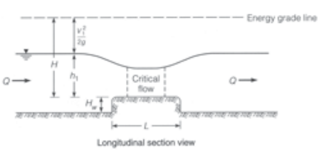
CE 433: Spring 2020

Review: Flow Measurement with Broad-Crested Weirs



$$Q = C_d b \sqrt{g}\left(\frac{2}{3}H\right)^{3/2}$$

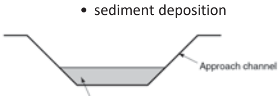
$$y_c = \frac{2}{3}H$$

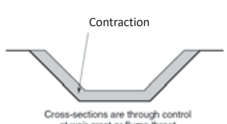
$$C_d = \frac{0.65}{(1 + H / H_w)^{1/2}}$$

- How do they work?
- What is the disadvantage?

Flow Control Sections

- **Weir**: a control section where the channel bottom is raised
  - Used to raise water surface to a certain height
  - Used to quantify flow
  - DA
    - large headloss
    - sediment deposition
- **Flume**: a control section where the channel is narrowed (and raised)
  - Avoids sediment deposition
  - Reduced headloss





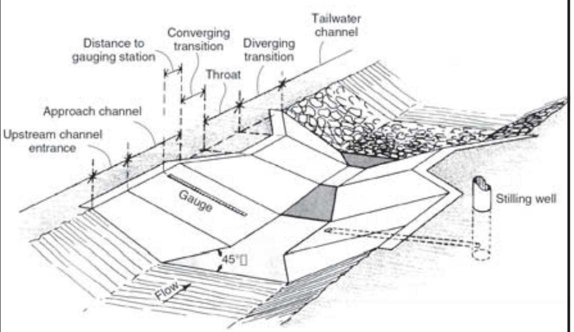
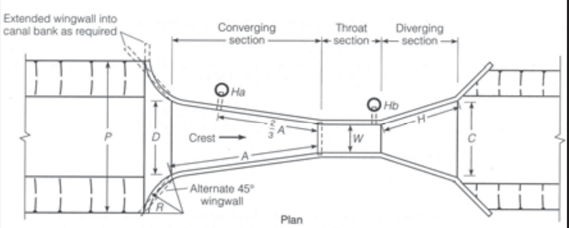


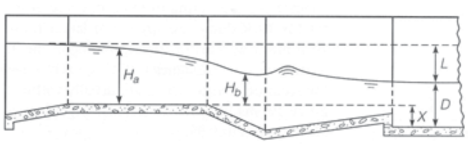
Figure 5.6.7 (p. 133)
General layout of a flow-measuring structure (from Bos et al. (1984)).

Parshall Flume

- **Converging section**: subcritical flow is accelerated and guided into throat, induces critical depth
- **Throat**: induces supercritical flow
- **Diverging section**: flow velocity reduced to subcritical flow; potential energy is recovered



Parshall Flume, cont…



- Two key depths:
  - H_a – flow depth at 1/3 of the distance into the converging section
  - H_b – flow depth in throat section
- Submergence: when tailwater is high, the hydraulic jump can be located under very slow moving, pooled water
- When the jump is not submerged, computing flow rate is simple:

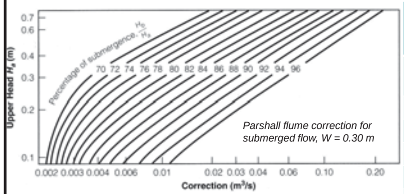
Flow Equations

Throat width	Equation	Free-flow capacity (m^3/s)
8 cm	$Q = 0.177H_a^{1.547}$	0.0008–0.054
15 cm	$Q = 0.381H_a^{1.58}$	0.0014–0.11
23 cm	$Q = 0.535H_a^{1.53}$	0.0025–0.25
30 cm to 2.4 m	$Q = 0.372W(3.281H_a)^{1.570W^{0.026}}$	up to 4.0
3.0 m to 15.2 m	$Q = (2.29W + 0.474)H_a^{1.6}$	up to 56

Submerged Jump in Parshall Flume

- If H_b / H_a exceeds submergence criteria →
  - then correction factors must be applied

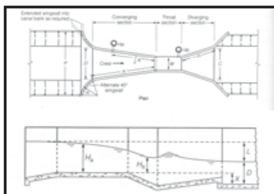
Parshall Flume Submergence Criteria	
Throat Width	H_b / H_a
2.5 cm, 5.1 cm, 7.6 cm	0.5
15.2 cm, 22.9 cm	0.6
30 cm – 2.4 m	0.7
2.4 m – 15.2 m	0.8



Correction factors relative to 0.30 m Parshall Flumes	
Throat Width (m)	Correction Factor
0.30	1.0
0.46	1.4
0.61	1.8
0.91	2.4
1.22	3.1
1.83	4.3

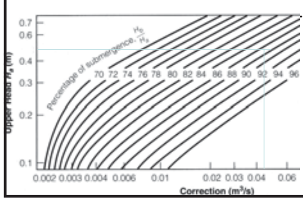
ΔQ = correction (m³/s) x correction factor

Parshall Flume Example



Parshall flume, throat width of 0.61 m. Depth in converging section is 45 cm. Depth in the throat is 39 cm.

- Is the hydraulic jump "submerged"?
- What is the flow rate through the flume?



$$Q = 0.372W\left(3.281H_a\right)^{1.570W^{0.026}}$$

Culverts

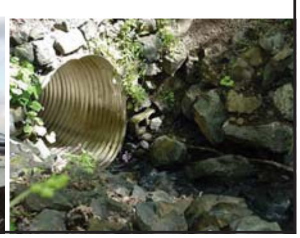
- Pass water under roads and highways
- Flow rate can depend on
  - Entrance diameter
  - Culvert length
  - Culvert slope
  - Culvert material & inlet configuration
  - Backwater conditions

What is a culvert?

- A metal, concrete, plastic, or wooden conduit through which surface water can flow under roads

Why are culverts used?

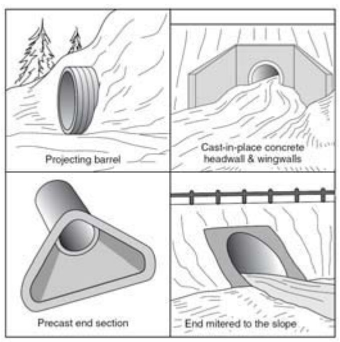
- They're cheaper than bridges
  - Generally used for lower flow rates.



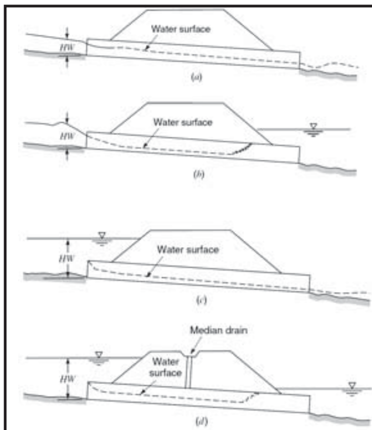
How are culverts sized?

- Hydrology data is used to identify the flow rate that will occur over a certain recurrence intervals.
  - i.e.: the "25-year" flow will be 25 m^3/s
- Depending on culvert slope, roughness, size, shape, and upstream / downstream conditions, the flow rate is dictated by one of SIX conditions.

Figure 16.2.1 (p. 651)
Four standard inlet types (schematic) (from Normann et al. (1985)).



What happens if the culvert is sized wrong?



Inlet Control

High velocity, shallow flow. Supercritical. Q by weir / orifice equation.

