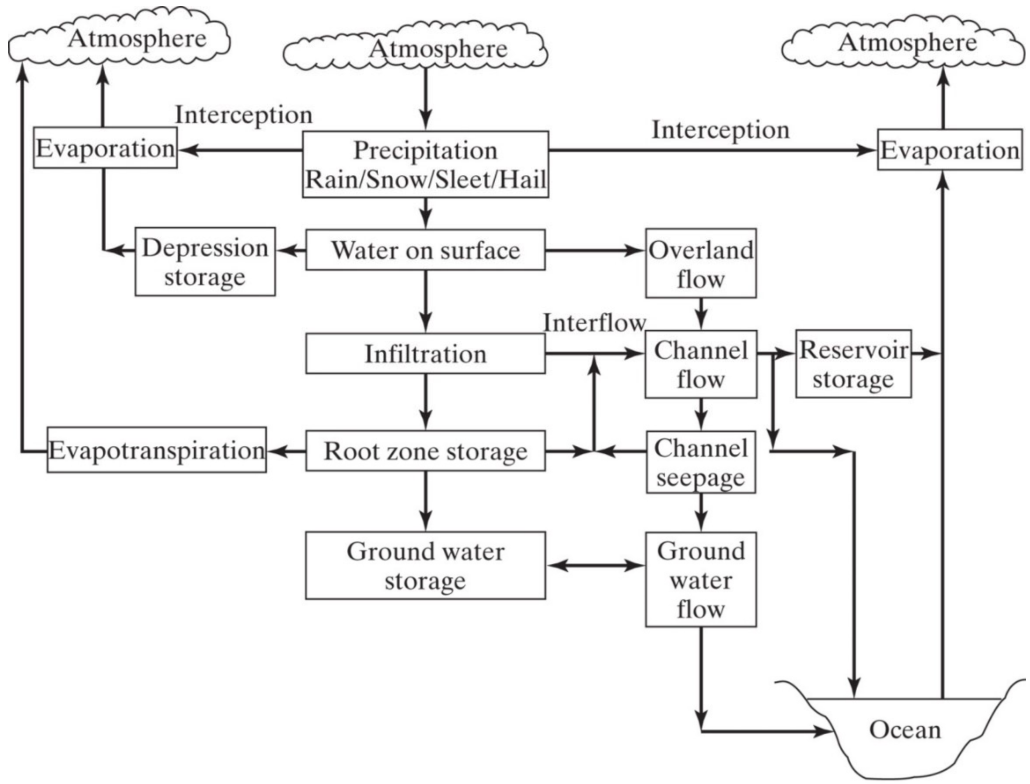
As it moves, water can transform into a liquid, a solid, or a gas. The different ways in which water moves between pools are known as **fluxes**. **Circulation** mixes water in the oceans and transports water vapor in the atmosphere. Water moves between the atmosphere and the Earth's surface through **evaporation**, **evapotranspiration**, and **precipitation**. Water moves across the land surface through **snowmelt**, **runoff**, and **streamflow**. Through infiltration and **groundwater recharge**, water moves into the ground. When underground, groundwater flows within aquifers and can return to the surface through **springs** or from natural **groundwater discharge** into rivers and oceans.

Humans alter the water cycle. We redirect rivers, build dams to store water, and drain water from wetlands for development. We use water from rivers, lakes, reservoirs, and groundwater aquifers. We use that water (1) to supply our **homes** and **communities**; (2) for **agricultural** irrigation and **grazing** livestock; and (3) in **industrial** activities like thermoelectric power generation, mining, and aquaculture. The amount of available water depends on how much water is in each pool (water quantity). Water availability also depends on when and how fast water moves (water timing), how much water is used (water use), and how clean the water is (water quality).

Human activities affect **water quality**. In agricultural and urban areas, irrigation and precipitation wash fertilizers and pesticides into rivers and groundwater. Power plants and factories return heated and contaminated water to rivers. Runoff carries chemicals, sediment, and sewage into rivers and lakes. Downstream from these types of sources, contaminated water can cause harmful algal blooms, spread diseases, and harm habitats. **Climate change** is also affecting the water cycle. It affects water quality, quantity, timing, and use. Climate change is also causing ocean acidification, sea level rise, and extreme weather. Understanding these impacts can allow progress toward sustainable water use.

USGS (2022), https://www.usgs.gov/media/images/water-cycle-png

The hydrological cycle



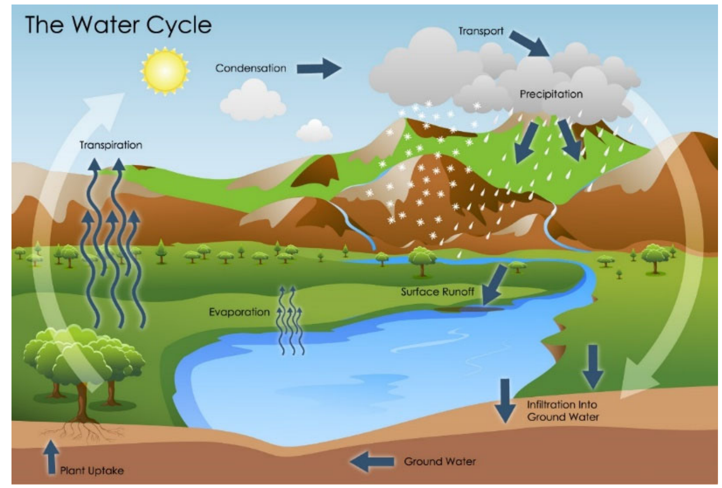
To think about (previous slide and this slide):

- **Scale effects**: processes occur at small (microscopic), medium (watershed to river basin), and large (continental to global) scales
- **Human interactions** with the hydrological cycle

Fig. 1-1b in Bedient et al. (2019)

3. WATERSHEDS

- Watershed concept is fundamentally important:
  1. Characteristics of watersheds – e.g. geology, soils, topography, and land use – determine the **magnitude, timing, and quality** of water flows over or under the surface (Dingman, 2015)
  2. Hydrologists are concerned with the **amount of surface runoff** generated by a given rainfall pattern. They can generate predictive relationships for streamflows by using historical data and information on watershed characteristics (Ponce, 1989)



https://www.bcwater.org/about-our-water/the-water-cycle/

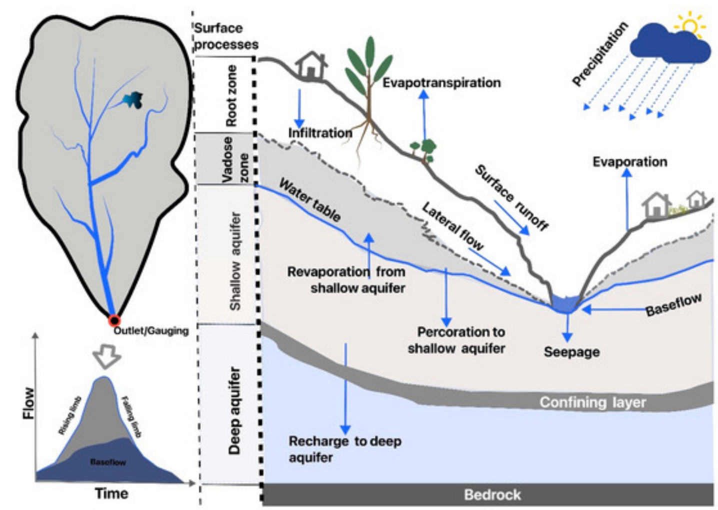


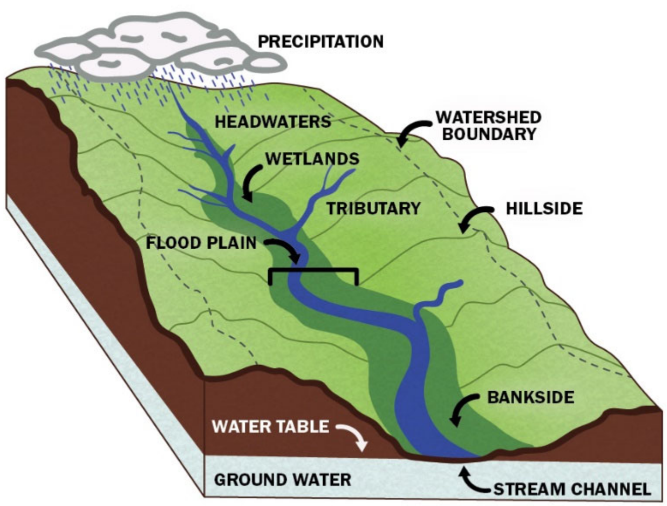
Fig. 1 in Yifru et al. (2024), *Sustainability* 16(4), 1376

