Hydrology

Hydrology

- Hydrology and its issues
- Water sources and hydrological cycle
- Water budget
- Surface water topics: Watershed, hydrograph, runoff coefficient
- Low impact development
- Groundwater hydrology
  - Terminologies
  - Darcy's law and groundwater velocity

Hydrology

- Definition

  A multidisciplinary subject that deals with the question of how much water can be expected at any particular time and location

- Application of hydrology
  - ensure adequate water supply for drinking, irrigation, industrial uses, etc.
  - prevent flooding

Issues of hydrology

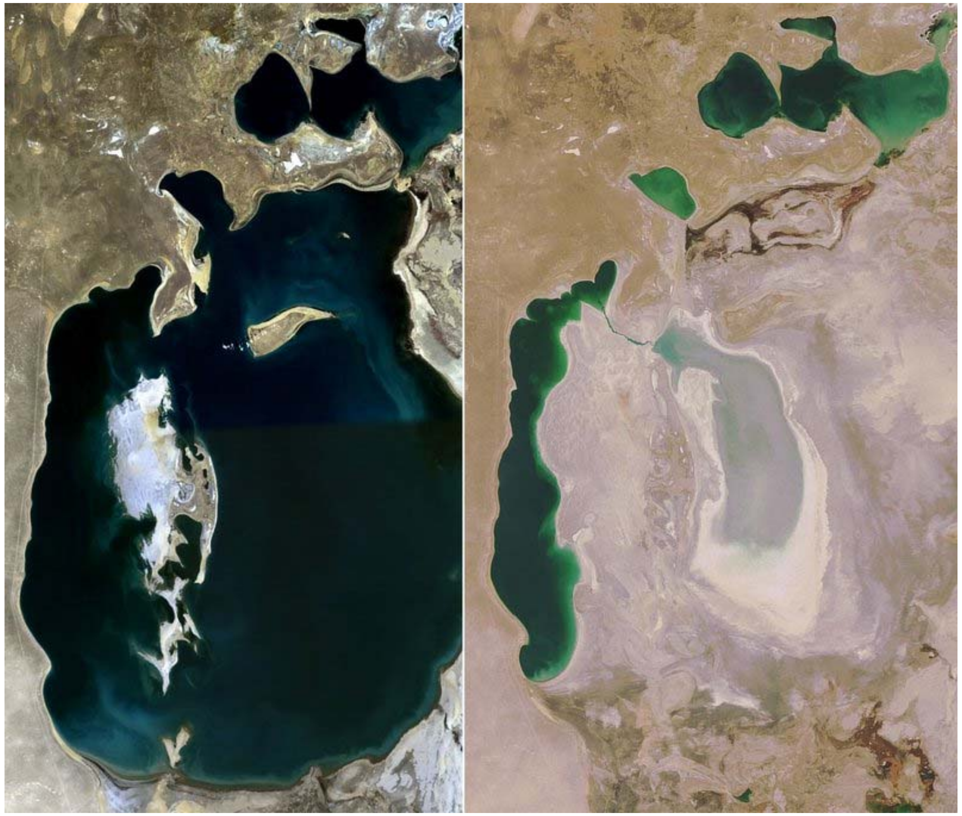
- Flood and droughts

Issues of hydrology

- Climate change

Issues of hydrology

- Water use sustainability



Aral Sea, Kazakhstan & Uzbekistan, change from 1989 to 2008

Particularly significant

- For dry regions
- In regions with high water demand (high population, significant agricultural activities, etc.)
- Rely on water resources with long residence time
- Rely on water resources shared by multiple countries

Issues of hydrology

- Water use sustainability

Land subsidence due to groundwater pumping

Issues of hydrology

- Hot in Korea - sinkholes

Water balance and residence time

Table 1.1 Estimate of the Water Balance of the World

Parameter	Surface area $(km^2) \times 10^6$	Volume $(km^3) \times 10^6$	Volume (%)	Equivalent depth (m)*	Residence time
Oceans and seas	361	1370	94	2500	~4000 years
Lakes and reservoirs	1.55	0.13	<0.01	0.25	~10 years
Swamps	<0.1	<0.01	<0.01	0.007	1–10 years
River channels	<0.1	<0.01	<0.01	0.003	~2 weeks
Soil moisture	130	0.07	<0.01	0.13	2 weeks–1 year
Groundwater	130	60	4	120	2 weeks–10,000 years
Icecaps and glaciers	17,8	30	2	60	10–1000 years
Atmospheric water	504	0.01	<0.01	0.025	~10 days
Biospheric water	<0.1	<0.01	<0.01	0.001	~1 week

SOURCE: Nace, 1971.

*Computed as though storage were uniformly distributed over the entire surface of the earth.

- Water useful for humans: i) lakes & reservoirs, ii) rivers, iii) (shallow) groundwater
- These waters constitute only a small fraction