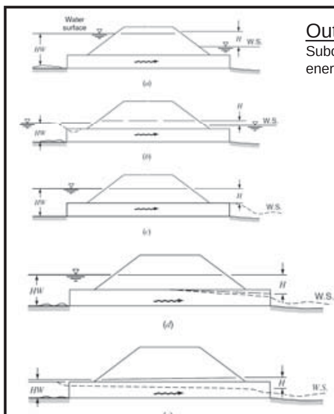
Submerged orifice…

$$\frac{HW}{D} = C\left[\frac{Q}{AD^{0.5}}\right]^2 + Y + Z$$

for

$$\left[\frac{Q}{AD^{0.5}}\right]^2 \geq 4.0$$

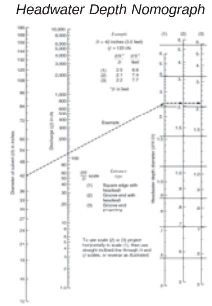
D: interior height (ft)
Q: discharge (cfs)
A: cross-sectional area (ft^2)
Z: slope correction factor = -0.5 S_0
C, Y: empirical constants (Table 16.2.1)



Outlet Control

Subcritical or full-culvert flow. Find Q by energy balance.

Headwater Depth Nomograph



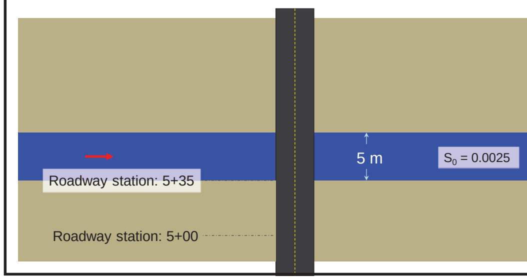
An Easy Way to Size Culverts

- Free software from US Federal Highways Administration
  - Has been used for a long time and is very well respected
  - Graphical Interface
  - Allows for multiple culverts to be specified at a variety of locations on a map

http://www.fhwa.dot.gov/engineering/hydraulics/software/hy8/

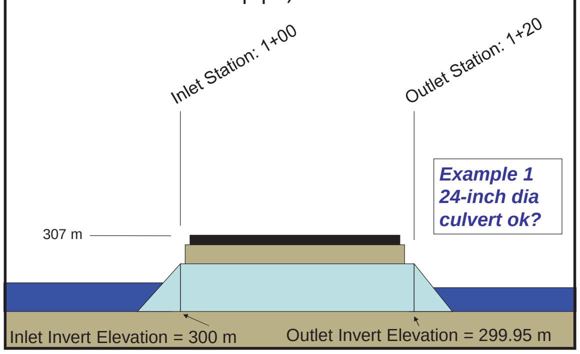
Example: Top View

- Rectangular Channel,
  - Design flow: 25 m^3/s Maximum Flow: 30 m^3/s
  - n = 0.05

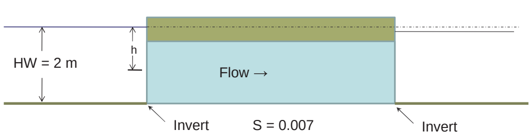


Cross-Sectional View

- Circular concrete pipe, conventional outlet



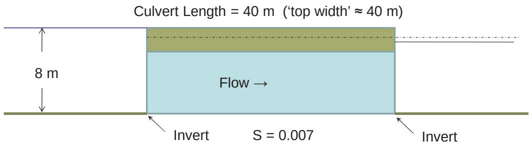
Culvert Example 2: Analysis



- Culvert: 1.5 m x 1.5 m, n = 0.013, S_o = 0.007, L = 40 m
- Channel: n = 0.05

- Find:
  a) Q that will cause the HW depth to be 2 m, with channel width = 5.0 m
  b) Rectangular channel width that will cause TW depth to be 2 m, for the Q found in Part A
     - Key:
       - iteration of TW rating curve with various channel width values
       - Repeated analysis of culvert to find at what Q the HW = 2 m

Culvert Example 3: Design



- A trapezoidal natural channel (b=3 m, n = 0.025, 1:1 side slopes) carries 10 m^3/s.
  - Design a culvert so that the maximum HW = 7 m
  - Design a culvert that allows up to 1 m^3/s overtopping

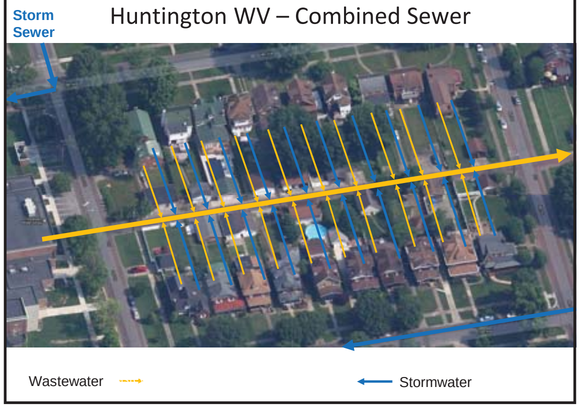
Stormwater Control: Sewers & Detention

- ***stormwater management*** – the control and utilization of water in different forms within the hydrologic cycle

Drainage systems:

1. Remove stormwater from streets (safety & pavement longevity)
2. Controls rate and velocity of water in gutters (safety & pavement longevity)
3. Conveys runoff to natural or manmade drainage ways
4. Controls the mass of pollutants entering receiving waters
5. Detention facilities can have multiple uses (parks, etc)

Huntington WV – Combined Sewer



Data Needed for Storm Sewer Design

- Local design standards / drainage criteria
- Topographic maps of system area
- Info on existing storm sewers & channels
- Utility (existing & proposed) information
- Layout of design area (e.g., street profiles and grades)
- Soil data (to help select pipe material)
- Water table levels (& seasonal variations)
- IDF curve for project area
- Pipe properties (& list of pipes allowed by local authorities)

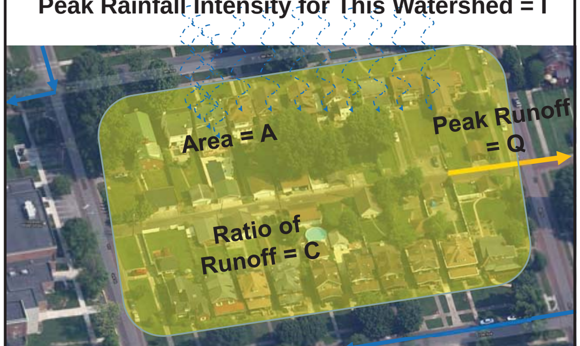
Design Assumptions and Constraints

- Gravity flow (sloping downward)
- Circular pipe, commercially available
- Smallest pipe diameter that will convey flow
- Depth: avoid frost, minimum cover (loads), drain basements (optionally)
- Minimum velocity specified to avoid sediment deposition
- Maximum velocity specified to avoid scour & erosion
- Pipes only get bigger, not smaller.
- Dendritic network converging towards downstream – no closed loops

Storm Sewer – Typical Constraints

Parameter	Constraint
Velocity (min)	2 - 3 ft/s
Velocity (max)	15 - 21 ft/s (rigid) 10 - 15 ft/s (flexible)
Manhole spacing (max)	400 – 600 ft
Pipe size (min)	12 – 24 in
Vertical alignment at manholes	Match crown (different size pipe) 0.1 – 0.2 ft drop (same size pipe)
Soil cover (min)	12 – 24 in
Inlet location	Governed by gutter capacity
Final hydraulic design	Check for surcharge (pressure flow) and junction losses

Peak Rainfall Intensity for This Watershed = I



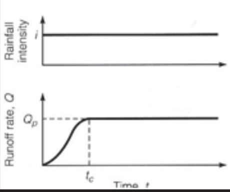
Rational Method

$$\boxed{Q = CiA}$$

- Simplest peak discharge method
- Over-estimates peak discharge
- Best for catchments less than 80 ha
- Minimum time of concentration is 5 min.