Watersheds

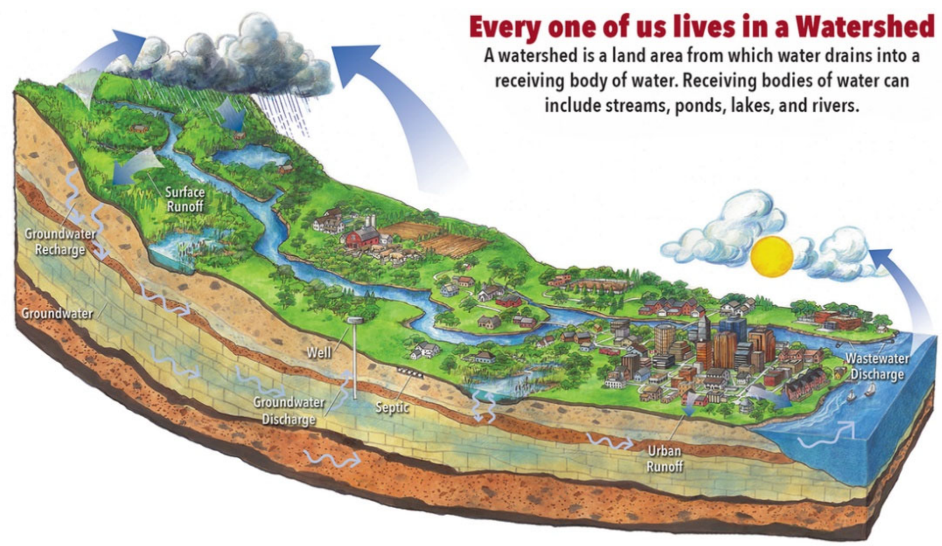
- **Definition One:** A "**watershed**" is,

  *"… a **contiguous area that drains to an outlet**, such that precipitation that falls within the watershed runs off through that single outlet"* (Bedient et al., 2019: 35)

  *(Note: related terms are "**basin**", which is large (multiple catchments and watersheds: S. Sask., Mississippi), while "**watershed**" is typically smaller (streams), and "**catchment**", which is the surface portion of the watershed)*



https://littleconestoga.org/our-watershed/what-is-a-watershed/



https://www.lacrosseareawaters.org/resources/what-is-a-watershed/

Watershed terminology

- **Watershed boundary:** also called **ridge line**, or **watershed divide.** It separates adjacent watersheds, which drain to different outlets
- **Outlet:** furthest **downstream** point
- **Tributary:** drains small watershed, catchment, or subbasin, to larger watershed
- **Confluence:** a point where a tributary meets the main stream
- **Headwater:** source of a stream
- **Drainage area:** the horizontal projection of the watershed

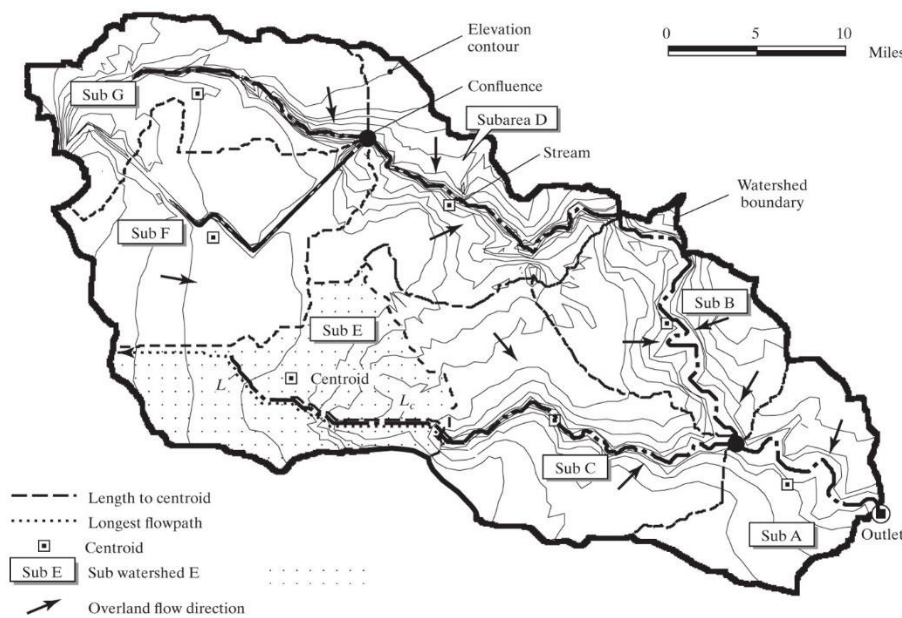


Fig. 1-19b in Bedient et al. (2019)

Watershed terminology

- Aside: Streams versus rivers?
  - A "stream" forms as water in an area collects and moves downhill in a continuous flow. Streams connect, grow larger, and at some point become a "river"
    - **Stream**: smaller, possibly temporary and often a tributary
    - **River**: larger, and a main watercourse leading to larger waterbody

https://education.nationalgeographic.org/resource/stream/

https://thecanadianencyclopedia.ca/en/article/athabasca-river

Major river basins in Canada

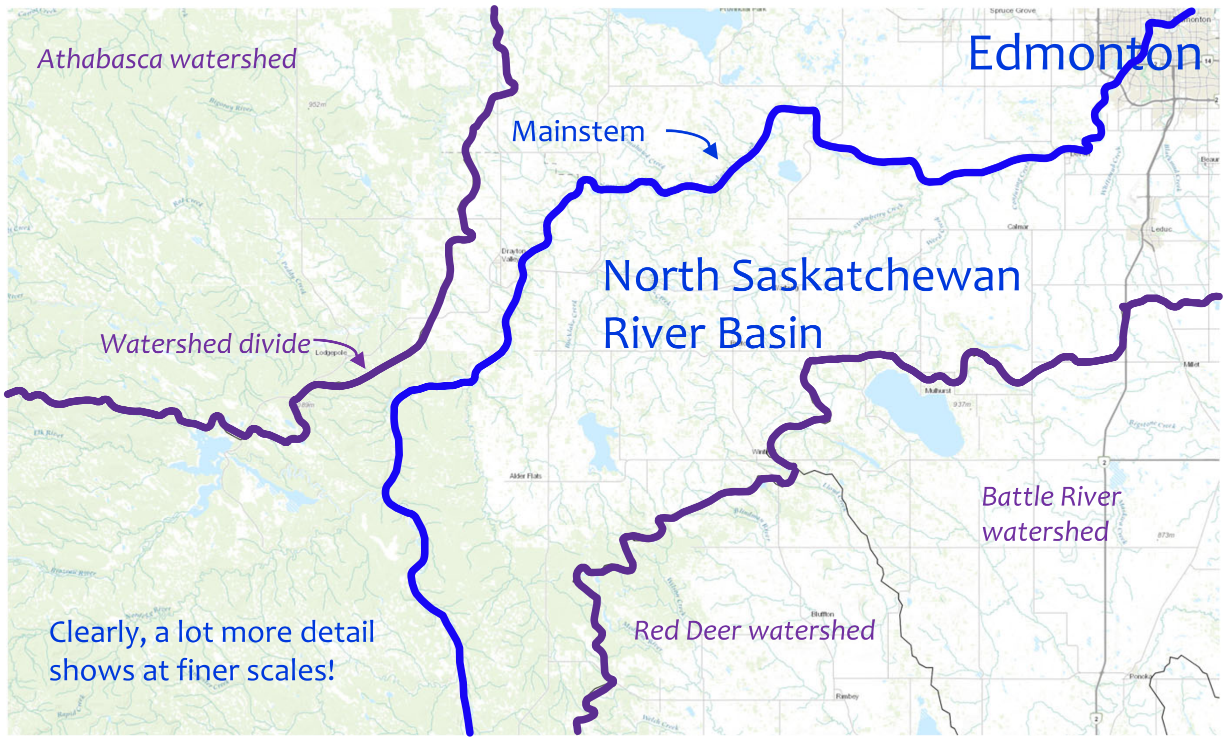
Source(s): Pearse, P.H., F. Bertrand and J.W. MacLaren, 1985, *Currents of Change: Final Report of the Inquiry on Federal Water Policy*, Environment Canada, Ottawa.
Statistics Canada, Environment Accounts and Statistics Division.