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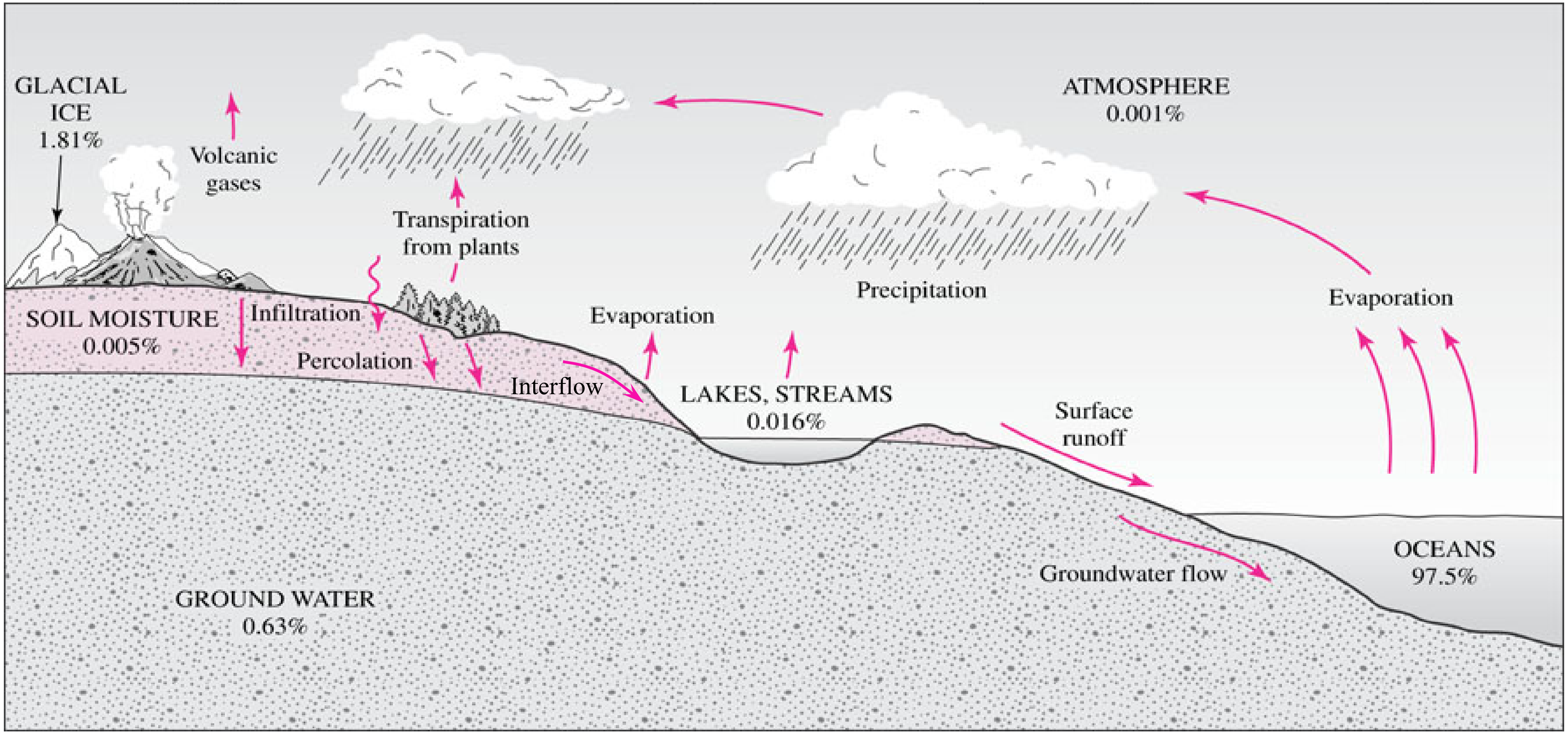
- Long residence time for groundwater – once depleted, it takes a long time to recover (effectively nonrenewable)
- Significant temporal and spatial variation of freshwater availability & water needs → dams, reservoirs, pipelines, etc. needed

Hydrological cycle



Processes in the hydrological cycle

- Earth’s surface → atmosphere
  - evaporation: conversion of liquid water from lakes, streams, and other bodies of water to water vapor
  - transpiration: the process by which water is emitted from plants through the stomata

    * evapotranspiration = evaporation + transpiration

- Earth’s atmosphere → surface
  - precipitation (rain+snow+hail+…)

Processes in the hydrological cycle

- Within Earth's surface
  - surface (direct) runoff: water running over the ground into streams and rivers
  - interflow: portion of precipitation that infiltrates into the soil and moves horizontally through the shallow soil horizon without ever reaching the water table
  - infiltration (percolation): vertical movement of water from the surface into the soil

Water budget

- Water budget: mass balance for water

  (rate of accumulation) = (rate in) – (rate out)

$$\frac{\Delta S}{\Delta t} = \sum (rate\ \ in) - \sum (rate\ \ out)$$

$\Delta S/\Delta t$ = change in storage over time $[L^3/T]$

ex) For a lake: define the control volume as the lake itself

- possible "in" processes: flow of streams entering the lake, precipitation, runoff, seepage into the lake
- possible "out" processes: flow of streams exiting the lake, evapotranspiration, seepage out of the lake

$$\frac{\Delta S}{\Delta t} = (Q_{in} + P + R + I_{in}) - (Q_{out} + E_T + I_{out})$$