Q [=] ft^3/s or m^3/hr
C [=] unitless
i [=] in/hr or m/hr
A [=] acres or m^2

Assumptions:



Method:

- Calculate time of concentration, t_c
- Determine rainfall intensity corresponding to that time of concentration (use IDF curve)
- Determine C, including composite information for the catchment, if needed
- Solve for Q

Character of Surface	2	5	10	25	50	100	500
	Return Period (years)						
Developed							
Asphaltic	0.73	0.77	0.81	0.86	0.90	0.95	1.00
Concrete/roof	0.75	0.80	0.83	0.88	0.92	0.97	1.00
Grass areas (lawns, parks, etc.)							
Poor condition (grass cover less than 50% of the area)							
Flat, 0–2%	0.32	0.34	0.37	0.40	0.44	0.47	0.58
Average, 2–7%	0.37	0.40	0.43	0.46	0.49	0.53	0.61
Steep, over 7%	0.40	0.43	0.45	0.49	0.52	0.55	0.62
Fair condition (grass cover 50% to 75% of the area)							
Flat, 0–2%	0.25	0.28	0.30	0.34	0.37	0.41	0.53
Average, 2–7%	0.33	0.36	0.38	0.42	0.45	0.49	0.58
Steep, over 7%	0.37	0.40	0.42	0.46	0.49	0.53	0.60
Good condition (grass cover larger than 75% of the area)							
Flat, 0–2%	0.21	0.23	0.25	0.29	0.32	0.36	0.49
Average, 2–7%	0.29	0.32	0.35	0.39	0.42	0.46	0.56
Steep, over 7%	0.34	0.37	0.40	0.44	0.47	0.51	0.58
Undeveloped							
Cultivated land							
Flat, 0–2%	0.31	0.34	0.36	0.40	0.43	0.47	0.57
Average, 2–7%	0.35	0.38	0.41	0.44	0.48	0.51	0.60
Steep, over 7%	0.39	0.42	0.44	0.48	0.51	0.54	0.61
Pasture/range							
Flat, 0–2%	0.25	0.28	0.30	0.34	0.37	0.41	0.53
Average, 2–7%	0.33	0.36	0.38	0.42	0.45	0.49	0.58
Steep, over 7%	0.37	0.40	0.42	0.46	0.49	0.53	0.60
Forest/woodlands							
Flat, 0–2%	0.20	0.25	0.28	0.31	0.35	0.39	0.48
Average, 2–7%	0.31	0.34	0.36	0.40	0.43	0.47	0.56
Steep, over 7%	0.35	0.39	0.41	0.45	0.48	0.52	0.58

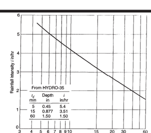
Rational Method Example

- During a 5 year, 24 hour storm, the peak rainfall intensity is 95 mm/hr. A certain catchment consists of 4 ha of parking, 12 ha of “fair” lawns on a 4% slope, a 4 ha rail yard, and 18 ha of single-family housing.
  - Estimate the peak runoff flow rate, Q.

$$Q = CiA$$

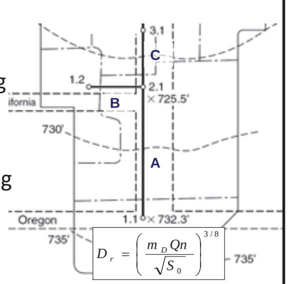
Rational Method Design:

Determining Required Pipe Size



Q=CiA

- Find the CA for each sub-basin
- Compute time of concentration for each junction and corresponding rainfall intensity at each junction
- Calculate required pipe diameter based on resulting flowrate
  - Flow velocity used in downstream t_c calculations

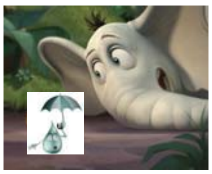


$$D_r = \left(\frac{m_D Q n}{\sqrt{S_0}} \right)^{3/8}$$

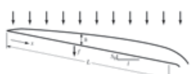
Rational Method Example: *Handout*

Overland Flow

- ***Hortonian overland flow***: when rainfall rate exceeds infiltration capacity – sufficient water ponds on the surface to overcome surface tension effects and fill small depressions.
  - Overland flow: surface runoff, sheet flow on land surface without concentration in clearly defined channels



Time of Concentration: **Kinematic Wave**



$$t_c = 6.99 \frac{(nL)^{0.6}}{i^{0.4} S_o^{\ 0.3}}$$

n = Manning's roughness coefficient for overland flow

i = rainfall intensity (mm/hr)

L = length of travel (m)

S_o = ground slope

t_c = time of concentration (min)

- Limited to distances of ~100 m
- **<u>A trial and error </u>** approach
  1. Assume a trial rainfall intensity
  2. Find overland travel time, t_c
  3. Find actual rainfall intensity for storm with duration of t_c
  4. Compare intensities, and if not equal, repeat

Table 8.9.1 Recommended Manning's Roughness Coefficients for Overland Flow

Cover or treatment	Residue rate, Tons/Acre	Value recommended	Range
Concrete or asphalt		0.011	0.010–0.013
Bare sand		0.01	0.010–0.016
Graveled surface		0.02	0.012–0.03
Bare clay loam (eroded)		0.02	0.012–0.033
Fallow, no residue		0.05	0.006–0.16
Chisel plow	<1/4	0.07	0.006–0.17
	<1/4–1	0.18	0.07–0.34
	1–3	0.30	0.19–0.47
	>3	0.40	0.34–0.46
Disk/harrow	<1/4	0.08	0.008–0.41
	1/4–1	0.16	0.10–0.25
	1–3	0.25	0.14–0.53
	>3	0.30	—
No till	<1/4	0.04	0.03–0.07
	1/4–1	0.07	0.01–0.13
	1–3	0.30	0.16–0.47
Moldboard plow (fall)		0.06	0.02–0.10
Colter		0.10	0.05–0.13
Range (natural)		0.13	0.01–0.32
Range (clipped)		0.10	0.02–0.24
Grass (bluegrass sod)		0.45	0.39–0.63
Short grass prairie		0.15	0.10–0.20
Dense grass[1]		0.24	0.17–0.30
Bermuda grass[1]		0.41	0.30–0.48

[1]Weeping lovegrass, bluegrass, buffalo grass, blue gamma grass, native grass mix (OK), alfalfa, lespedeza (from Palmer, 1946).

Sources: Woolhiser (1975), Engman (1986), Woolhiser et al. (1990).

NRCS Time of Concentration Method

- Differentiates between sheet flow and shallow concentrated flow
  - Sheet flow (~100m):

$$t_f = 0.0288 \frac{(nL)^{0.8}}{P_2^{0.5} S_o^{0.4}}$$

t_f = travel time (hours)
n = Manning's number
L = length (meters)
P_2 = rainfall, two-year 24-hour storm (cm)
S_o = slope

  - Shallow Concentrated Flow

$$t_{sc} = \frac{L_{sc}}{V_{sc}}$$

Using Manning's equation to find flow velocity.