(Source: https://en.wikipedia.org/wiki/List_of_rivers_of_Canada)

Alberta watersheds

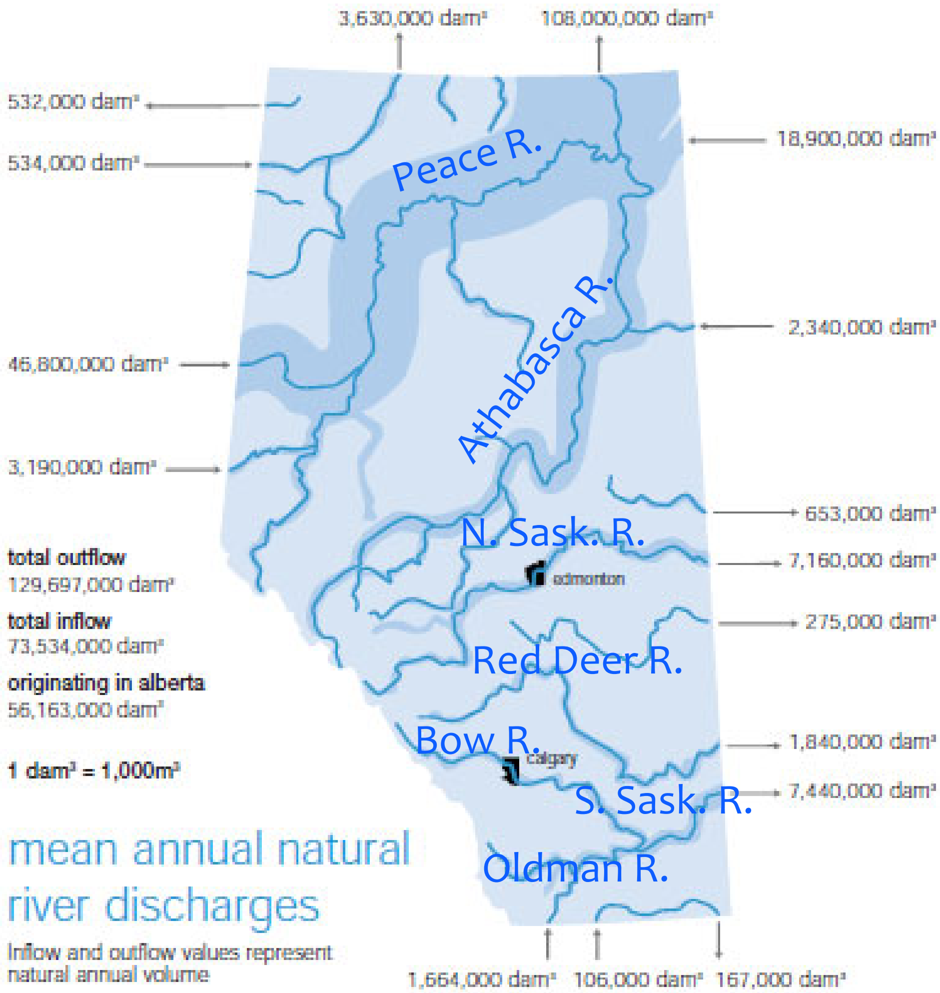
A comprehensive collection of Alberta watershed maps and information is available from https://waterportal.ca/water-maps/