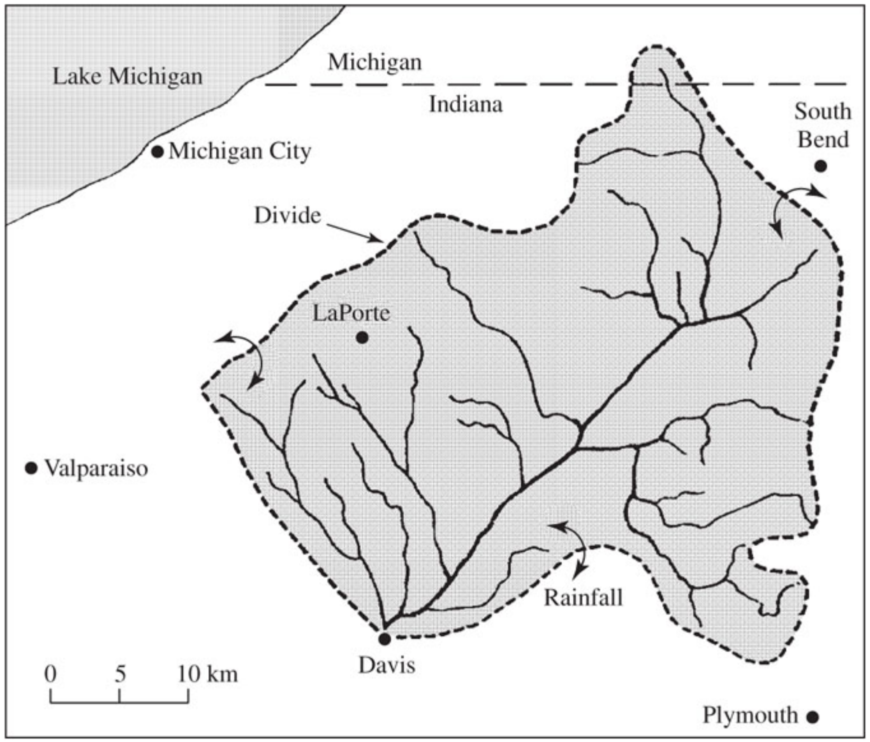
Water budget

Q: Sulis Lake has a surface area of 708,000 m^2. Okemos Brook flows into the lake at a flow rate of 1.5 m^3/s and the Tamesis River flows out of the lake at a flow rate of 1.25 m^3/s during the month of June. The evaporation rate was measured as 19.4 cm/month. Transpiration is ignored because there are few water plants. A total of 9.1 cm of precipitation fell this month. Seepage and runoff is negligible. The average depth in the lake at the beginning of the month was 19 m. Calculate the **average depth at the end of the month**.

Watershed

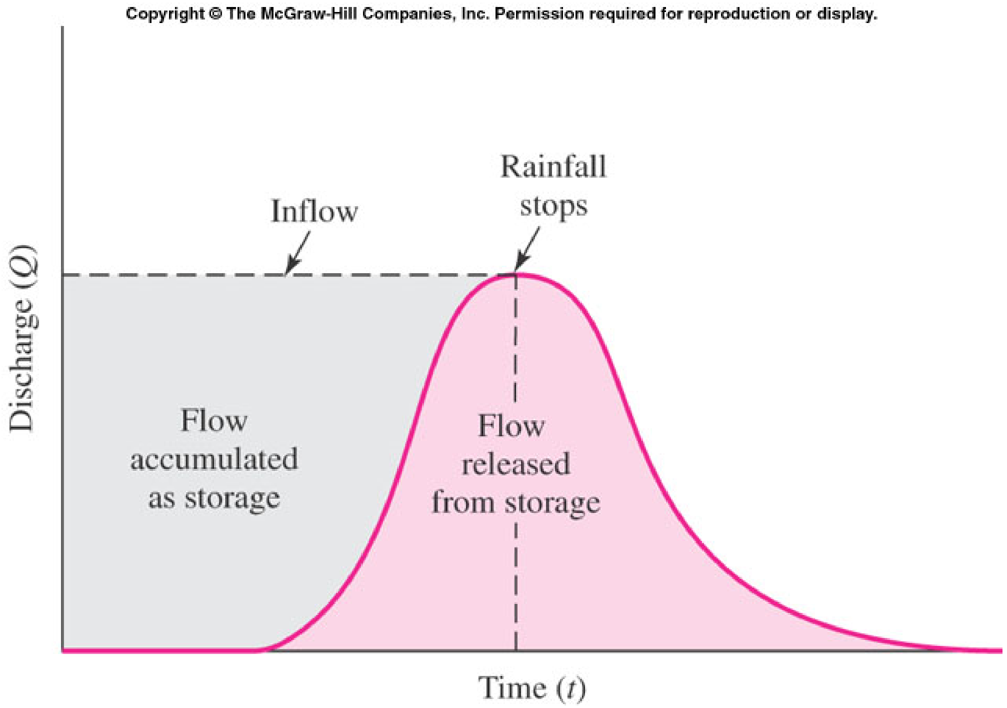
- **Watershed (basin)**: the area of land where all of the water that is under it or drains off of it goes to the same place

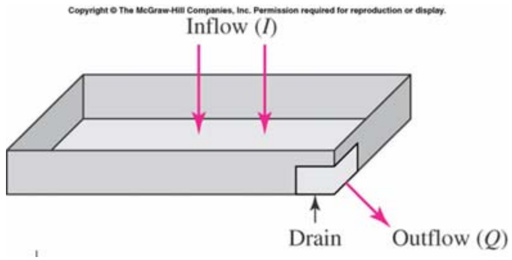
- **Divide**: the boundary of the watershed



Hydrograph

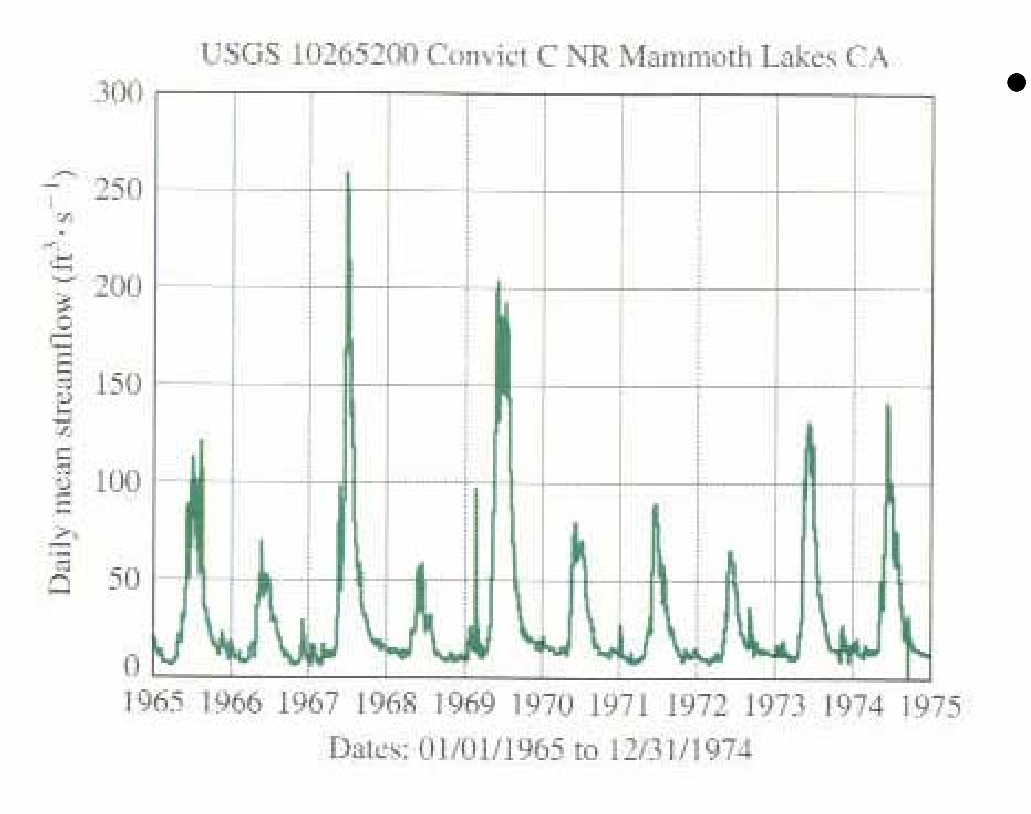
- A chart in which flow rate is plotted vs. time