Time of Concentration: **Kirpich**

- Kirpich: Best for natural basins with well-defined channels, bare-earth overland flow, or flow in mowed channels. Less than 80 ha.
  - Overland flow on concrete or asphalt, x 0.4
  - Concrete channels, x 0.2
  - General overland flow, flow in natural grass channels, x 2

$$t_c = 0.019 \frac{L^{0.77}}{S_o^{0.385}}$$

t_c [=] min
L [=] m
So = slope

Time of Concentration: **Izzard**

- Izzard: Derived from pavement & turf experiments where overland flow dominant.

$$t_c = \frac{530KL^{1/3}}{i_e^{2/3}}$$

when:
$i_e L$<3.9 m²/h

Surface	**c_r**
Very smooth asphalt	0.007
Tar and sand pavement	0.0075
Crushed-slate roof	0.0082
Concrete	0.012
Tar and gravel pavement	0.017
Closely clipped sod	0.046
Dense bluegrass	0.060

t_c [=] min
L [=] m (overland flow dist.)
S_o = slope
c_r = retardence coefficient
i_e= effective rainfall intensity, mm/hr

$$K = \frac{2.8\times10^{-6} i_e + c_r}{S_o^{1/3}}$$

Time of Concentration: **Kerby**

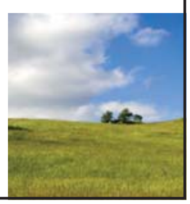
- Kerby Equation: for catchments less than 4 ha, slopes less than 1%, L < 365 m

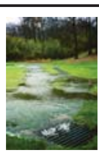
$$t_c = 1.44(LrS_o^{-0.5})^{0.467}$$

Surface	r
Smooth pavements	0.02
Smooth bare packed soil, free of stones	0.10
Poor grass, bare sod	0.30
Average grass	0.40
Deciduous timberland	0.06
Conifer timberland, dense grass	0.80

Time of Concentration: Example

- A grassy area has an average slope of 1.5%, and the distance from catchment boundary to outlet is 75 m. For a 20-minute storm with effective rainfall rate of 45 mm/hr, find t_c.
  - Kinematic wave
  - NRCS method
  - Kirpich equation
  - Izzard equation
  - Kerby equation





Rational Method – Units Example

$$\boxed{Q = CiA}$$

- Area, A = 10 acres = 40,469 m^2
- Storm Intensity, i = 4 in/hr = 0.1016 m/hr
- Runoff Coefficient, C = 0.70

What is the peak runoff, in terms of ft^3/s and m^3/hr?



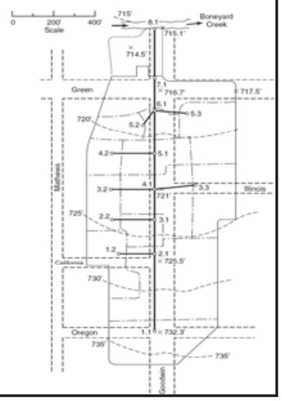




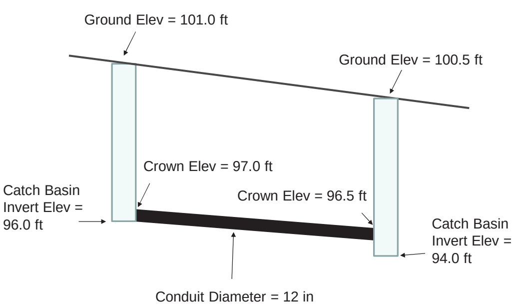
- Japan's solution:
  http://edition.cnn.com/2012/10/31/world/asia/japan-flood-tunnel/index.html

StormCAD

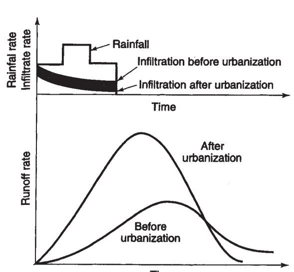
- Solve previous Urban Hydrology example using StormCAD
  - Handout of example solution
  - Units
  - Input storm data
  - Catchments – how to draw them
  - Network annotation



Specifying Elevations in StormCAD



Urbanization Effects: Runoff & Infiltration

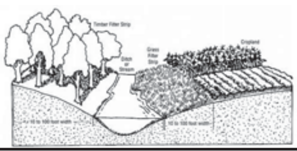


- Reduced infiltration depth / volume
- Increases the flow rate of runoff
- Decreases the time of concentration

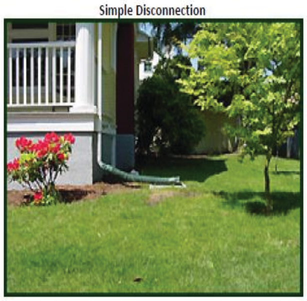
Vegetated Filter Strips

Vegetated areas that manage runoff from adjacent impervious areas by slowing the runoff and allowing sediment and attached pollutants to settle out, filter runoff through the vegetation, and infiltrate into the existing or amended soils.

- Applies to small commercial and residential impervious areas.
- Utilizes filtration, infiltration, sedimentation, sorption of pollutants into the soil, and uptake of runoff and pollutants by vegetation.
- Critical design elements include maximum allowable contributing impervious area, slope, and minimum dimensions.



Simple Disconnection



Landscape practice that directs runoff from rooftops and other small impervious surfaces to adjacent pervious areas as sheet flow.

- Relatively small scale (as compared to filter strips) and intended for residential or small commercial areas;
- Utilizes filtration, infiltration, sedimentation, sorption of pollutants into the soil, and uptake of runoff and pollutants by vegetation.
- Critical design elements include maximum allowable drainage area, slope, and minimum dimensions

Simple Disconnection with Alternative Practices

Alternative Practices are utilized when there is insufficient room to establish sheet flow or meet other Simple Disconnection criteria.

- Alternative Practices include **Soil Amendments**, **Residential Raingardens** (or Micro-Scale Bioretention), **Rainwater Harvesting**, **Stormwater Planters**, and **Infiltration.**
- Effectiveness is based on the same performance mechanisms as the individual practices (covered separately in more detail utilizes).
- Critical design elements include the volume and depth of incorporation of soil amendments, and

Bioretention

Landscaped practice that uses plants, mulch, and soil to treat runoff. Commonly used in parking lot islands and edges and as part of commercial site plans.

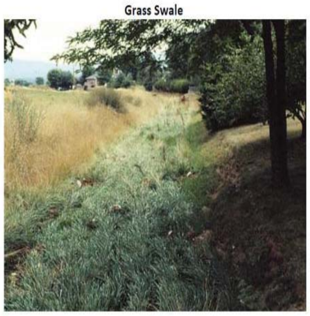
- Can be designed as an infiltration practice, an extended filtration practice (with an underdrain), or an enhanced extended filtration practice with an internal infiltration sump under the underdrain.
- Utilizes flow attenuation, extended filtration, infiltration, sedimentation, sorption, and vegetative uptake.
- Critical design elements include surface ponding volume, soil media depth, and underdrain. Includes several design variations.

Permeable paving materials include concrete, asphalt, and interlocking pavers that allow runoff to filter through voids into a gravel storage reservoir.

- Can be designed as an infiltration practice, an extended filtration practice (with an underdrain), or an enhanced extended filtration practice with an internal storage sump.
- Utilizes flow attenuation, sedimentation, filtration, sorption, infiltration.
- Critical design elements include surface slope, highly impervious drainage area, and upper limits on the amount of drainage are "run-on".

Porous Concrete Video:
http://www.youtube.com/watch?v=ScsQYHMfabU

Grass Swale



Grass Swales are designed as conveyance systems with enhanced design features to also provide a level of stormwater treatment and retention.