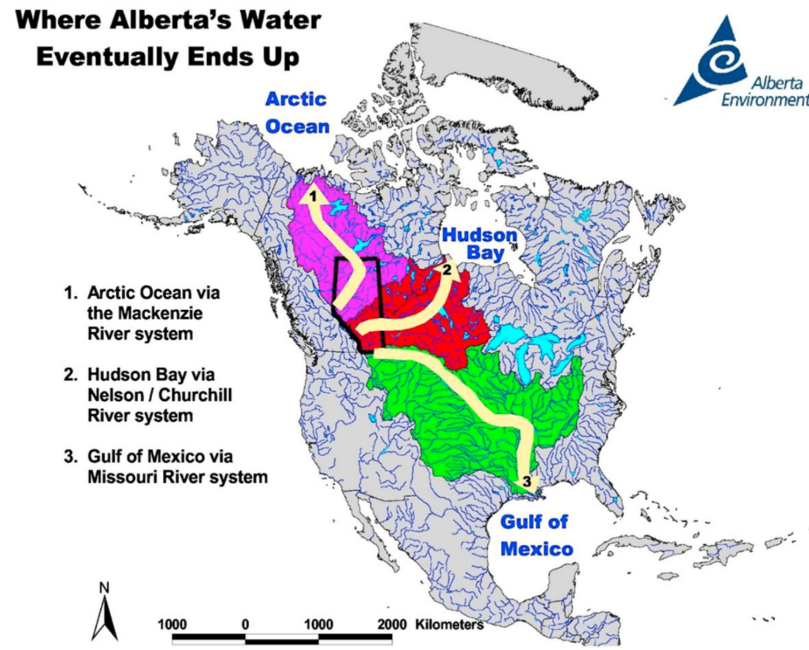
Our Watershed: The North Saskatchewan



These maps are from https://rivers.alberta.ca/

Alberta watersheds

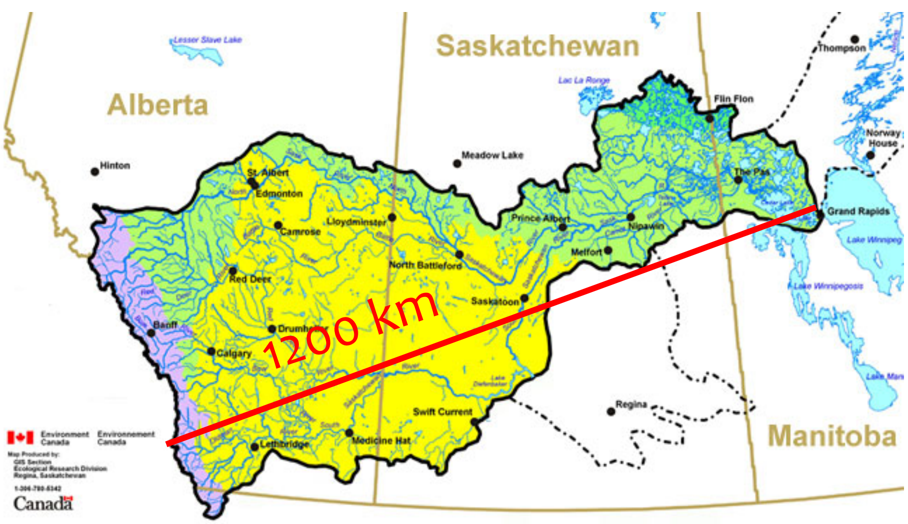


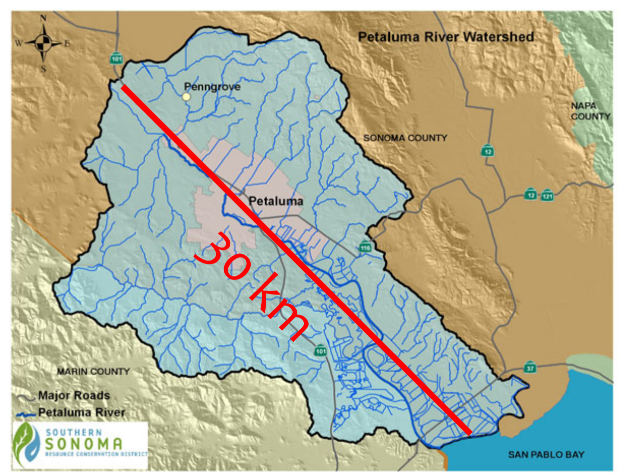


Govt. of Alberta (2002), "Water for Life: Facts and Info"

WATERSHED CHARACTERISTICS

- *What does a watershed look like, and what are some defining characteristics?*
  - Watersheds can be small (*a few hectares in urban areas*)
    - Runoff controlled by overland (“sheet”) flow processes
  - Watersheds can be huge (1000s of km^2: Mississippi, Amazon, Nile, Yagtze, St Lawrence, North Saskatchewan)
    - Runoff controlled by storage processes in river channel



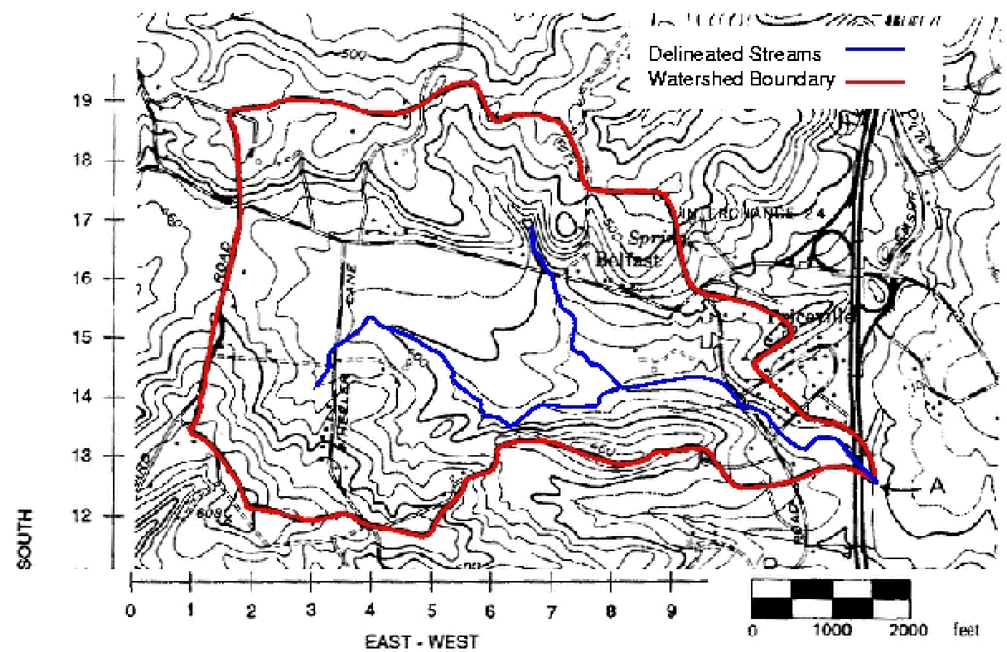


http://www.sonomarcd.org/watershed-petaluma-river.php

Ponce (1989)

Watershed characteristics

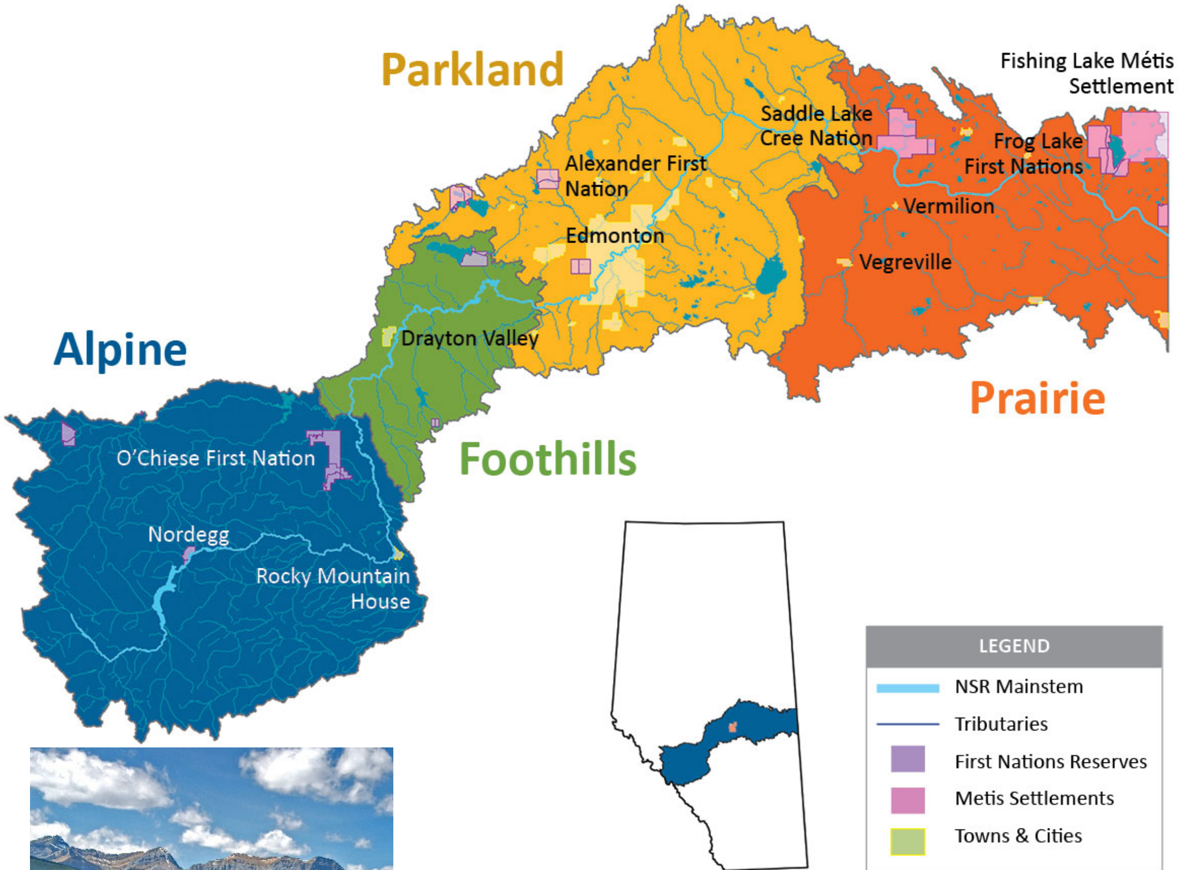
- *There is an infinite variety of watersheds!* So, hydrological characteristics of watersheds are described in terms of the following general properties:
    1. Area
    2. Shape
    3. Relief
    4. Linear measures
    5. Drainage patterns



http://www.utdallas.edu/~brikowi/Teaching/Applied_Modeling/SurfaceWater/LectureNotes/Watershed_Dynamics/Watershed_Boundary.html

 Ponce (1989)