An example hydrograph for a simple parking lot

Hydrograph



10-year hydrograph for a creek (example)

- The shape of the hydrograph is affected by various factors such as: precipitation, weather, topography of the watershed, density and type of ground cover, ...

Runoff coefficient

- Runoff coefficient

  = {rate of runoff (*R*)} / {rate of precipitation (*P*)}

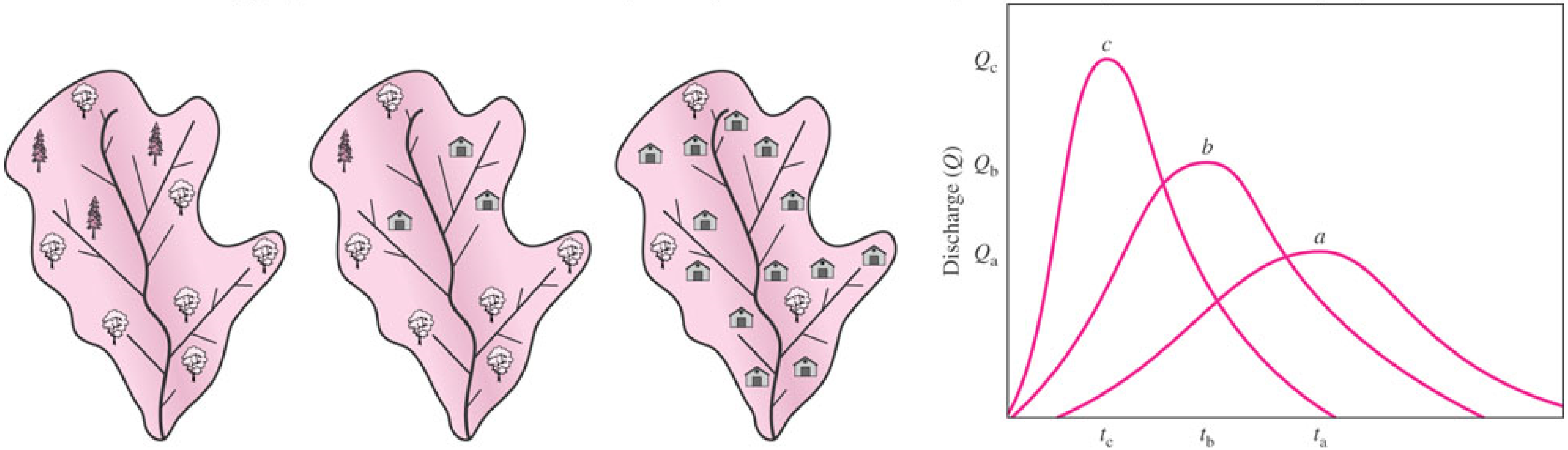
Typical Runoff Coefficients

Description of Area or Character of Surface	Runoff Coefficient	Description of Area or Character of Surface	Runoff Coefficient
Business		Railroad yard	0.20–0.35
Downtown	0.70–0.95	Natural grassy land	0.10–0.30
Neighborhood	0.50–0.70	Pavement	
Residential		Asphalt, concrete	0.70–0.95
Single-family	0.30–0.50	Brick	0.70–0.85
Multi-units, detached	0.40–0.60	Roofs	0.75–0.95
Multi-units, attached	0.60–0.75	Lawns, sandy soil	
Residential, suburban	0.25–0.40	Flat (<2%)	0.05–0.10
Apartment	0.50–0.70	Average (2–7%)	0.10–0.15
Industrial		Steep (>7%)	0.15–0.20
Light	0.50–0.80	Lawns, heavy soil	
Heavy	0.60–0.90	Flat (<2%)	0.13–0.17
Parks, cemeteries	0.10–0.25	Average (2–7%)	0.18–0.22
Playgrounds	0.20–0.35	Steep (>7%)	0.25–0.35

Source: Joint Committee of the American Society of Civil Engineers and the Water Pollution Control Federation, 1969.

The more developed, the bigger runoff coefficient

Runoff coefficient



(a) Undeveloped (b) Partially developed (c) Fully developed

$Q_c > Q_b > Q_a$, $t_c < t_b < t_a$

- Urban & industrial development increases the impact of flood

Runoff coefficient

Q: A watershed with an area of 4530 km^2 received 77.7 cm of precipitation in 2013. The average rate of flow measured in a river which drained the watershed was 39.6 m^3/s. Infiltration occurred at an average rate of 9.2×10^{-7} cm/s and evapotranspiration was estimated to be 45 cm/year. What was the change in storage in the watershed in 2013? What was the runoff coefficient?