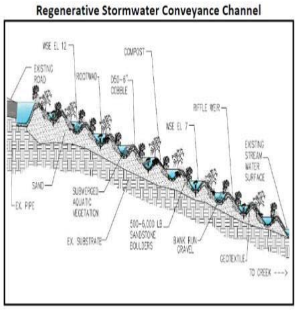
- Designs can be cost effective when used in place of curb & gutter, pipes, and other conveyance systems.
- Utilizes flow attenuation, filtering, and infiltration. Performance can be boosted with the addition of soil amendments.
- Design features include maximum allowable longitudinal slope (or the use of check dams), maximum velocity and depth of flow for the treatment volume and large storm conveyance, trapezoidal cross-section geometry.

Infiltration

Infiltration practices utilize temporary surface or
underground storage to allow incoming stormwater runoff to exfiltrate into underlying soils. Runoff first passes through multiple pretreatment mechanisms to trap sediment and organic matter before it reaches the practice.

- Highly effective as a runoff reduction practice.
- Utilizes chemical adsorption (sorption, precipitation) and biological transformation to process and remove pollutants.
- Key design features are runoff pre-treatment, soil permeability, and subsoil conditions – such as groundwater. Strict limitations on use at hotspots or brownfields.

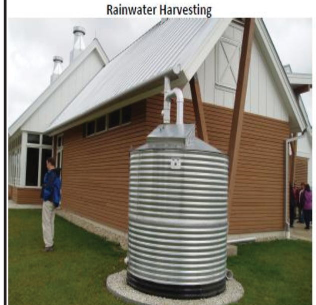
Regenerative Stormwater Conveyance Channel



The RSCC is an open-channel conveyance structure that encourages surface flow to transition to shallow groundwater flow through small attenuation ponds and a sand seepage filter. Ideally suited for steep slopes (<10%).

- Functions much like a cross between a sand filter and a series of bioretention basins in terms of RR and PR.
- Utilizes attenuation, filtration, sorption, settling, and transformation.
- Critical design features include storage volume of step pools, adequate energy dissipation and anchoring system, hydraulic design for large storms.

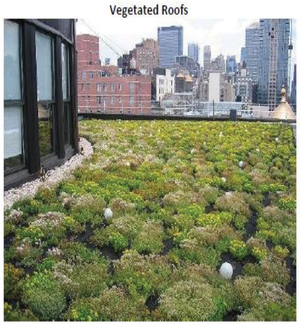
Rainwater Harvesting



System provides for the capture, storage, and release of rainwater for future use. Rooftop runoff is the ideally suited since it is relatively clean of solids and can be stored above ground for easy release.

- Systems are available from 200 to 10,000 gallons with pre-installed pre-treatment, pumps (if needed), and water level indicators.
- Utilizes volume reduction through reuse, settling, and filtering.
- Benefits include reducing use of potable water for irrigation and other outdoor uses, flushing, etc.
- Design elements include establishing a reliable water budget and pretreatment.

Vegetated Roofs



An alternative roof surfaces that typically consists of waterproofing and drainage materials and an engineered growing media that is designed to support plant growth.

- Captures and temporarily stores stormwater within the growing media.
- Utilizes vegetative uptake, attenuation, and evapotranspiration to reduce volume and peak rate of runoff. PR is marginal due to the plant soil media, although research is ongoing.
- Provides significant life-cycle cost benefits to the building and the environment beyond the stormwater credit.

Filtration Practices

Can be designed as either surface or subsurface system, but is typically utilized as an underground system where surface area is limited.

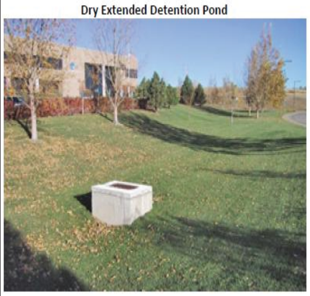
- Includes a pretreatment separation chamber to remove particulates and oils, and can effectively target hotspot pollutants.
- Utilizes gravitational separation, filtering, and potentially sorption and ion exchange depending on the media.
- Design features include sizing of the pre-treatment and filter bed components to prolong the operational life, and adequate maintenance access.

Constructed Stormwater Wetland

Shallow vegetated depressions with a permanent pool of varying depth that collects stormwater.

- Design typically includes multiple cells: a pre-treatment forebay, and at least one or two additional cells separated by a submerged weir or overflow.
- Utilizes settling, filtering, sorption, and biological uptake. Can also include very complex biological processes to cycle nutrients.
- Design features include the number of cells and corresponding pool volume, depth zones, maximum allowable storm ponding depth, and vegetation plan.,

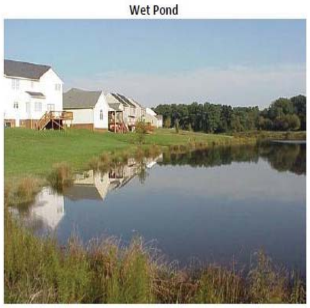
Dry Extended Detention Pond



Dry Extended Detention basins do not provide any runoff volume reduction credit; however, individual volume reduction or pollutant removal pathways may be incorporated into the design when addressing peak rate or flooding requirements.

- Designs can incorporate bioretention, filter strips and grassed swales (ponding depths above these features will be limited by the individual BMP criteria)
- Dry ED basin alone utilizes settling, filtering, and possible infiltration (depending on soils).
- Design features include establishing sheet flow and good vegetative cover within the basin.

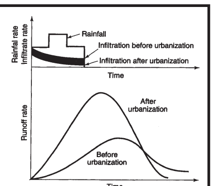
Wet Pond



Wet Ponds do not provide any runoff volume reduction credit; however, individual volume reduction pathways may be incorporated into the design when addressing peak rate, flooding, or pollutant removal requirements.

- Designs can incorporate fringe bioretention cells, grass channels, and/or filter strips to intercept surface runoff or inflow.
- Wet Ponds utilize settling, biological uptake, chemical transformation, and sorption.
- Design features include pre-treatment forebay, permanent pool volume, multiple cells, aquatic bench, aeration system, and landscaping plan.

Stormwater Ponds



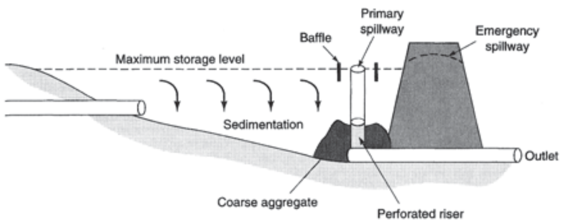
Purpose: Mitigate the effects of urbanization on stormwater drainage:

- Increased total volume of runoff
- Higher peak flow rates
- Pollutants
  - Inorganic (salts, heavy metals)
  - Organic (gas, oil, decaying leaves & grasses)
  - Particulates (sand, grit, etc.)
- *Try to make the "after urbanization" hydrograph look more like the "before urbanization" hydrograph*

Control Measures

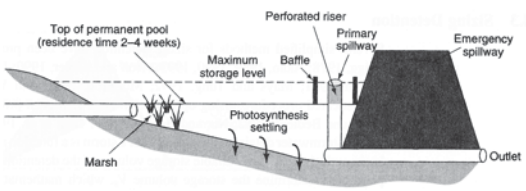
- *Source control*: local disposal, inlet control, onsite detention
- *Downstream control*: in-line detention, off-line detention, detention at WWTP