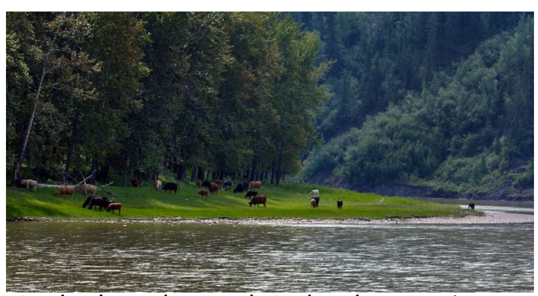
The North Saskatchewan River Watershed
River Reaches




The NSR through Edmonton by Clayton Reitzel


The Vermilion River meets the NSR
by Steve Ricketts


Crescent Falls at the head of the Bighorn Canyon by Derald Lobay

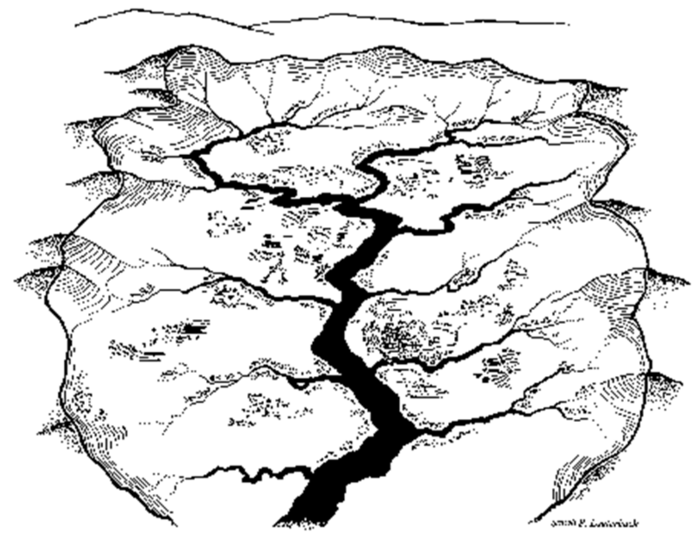

Cattle along the North Saskatchewan River by Robert Burkholder

Source: https://www.nswa.ab.ca/explore

i. Watershed area

- ***Area*** is perhaps the most important watershed property
  - Determines the *potential runoff volume*

- ***Watershed divide*** ("ridge line") separates adjacent watersheds, which *drain to different outlets*
  - Topographical divide usually drawn on maps
  - Map shows high points and contours of constant elevation to determine surface runoff direction
  - *Area encompassed by **divide** is the **watershed**!*



http://www.cleanwateroxford.org/watershed.htm

Ponce (1989)

i. Watershed area

- Runoff begins at higher elevations and moves to lower elevations, *perpendicular to contours (effect of gravity)*
- In general, the larger the watershed, the greater the surface runoff, the greater the overland flow rate, and the greater the streamflow rate

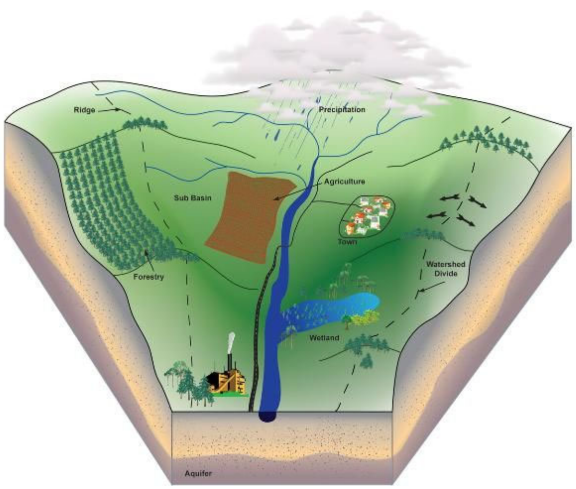
- Simple (imperfect!) calculation for **runoff:** $Q_p = cA^n$
  - Where Q_p = peak flow, *A* = watershed area, and c and *n* are parameters found through regression analysis → *more on such equations later*
- Note: because of subsurface flow (groundwater), the *hydrological watershed divide* may not perfectly coincide with the *topographical divide*

Bedient et al. (2019)

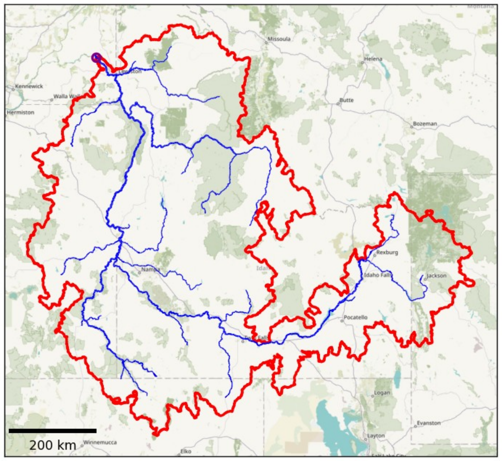
i. Watershed area

- To identify watershed **area**: delineate *topographical divide* on USGS "quadrangle" map or other suitable topographical map
  - "Watershed delineation" is the process of identifying and mapping the boundary of a watershed

- Two approaches: **manual** and **digital** delineation



G. Means, https://edis.ifas.ufl.edu/publication/SS568

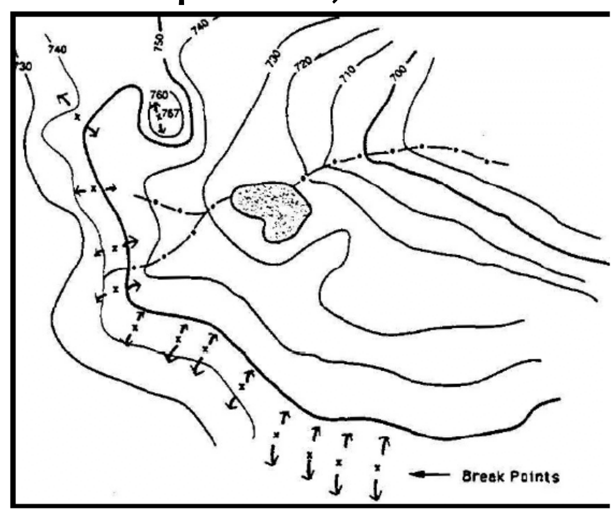


M. Heberger, https://mghydro.com/

Ponce (1989)

i. Watershed area

- **Manual delineation**
  - Although digital methods are much more common, understanding process of manual delineation provides insight into watershed concept
- Process:
  1. Identify and *mark highest points* first, based on contours → called "break points"
  2. Draw *overland flow directions* from the break points, perpendicular to contours
  3. Connect the break point markings
  - ***Area enclosed within the connected break points – at the topographical divide – is the watershed area!***



http://www.uri.edu/smile/documents/maine_appD watershed-delineate-1.pdf

Ponce (1989); Maine Dept. of Env. Protection

i. Watershed area

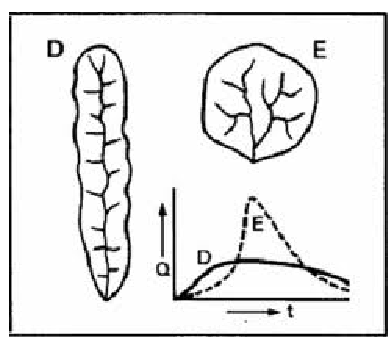
- **Digital delineation**
  - Based on **digital elevation models** (DEMs), or computer data files that give land-surface elevations at grid points. These are typically from radar reflections collected by satellite
  - Some web-based services that provide automated watershed delineation:
    - Hydrological Data and Maps Based on Shuttle Elevation Derivatives at Multiple Scales (HydroSHEDS): https://www.hydrosheds.org/
    - Canadian Lake and River Hydrofabric (CLRH): https://hydrology.uwaterloo.ca/CLRH/Hydrofabric.html
    - U.S. Geological Survey (USGS) StreamStats: http://water.usgs.gov/osw/streamstats

ii. Watershed shape

- The outline described by horizontal projection of watershed:
  - “Normal shape” is a “*pear-shaped ovoid*”
  - Large watersheds vary widely in shape