Low impact development (LID)

- A developing area of study and practice
- A land planning and engineering design approach to minimize the hydrological impact of urban development
- Some effect on the treatment of stormwater pollutants is also expected

An LID project in Seattle, USA
(*http://www.mapc.org*)

LID practices

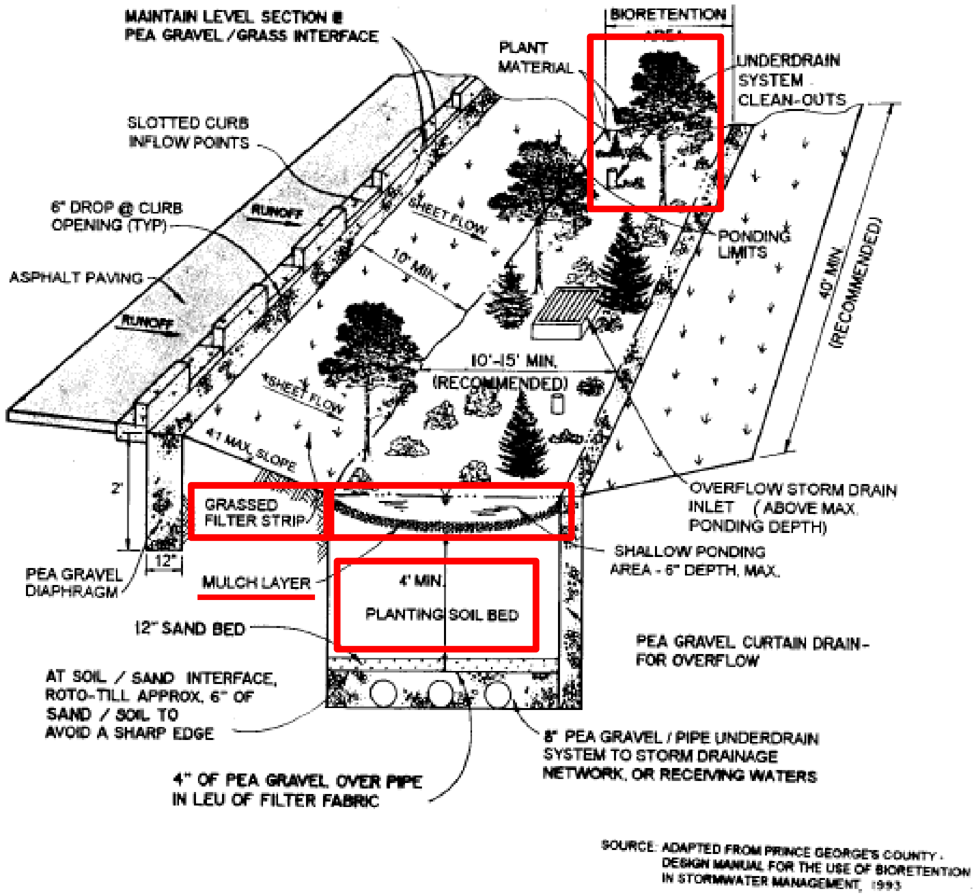
- Bioretention zone

Grass buffer strips: reduce the velocity of runoff, filter particulate matter

Plants: take up nutrients, transpiration

Organic layer: support microbial growth (organic material degradation), sorb pollutants

Planting soil: water retention, sorb pollutants



http://www.georgiastormwater.com

LID practices

- Green roofs

LID practices

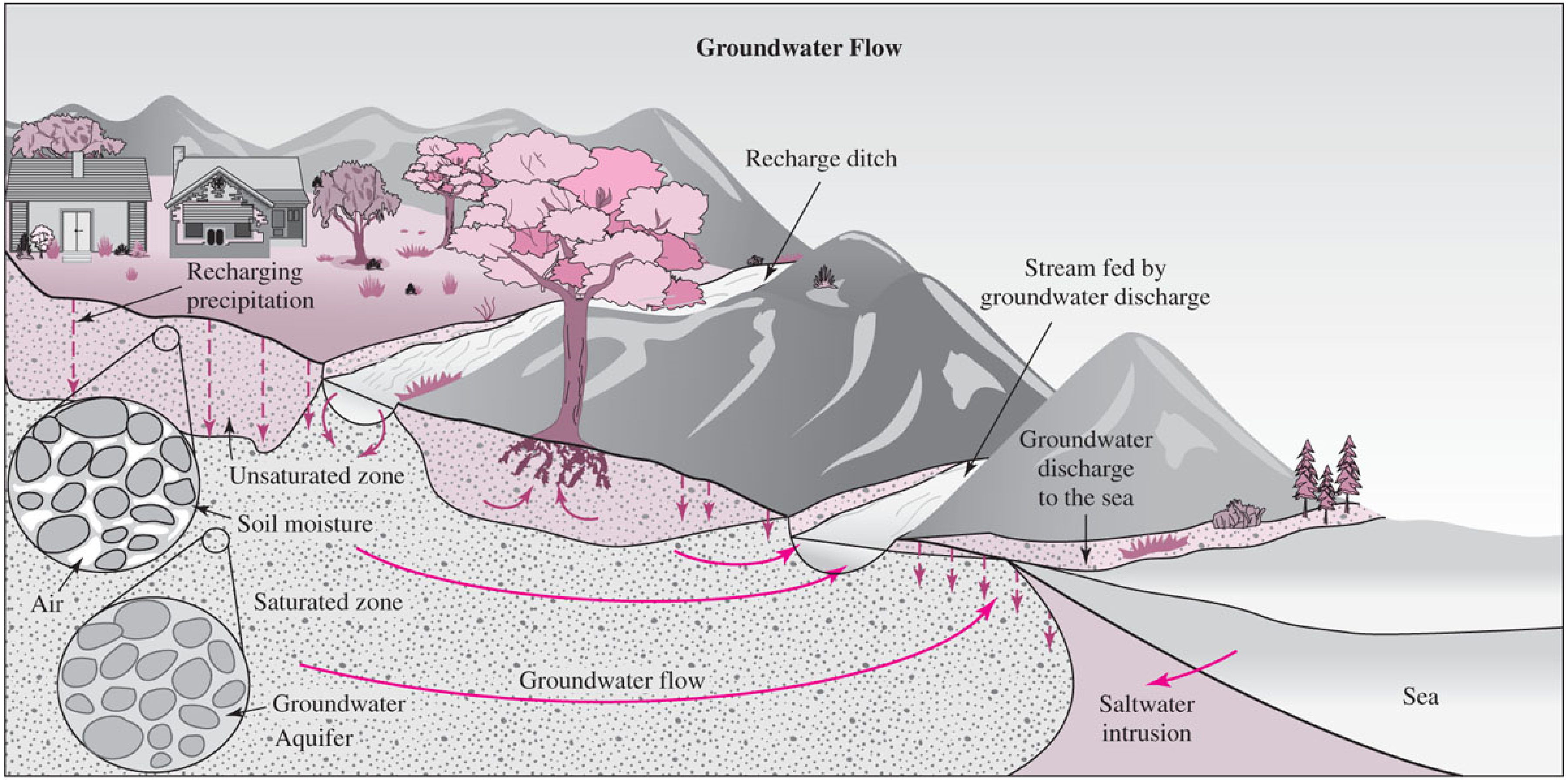
- Permeable pavements
  - sidewalks, bike roads, parking lots