Extended Detention Basin



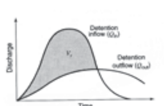
- Most efficient for 24+ hr. detention times
- Settle particulate pollutants (passes soluble pollutants)
- Moderate maintenance
- Risk of mosquito breeding
- Suitable for service of up to 100 – 200 acres

Retention Pond



- Pollutant removal: settling & biochemically
- Requires occasional major cleanouts
- Effective even for small storms
- Risk of anoxic conditions at pond bottom

Pond Storage Volume, V_s

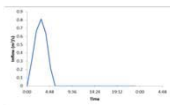


- <u>Ideal sizing method</u>
  - Inflow hydrograph data at high resolution (small time increments)
  - Compute volume in during time increment
  - Calculate the accumulated volume
  - Determine pond height based on volume in
  - Compute flow rate out for this pond height
  - Next time increment: previous volume stored + additional volume in – previous volume out

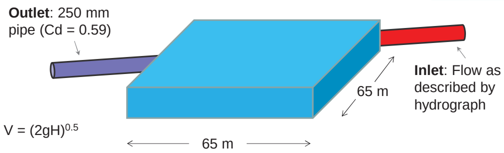
Stormwater Detention Pond Example

a) What will be the peak flow rate out of the pond?

b) How long will it take to drain the pond to 10% of its peak volume?

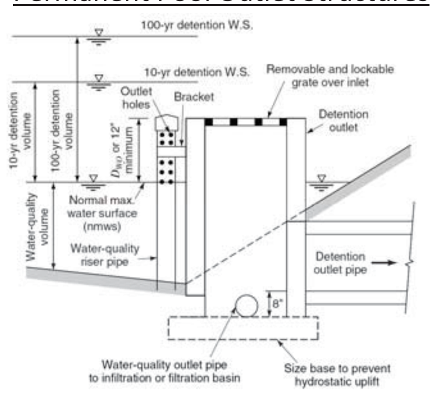


Time	Inflow (cms)
0:00	0
1:00	0.3
2:00	0.67
3:00	0.81
4:00	0.67
5:00	0.22
6:00	0
7:00	0
8:00	0
9:00	0
10:00	0
11:00	0



$V = (2gH)^{0.5}$

Permanent Pool Outlet Structures



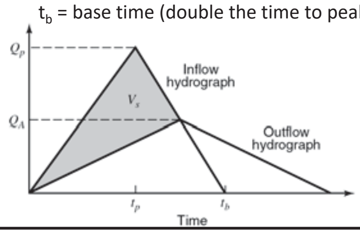
AASHTO Storage Volume Estimate

$$V_s = 0.5 t_b \left(Q_p - Q_A \right)$$

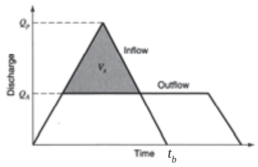
Q_p = peak inflow rate

Q_A = allowable peak outflow rate

t_b = base time (double the time to peak)



Abt and Grigg Storage Volume Estimate



$$V_s = V_r \left(1 - \frac{Q_A}{Q_p}\right)^2$$

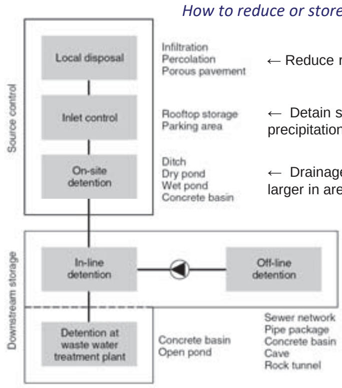
- V_r = total runoff volume = ½ · $t_b \cdot Q_p$

Example: Comparing AASHTO and Abt and Grigg

- Compare the estimated pond volume required for a storm with peak runoff flow rate of 450 L/s, an allowable discharge of 80 L/s, and a inflow discharge duration of 90 minutes.

Stormwater Storage Options

How to reduce or store runoff?



← Reduce runoff volume (lower C value)

← Detain stormwater at the area where precipitation occurs

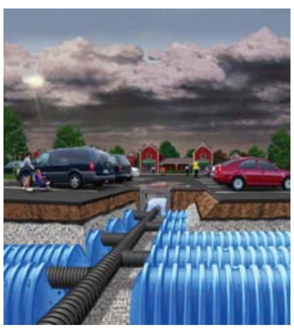
← Drainage from a single development, larger in area than local or inlet.

Local Disposal

Reduce runoff volume and decrease C

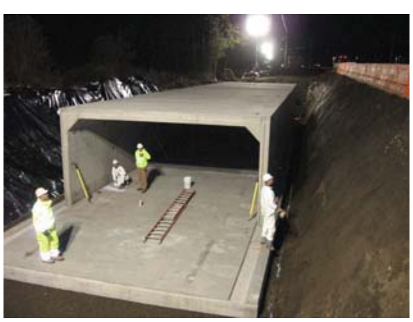
Inlet Control

Detain stormwater where the precipitation occurs.



In-Line Detention

Underground stormwater vault between source and destination.



Detention at WWTP

Flow equalization basin.

Hydrology is important in "wet" climates!

home on fire, while it floats downstream.

How important is hydrology in an arid region?

Hydrology → Hydraulic Engineering

Hydrology

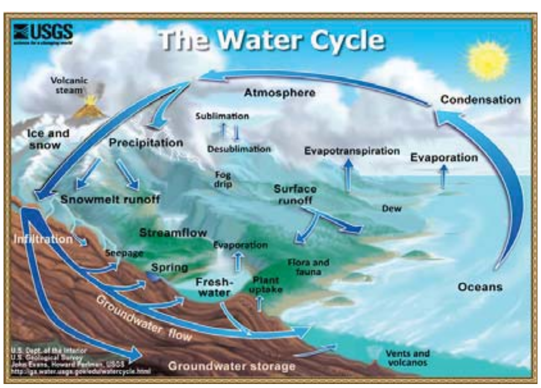
- Surface: amount and distribution of rainfall
- Sub-surface: water flow through the soil

Open Channel Flow

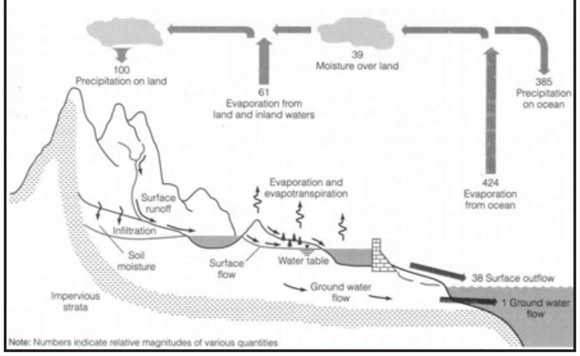
- Flow of water in rivers and canals; from runoff to lake, from lake to irrigation (e.g.: size the channel or culvert based on Q)

Pipe Flow

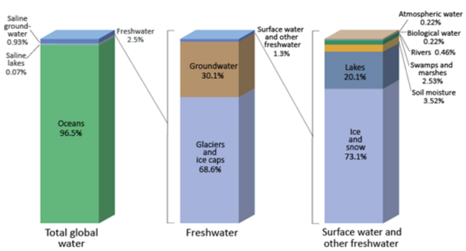
- Flow of water from treatment plant to homes and businesses (e.g.: size the pipe based on Q)



Relative Quantities of Water Transport

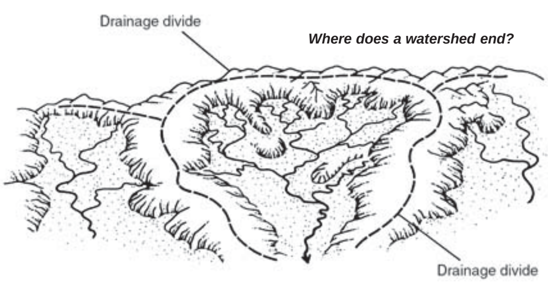


Water Quality and Quantity in the Hydrologic Cycle

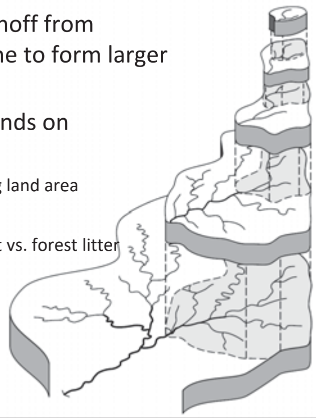


Source: Igor Shiklomanov's chapter "World fresh water resources" in Peter H. Gleick (editor), 1993, Water in Crisis: A Guide to the World's Fresh Water Resources.