A watershed as a leaf

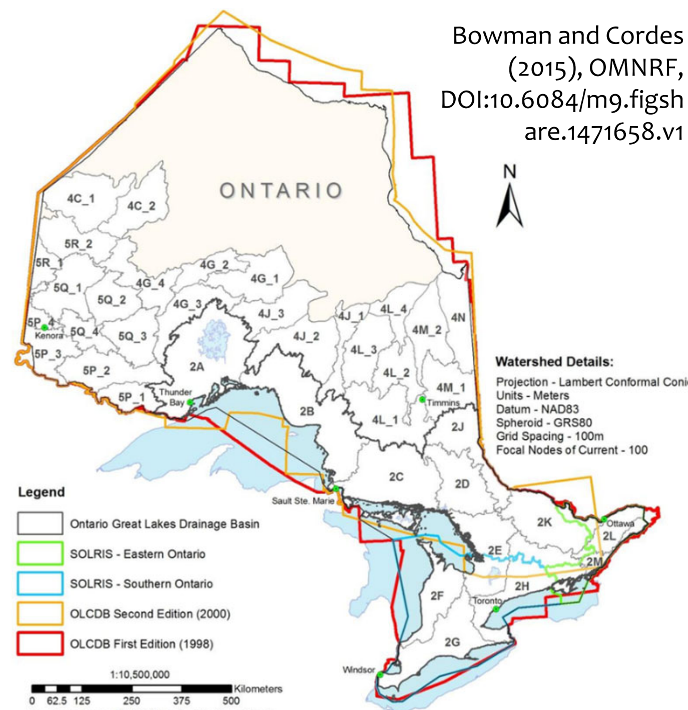
https://images.app.goo.gl/Bg8fsHhiwyLLZUyy8



Gregory and Walling (1973)

Ponce (1989)

Bowman and Cordes (2015), OMNRF, DOI:10.6084/m9.figshare.1471658.v1



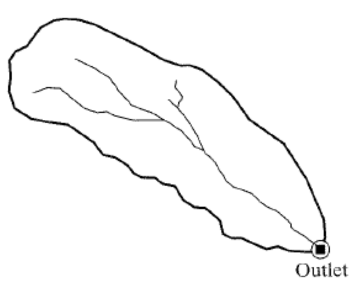
iii. Watershed relief

- **Watershed relief** is the elevation difference between two reference points in a watershed
  - **Maximum relief** is the difference between the highest point on watershed divide and the outlet
  - Longitudinal profile of main channel is plot of elevation vs. horizontal distance → indicator of channel slope, or channel gradient
    - Most rivers and streams have decreasing gradient moving downstream (e.g. 10% gradient in mountains, and 0.01% at coast)
    - Channel gradient of principal watercourse is a convenient measure of watershed relief

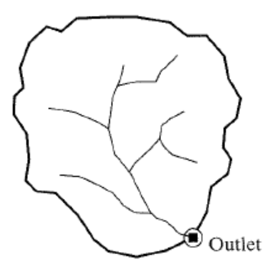
Bedient et al. (2019); Ponce (1989)

iv. Linear measures

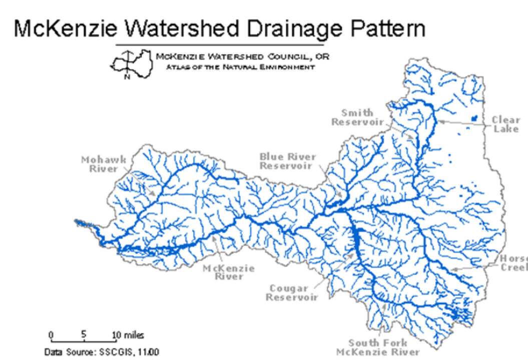
- Used to describe one-dimensional features
  - E.g. for small watersheds, the overland flow length is the distance surface runoff flows that is not confined to a clearly defined channel
- *“**Hydraulic length**” is the length measured along the principal watercourse*
  - Principal watercourse is the central and largest watercourse of the watershed



1. Elongated shape



2. Concentrated shape

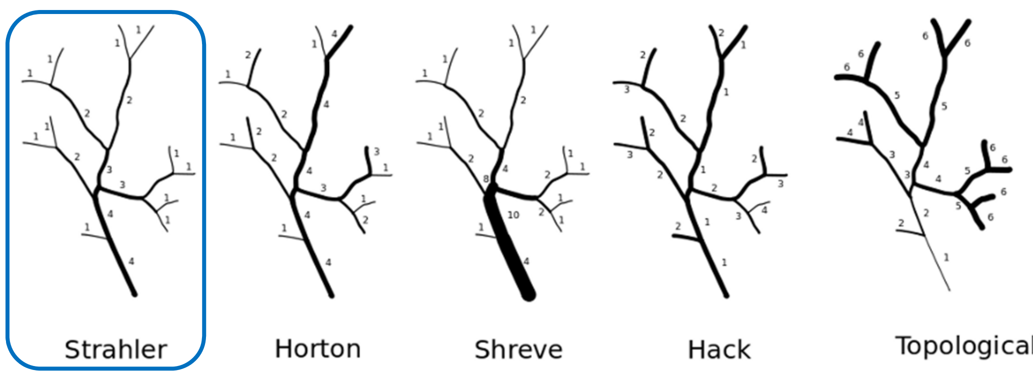


http://www.mckenziewc.org/mckenzieatlas/drainage_map.htm

Ponce (1989)

v. Stream order

- Stream order concept is essential to hierarchical description of streams in a watershed
  - **Overland flow** thought of as hypothetical stream of *zero-order*
  - **First-order** stream receives flow from these "zero order" streams
  - **Second-order** stream formed from combining two first-order streams
  - In general, two "m-order" streams combine to form *"m+1 order"* stream
  - ***The watershed's stream order is the order of the main stem***



http://svn.osgeo.org/grass/grass-addons/grass7/raster/r.stream.order/r.stream.order.html

Ponce (1989)