- Grass swales and channels
  - Redirect runoff from stormwater drains

- Rain barrels, cisterns
  - Collection of stormwater and use for irrigation / toilet flushing

Grass swale in Ottawa, Canada
(*http://www.ottawa.ca*)

Groundwater hydrology

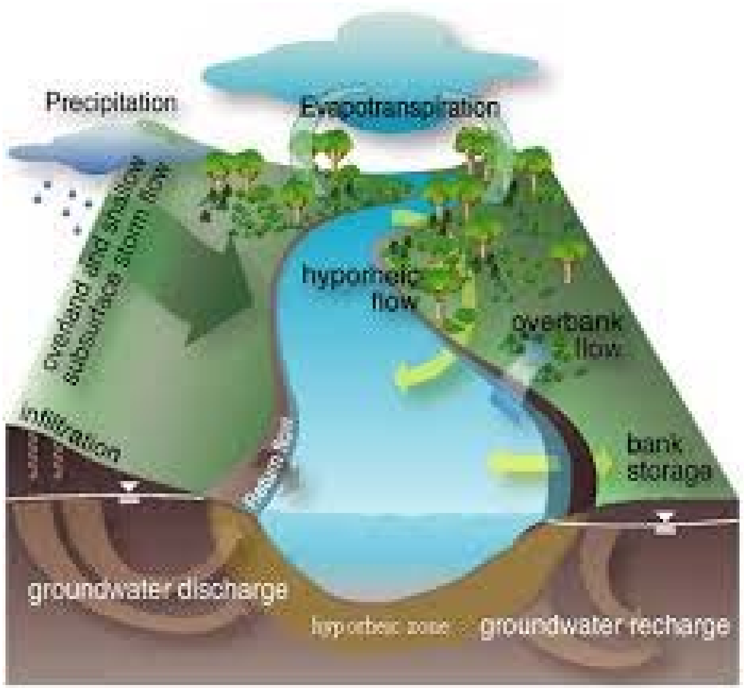


Groundwater hydrology

- Unsaturated zone (vadose zone): the voids in the soils are partially filled with water (the remaining portion is filled with air)
- Saturated zone: all voids in the soils are filled with water
- Groundwater: the water in the saturated zone
- Aquifer: the geologic formation through which water can flow horizontally and be pumped (ex: sand, sedimentary rocks, limestone, etc.)

Groundwater hydrology

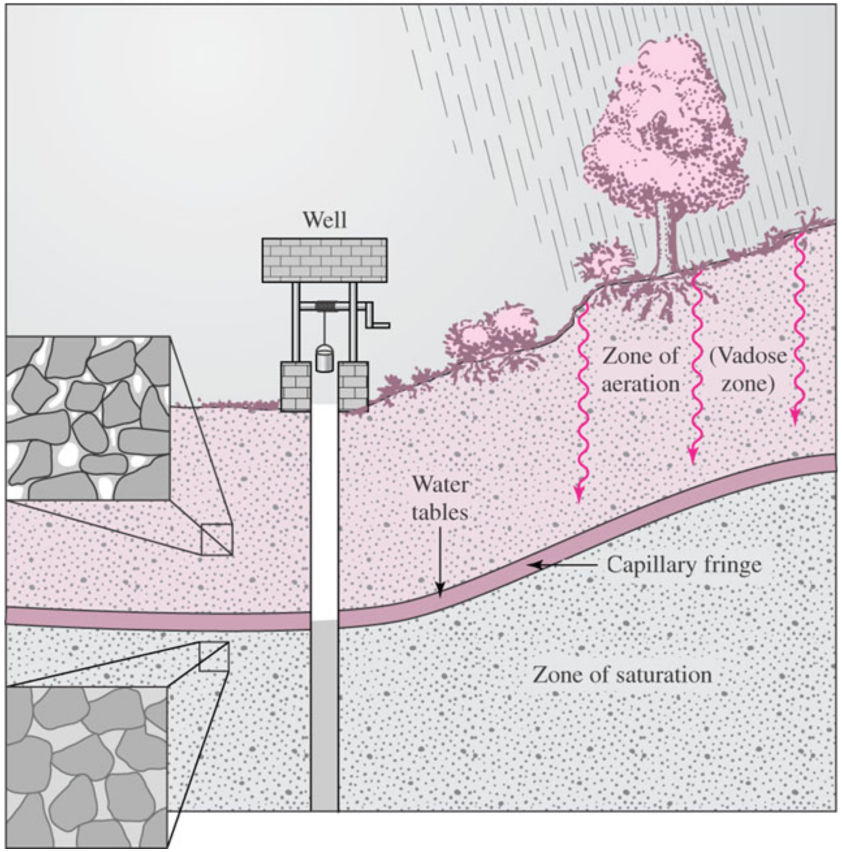
- Hyporheic zone
  - A region beneath and alongside a stream bed, where there is mixing of shallow groundwater and surface water
  - Important for:
    - Exchange of substances (e.g., nutrients, dissolved O_2, contaminants) between groundwater and surface water
    - Aquatic ecosystem – e.g., fish spawning, benthic invertebrates, microbes