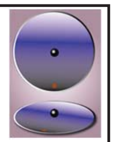
- ***Drainage basin, catchment, watershed***: topographic area that collects and discharges surface streamflow through one outlet.
  - *Google earth demo of "watershed" using terrain modeling (DEM)*



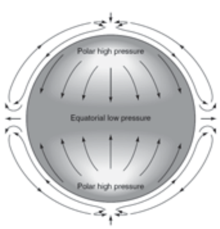
- ***Nested hierarchy***: runoff from smaller basins combine to form larger basins
- ***Runoff quantity*** depends on
  - Size of watershed
    - Upstream contributing land area
  - Land use
    - e.g., asphalt pavement vs. forest litter
  - Soil type
  - Terrain conditions
  - Rainfall intensity, amount, distribution



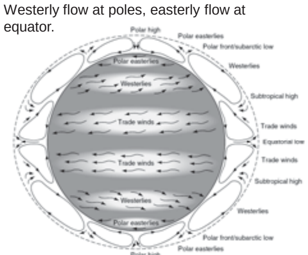
- Air movement depends on:
  - temperature differences at different altitudes
  - Heat / pressure differences at air:water interfaces
  - Earth's rotation



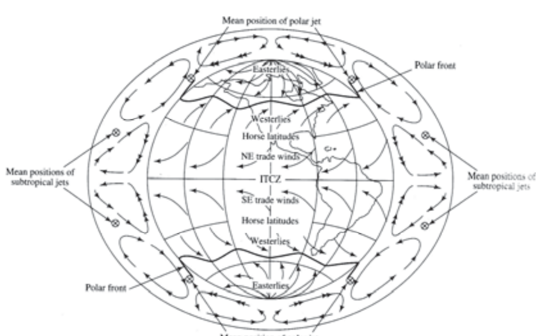
Hadley circulation: warmer equatorial air rises, cool air at poles descends



Coriolis force: decreasing radius (increasing velocity) as air moves towards poles. Westerly flow at poles, easterly flow at equator.

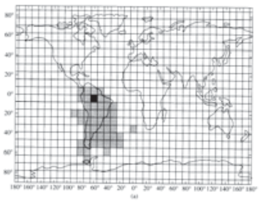


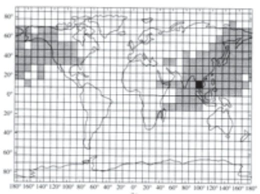
General Circulation of Atmosphere



Miller et al. (1984)

Water Transport – Evaporation and Precipitation



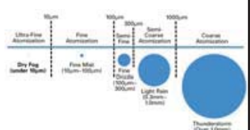


Black cell: location of evaporation

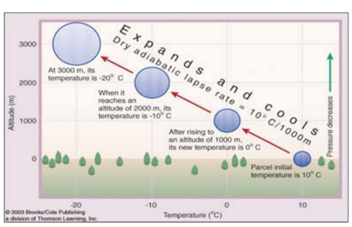
Grey cells: location of precipitation

Precipitation Formation

1. **Cooling** of air to dew-point temperature
   - Minor cooling: radiation, mixing, conduction, horizontal movement from high to low pressure regions
   - Hydrologically significant precipitation: vertical uplift
2. **Condensation** on nuclei
3. **Growth** of droplets
4. **Importation** of water vapor to continue process



Adiabatic Cooling by Vertical Uplift



As air rises, it cools, and the relative humidity increases… until saturation.

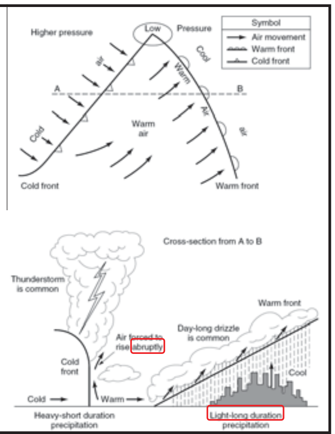
<u>Causes of uplift:</u>

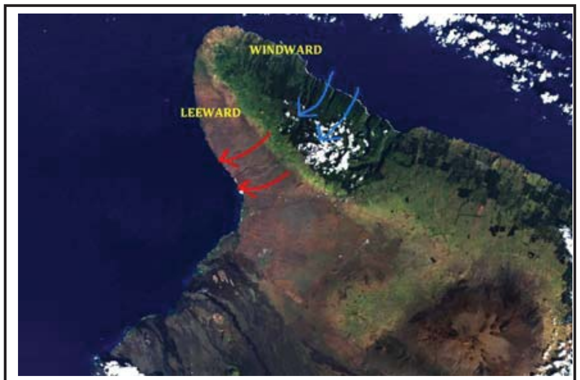
1. Convergence
2. Orography
3. Convection

Moisture Movement & Air Lifting

- Air rises and cools
  - dry adiabatic lapse rate: 9.8 °C/km
  - saturated adiabatic lapse rate: 6.5 °C/km

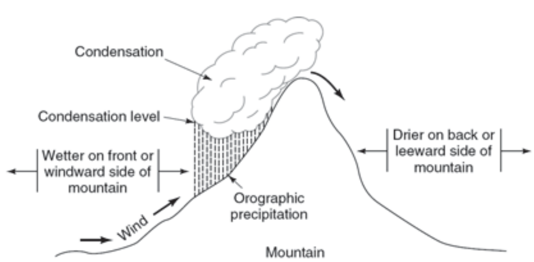
Convergence: Frontal Lifting →

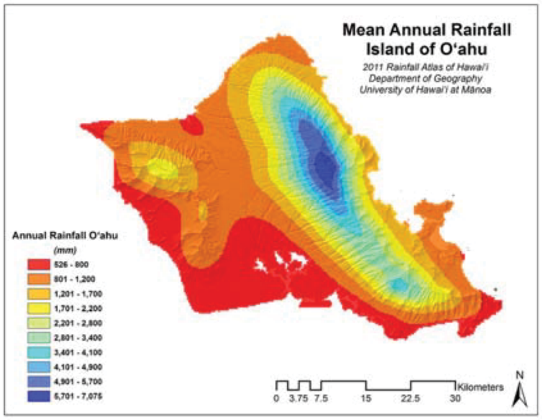




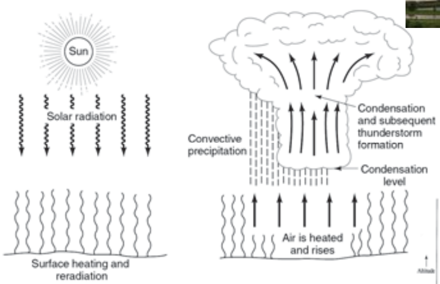
What is going on here?