vi. Drainage patterns

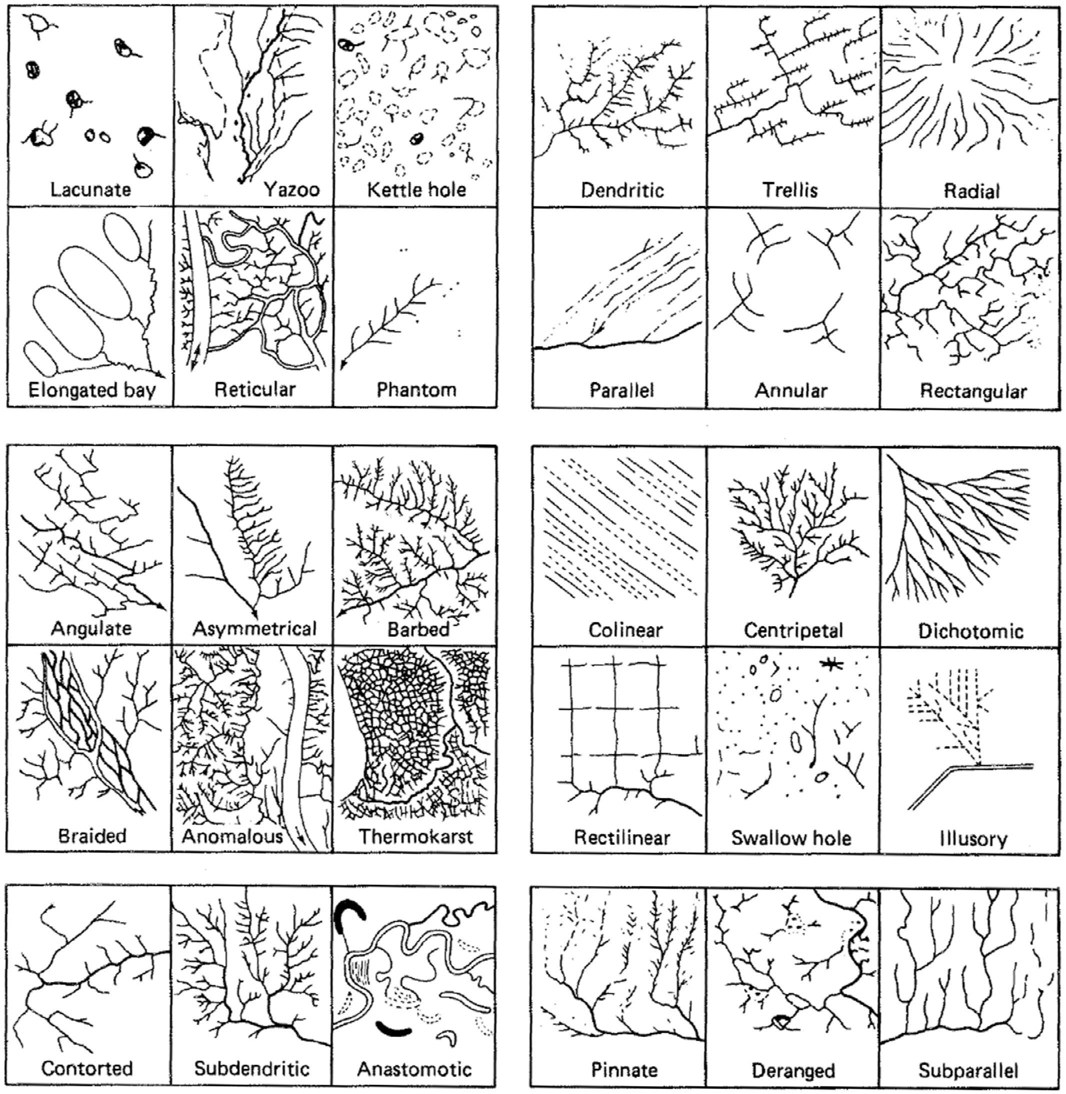
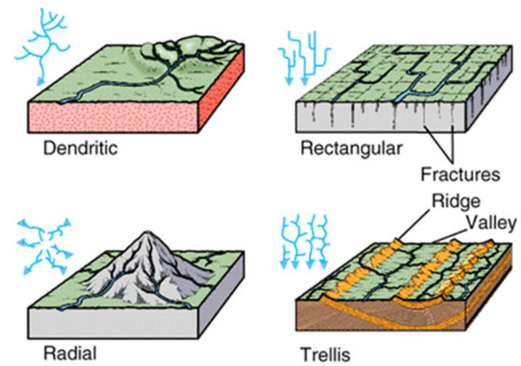


Figure 2-24. Drainage patterns recognizable on aerial photographs (By permission from "Photogrametric Engineering and Remote Sensing," copyright 1960, American Society of Photogrametry and Remote Sensing [27]).

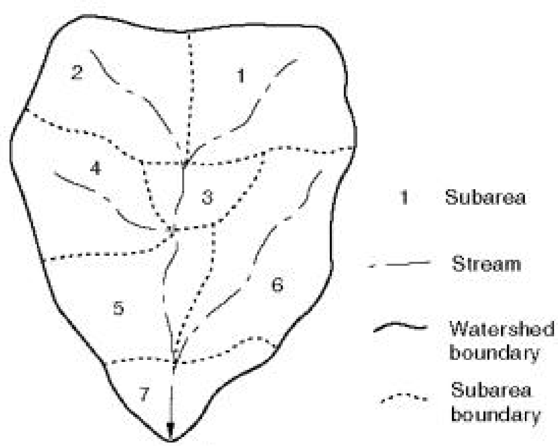


http://won.sdsu.edu/protected121/engineering_hydrology_101011_chapter_025.html

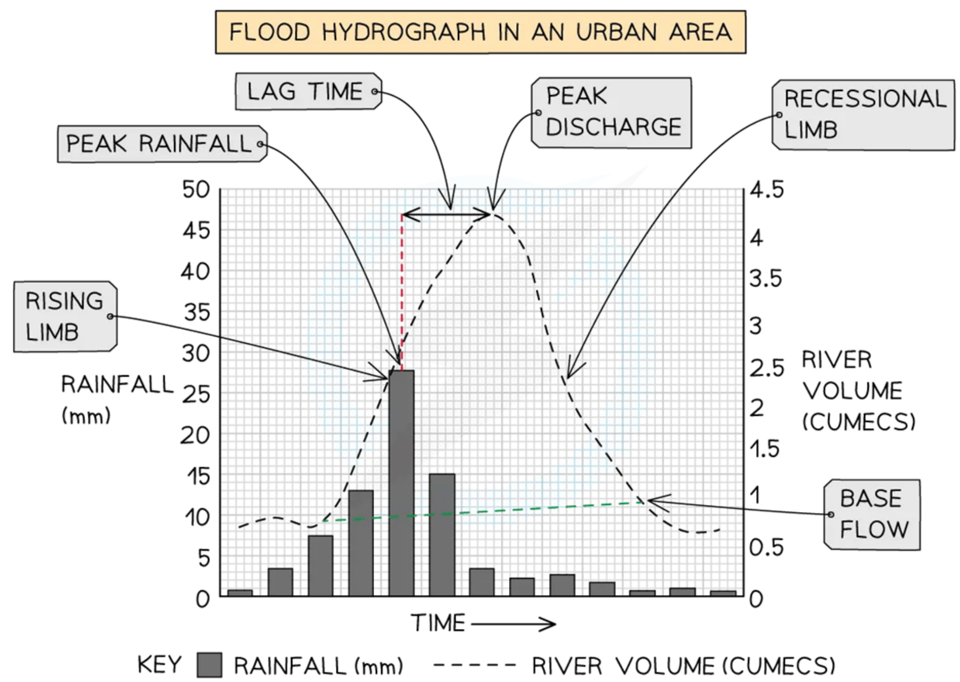
Fig. 2-24 in Ponce (1989)

4. WATERSHED RESPONSE AND WATER BALANCE

- Under well-defined conditions, we can calculate the **response** (*timing and concentration of **runoff***) of a watershed to *rainfall*, *infiltration* and *evaporation* with some simple assumptions…



http://unix.eng.ua.edu/~rpitt/Workshop/WSErorionControl/Module4/Module4.htm



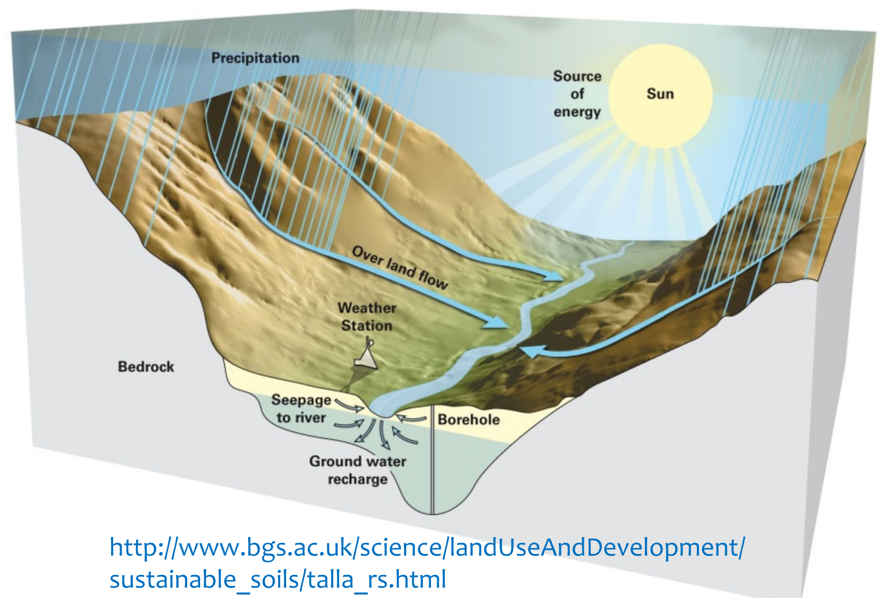
https://www.savemyexams.com/dp/geography/ib/17/hl/revision-notes/freshwater-drainage-basins/flooding-and-flood-mitigation/flood-hydrographs/