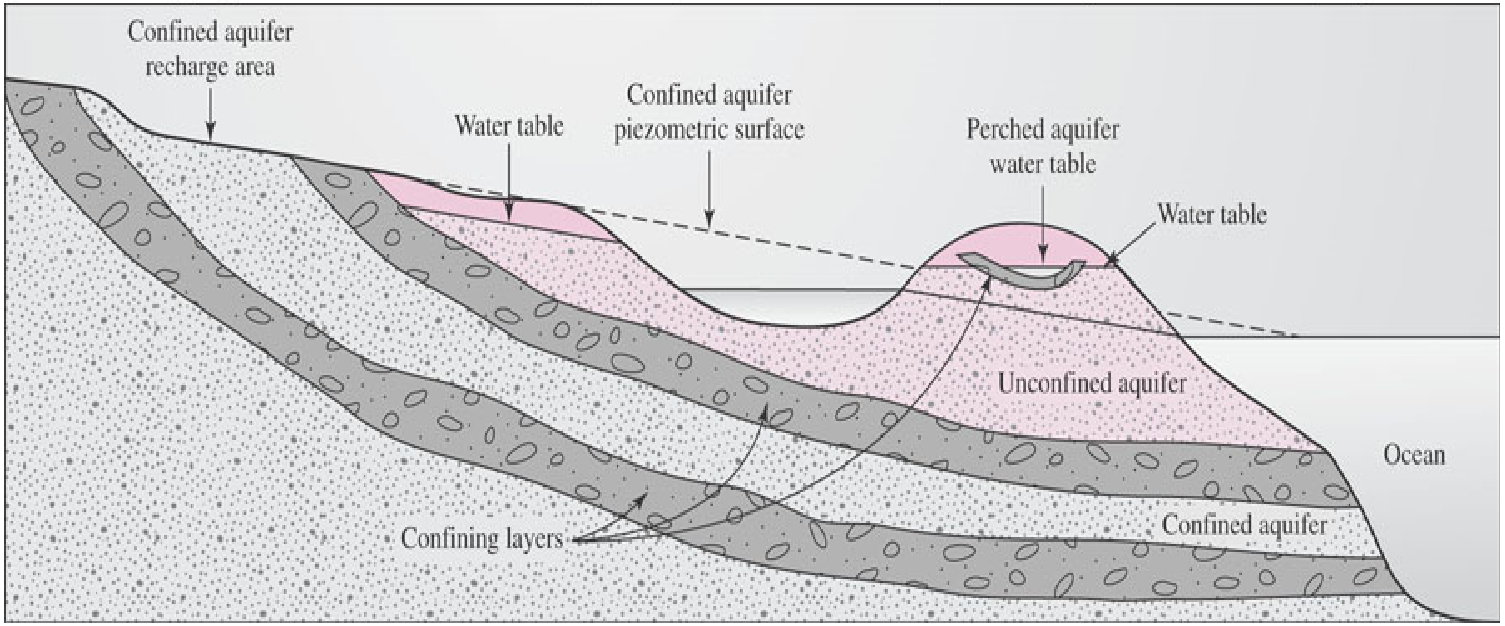
http://www.madrimasd.org

Unconfined aquifer

- **Unconfined aquifer**: an aquifer of which upper surface of its saturated zone is not confined by an impermeable layer
- **Water table**: The upper surface of the saturated zone in an unconfined aquifer
- **Capillary fringe**: the zone where capillary action occurs (the soil draws water above the water table)