Bedient et al. (2019)

Watershed response

- Extreme examples of **watershed response:**
  - If rainfall rate over watershed area is less than rate of infiltration into soil and if soil can store lots more moisture,
    - *Direct runoff from surface, and resulting streamflow, is zero*
  - If previous rainfall has filled the soil storage, and rainfall rate is so large infiltration and evaporation can be ignored,
    - *Volume of surface runoff = volume of rainfall*

Bedient et al. (2019)



http://www.bgs.ac.uk/science/landUseAndDevelopment/sustainable_soils/talla_rs.html

Watershed response

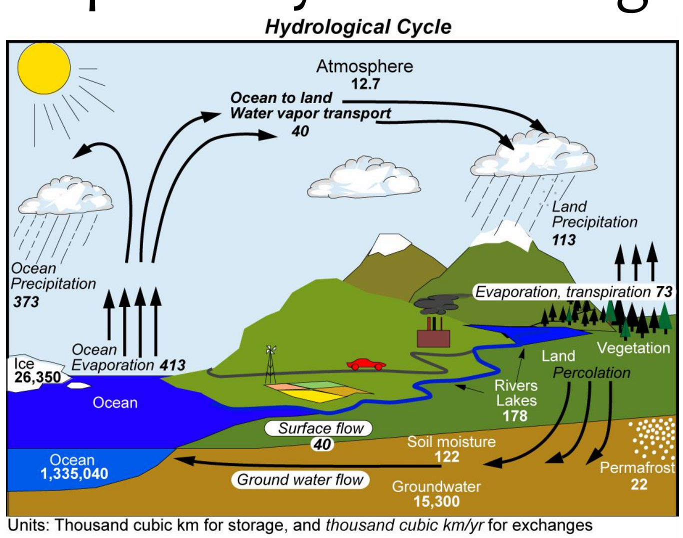
- Conditions usually lie between the two extremes…
  - So we must then measure or calculate more than one component of the cycle
  - And in these measurements and calculations,

Definition Two: *"The **watershed** is the basic hydrological unit within which all measurements, calculations and predictions are made…"*

Bedient et al. (2019: 36)

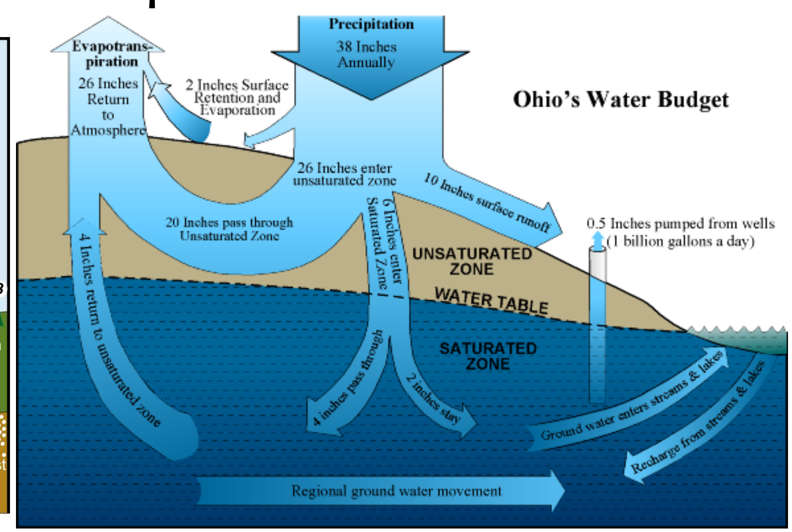
The water balance

- Complication: movement of water through the components of the hydrological cycle varies greatly in space and time
  - Hence the extremes of **flood** and **drought**
  - Magnitude and frequency of occurrence of both important to **engineering hydrologist** for both design and operations purposes
- To help understand watershed response, we can develop a **water budget** for any hydrological system to represent and quantify flow pathways and storage components



Bedient et al. (2019)

http://www.met.reading.ac.uk/~sgs02rpa/latest.html



http://www.dnr.state.oh.us/tabid/4101/default.aspx

Water budgets

- Simplest case of a water budget is given by the *hydrological continuity equation*,

$$I - Q = \frac{dS}{dt}$$

  - Where,
    - I = Inflow in volume/time
    - Q = Outflow in volume/time
    - dS/dt = Change in storage, in volume/time
  - *Note: We ignore E, I (infiltration), G, and T here*

Bedient et al. (2019)

Water budget example

- A simple example is a **parking lot** with a slight slope and one outlet. If it rains over a fairly long period of time,

Order of Events

  - Rainfall **accumulates** on the parking lot surface
  - Thus, **surface detention**, or storage, increases slowly
  - This stored water begins to flow downslope to the outlet

Result

  - *All input rainfall → outflow from area, with a slight delay*

Bedient et al. (2019)

Watershed water balance

- For small basins and large watersheds, add other hydrological cycle components,

$$P - R - G - E - T = \Delta S$$

  – Where,

Inflow

- P = precipitation

Outflows

- R = surface runoff
- G = groundwater flow
- E = evaporation
- T = transpiration
- ΔS = change in storage over a specified time period
- *Infiltration (I) cancels: loss from surface = addition to groundwater*

Recall simpler version:

$$I - Q = \frac{dS}{dt}$$

  – All terms are expressed in units of **DEPTH** (mm)

Bedient et al. (2019)

Common units in hydrology

- Hydrologists use two sets of units:
  - **Depth rates** (mm/day or in/day):
    - Used for rainfall, evaporation, infiltration, snowfall, and other surface or atmospheric exchanges
    - Represents a water volume distributed over a "unit area" of the watershed (m^2 or ft^2)
  - **Volume rates** (m^3/s or ft^3/s):
    - Primarily used for streamflow or river "discharge"
    - Represents the total volume of water passing a specific point per unit of time

- We can convert between these sets of units

Water balance calculations

- Multiplying previous depth terms *(P, R, G…)* by a surface area gives **volumes of water,**

$$Volume = (flow\ rate)(time) = (depth)(watershed\ area)$$

- To convert from a flow to a **change in depth,** rearrange and add a conversion factor,

$$depth = \frac{(flow\ rate)(time)(conversion\ factor)}{watershed\ area}$$

  - Conversion factors include (days/month), (hours/day), (m^2/hectare)

Bedient et al. (2019)

Example: Water balance in a basin

The Yukon River basin has area of 932,400 km2, average annual precipitation of 570 mm/yr, and average streamflow of 5,100 m3/s. Assume there are no groundwater inputs or outputs. Compute the long-term average evapotranspiration, in mm/yr, for this basin.

Example: Water balance in a lake

For a given month, a 120 hectare lake has 425 L/s of inflow, 368 L/s of outflow, and a total storage increase of 19.4 dam^3. A precipitation gauge next to the lake recorded a total of 33 mm of rain for the lake for the month. Assuming that infiltration loss is insignificant for the lake, determine the evaporation loss, in mm, over the lake for the month.

Adapted from Example 1-4 in Bedient et al. (2019)