Confined aquifer

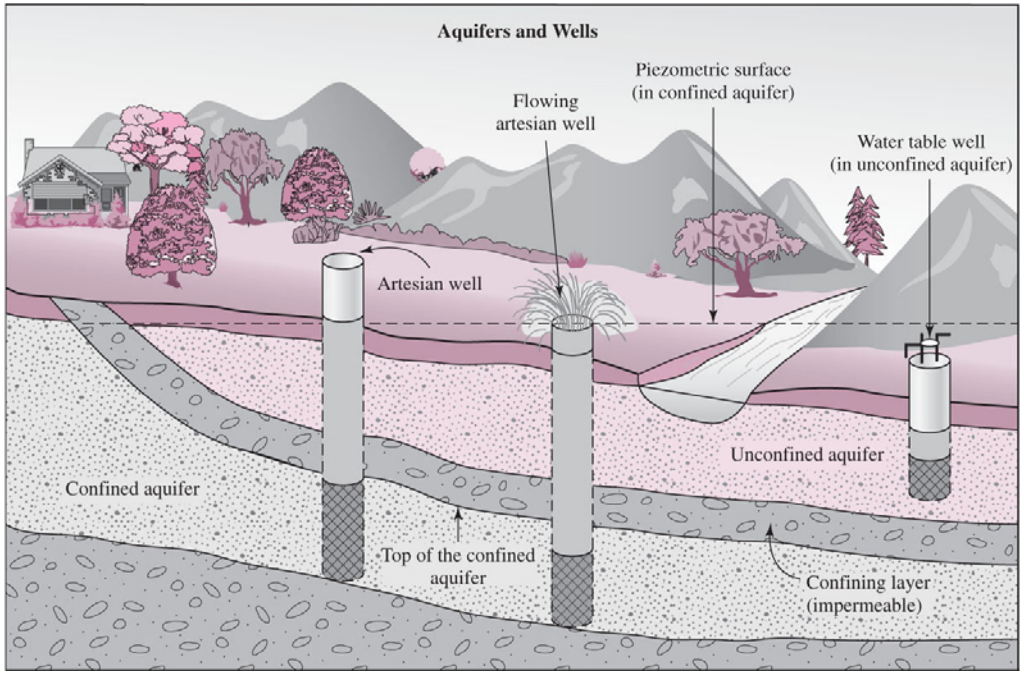


- **Confined aquifer**: an aquifer bounded by impermeable layers (called as confining layers) both at the top and the bottom
- Confining layers: *aquicludes* or *aquitards*

Piezometric head and surface

- Piezometer: a small tube device installed vertically into an aquifer
- Piezometric head: the height of the water in a piezometer → a measure of the pressure
- Piezometric surface: an impaginary plane drawn through the piezometric head of several piezometers

Piezometric head and surface



- Unconfined aquifer: piezometric surface = water table
- Confined aquifer: piezometric surface is higher than the top end of the aquifer

Groundwater flow

- Keep in mind that:
  - (Of course) surface water flows from higher to lower elevation
  - Groundwater flows from areas of higher head to lower head
- Hydraulic gradient, $\Delta h/L$

$$\frac{\Delta h}{L} = \frac{h_2 - h_1}{L}$$

h_2 = the head at location 2

h_1 = the head at location 1

L = the linear distance between location 1 and 2

Darcy's Law

$$v = K\frac{\Delta h}{L}$$

v = Darcy velocity (specific discharge) [L/T]

K = hydraulic conductivity [L/T]

The flow velocity is proportional to the hydraulic gradient and the hydraulic conductivity

In terms of the flow rate of groundwater,

$$Q = vA = \left(K\frac{\Delta h}{L}\right)A$$

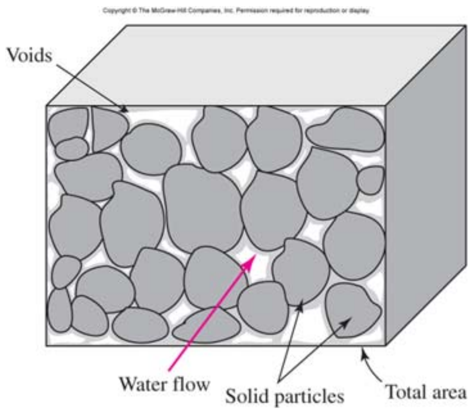
Q = flow rate [L^3/T]

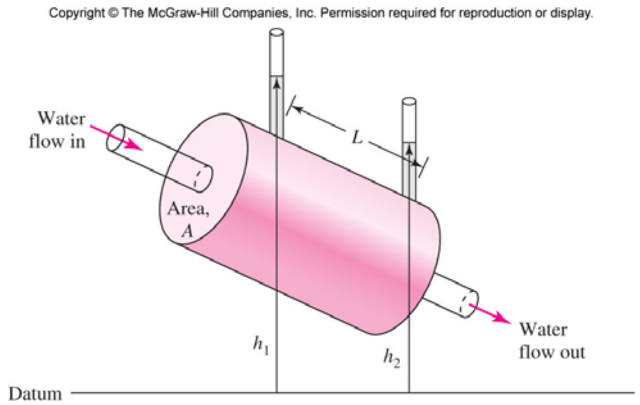
A = cross-sectional area [L^2]

Darcy's Law

Darcy's velocity $v = Q/A$

This is **NOT** a real velocity: the groundwater flows only through the voids (pores), not the entire cross-sectional area





Seepage velocity & porosity

- The average linear velocity (**seepage velocity**), *v'*

$$v' = \frac{v}{\eta}$$

η = porosity [-]

- Porosity: the ratio of the volume of voids (pores) in the aquifer material to the total volume

Typical values of aquifer parameters

Typical Values of Aquifer Parameters

Aquifer Material	Porosity (%)	Typical Values for Hydraulic Conductivit[y] $(m \cdot s^{-1})$
Clay	55	2.3×10^{-9}
Loam	35	6.0×10^{-6}
Fine sand	45	2.9×10^{-5}
Medium sand	37	1.4×10^{-4}
Coarse sand	30	5.2×10^{-4}
Sand and gravel	20	6.0×10^{-4}
Gravel	25	3.1×10^{-3}
Slate	<5	9.2×10^{-10}
Granite	<1	1.2×10^{-10}
Sandstone	15	5.8×10^{-7}
Limestone	15	1.1×10^{-5}
Fractured rock	5	1×10^{-8}–1×10^{-4}

Sources: Davis, M., D. A. Cornwell. *Introduction to Environmental Engineering*, 3rd ed. McGraw-Hill, New York (1998). Todd, D. A. *Groundwater Hydrology*, 2nd ed. John Wiley and Sons, New York (1980)

Groundwater flow

Q: While investigating the ground near Bldg. 35, you found water at 7 m below ground surface (bgs). One hundred meters away, you found water at 7.5 m bgs. Choose the datum as 25 m bgs. The aquifer is coarse sand which has a porosity of 30% and the hydraulic conductivity of 5.2×10^{-4} m/s. The cross-sectional area of the aquifer is 925 m^2. Determine the i) piezometric surface at each point, ii) the direction of groundwater flow, iii) the hydraulic gradient, iv) the Darcy velocity, v) the flow rate, and vi) the seepage velocity.

Reading assignment

Textbook Ch 7 p. 258-266, 276-285, 296-298