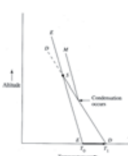
*Uplift (and cooling) due to **Orography***





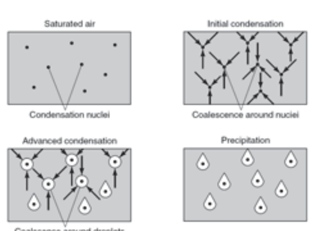
Convective Lifting





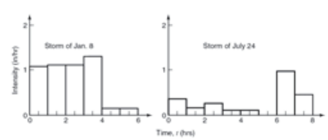
Condensation and Droplet Growth

- Snow, hail, sleet, **rainfall**.
- Condensation nuclei: dust, salt, 10^{-3} µm– 10 µm
- Droplets
  - Remain suspended & Repel
    - Negative charge
  - Evaporate
  - Impact & aggregate

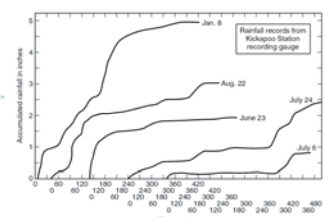


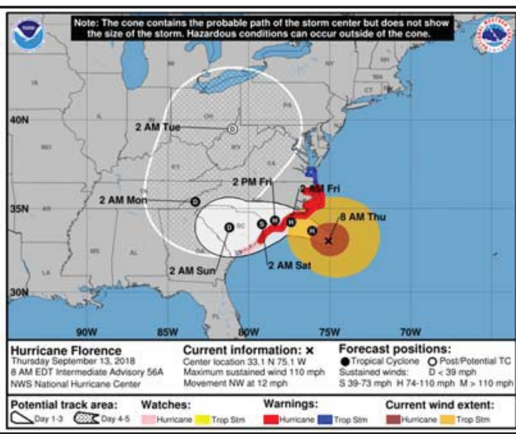
Precipitation Gages in the Region

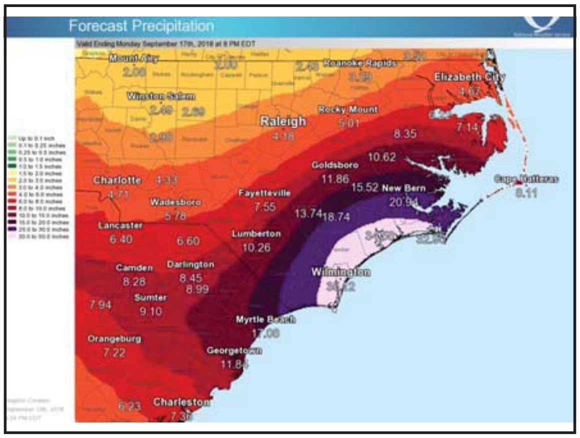
- ***Rainfall hyetograph***: plot of rainfall depth / intensity as a function of time



Cumulative Rainfall for the same two storms (and others)

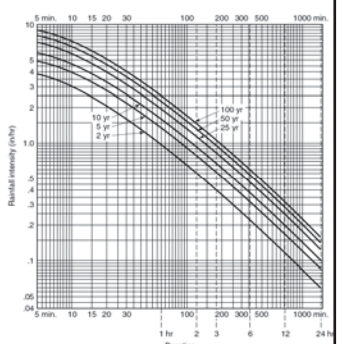






IDF Curves

- ***Intensity*** – rainfall intensity (depth per unit time)
- ***Duration*** – rainfall duration; the total length of the storm from beginning to end
- ***Frequency*** – return period; expected value of the recurrence interval (time between occurrences)



IDF Curve Calculation Procedure

From Raw Storm Data

- Rainfall data collected for many years

1. For some duration (i.e. – 5 minutes) go through data set and find maximum rainfall amount in each year
2. **Rank order** the precipitation amounts and calculate return period using Weibull:

$$T = \frac{n+1}{m}$$

T = return period [years]

n = total number of years of data

m = year rank of particular data point

3. Repeat 1 & 2 for other durations, through maximum needed duration (i.e. – 2 hr)
4. Interpolate (if needed) for return frequency of interest.
5. Convert amounts into intensities (using known duration) and plot data: x-axis is duration (min), y-axis is intensity (mm/hr), additional curves for each desired return frequency

IDF Curve Example

Return Period, T	Rank	Δ t in minutes					
		5	**10**	**15**	**20**	**25**	**30**
	1	12.1	18.5	24.2	28.3	29.5	31.5
	2	11.0	17.9	22.1	26.0	28.4	30.2
	3	10.7	17.5	21.9	25.2	27.6	29.9

- 32 years of rainfall data is available, recorded in 5 minute intervals. For the dataset, the #1 storm in each year **(annual maximum)** has been singled out – or all of the data is ranked **(partial duration),** and the top three years are shown above. Find the IDF curve for a return period of 20 years.
  - In other words, find the curve for the "20 year storm"

IDF Curve Example

Return Period, T	Rank	Δ t in minutes					
		5	**10**	**15**	**20**	**25**	**30**
33	1	12.1	18.5	24.2	28.3	29.5	31.5
16.5	2	11.0	17.9	22.1	26.0	28.4	30.2
11	3	10.7	17.5	21.9	25.2	27.6	29.9

- Step 1: Find maximum rainfall amount for each duration, each year.
- Step 2: Rank order data and calculate T.

$$T = \frac{n+1}{m}$$

T = return period [years]
n = total number of years of data
m = year rank of particular data point

$$T = \frac{32+1}{1}$$

IDF Curve Example

Return Period, T	Rank	Δ t in minutes					
		5	**10**	**15**	**20**	**25**	**30**
33	1	12.1	18.5	24.2	28.3	29.5	31.5
16.5	2	11.0	17.9	22.1	26.0	28.4	30.2
11	3	10.7	17.5	21.9	25.2	27.6	29.9

- Step 3: Repeat for other durations (already done)
- Step 4: Linearly interpolate to find desired return period.
  - 5 minute duration, between 16.5 and 33 years
  - 1.1 mm increase in 16.5 years (0.0667 mm per year)
  - 20 year, 5-minute storm will be: 11.0 + 3.5(0.0667) = 11.2 mm

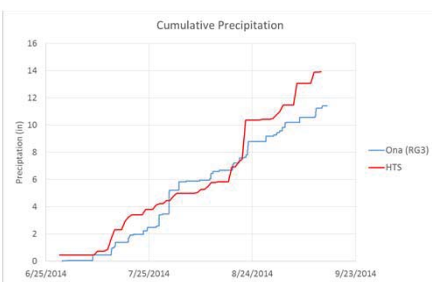
20 year storm

Duration (min)	5	10	15	20	25	30
Rainfall (mm)	11.2	18.0	22.5	26.5	28.6	30.5

Precipitation Data - Demonstration

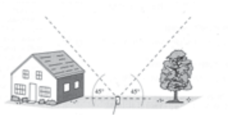
- PRISM - http://www.prism.oregonstate.edu/
- PFDS - http://dipper.nws.noaa.gov/hdsc/pfds/
- NCDC - http://www.ncdc.noaa.gov/cdo-web/
  - (Firefox browser may yield errors)
  - Data tools, Find a Station, Daily Summaries
  - Precip: mm or inches (inches to hundredths)

Spatial Variation - Local Rainfall Data

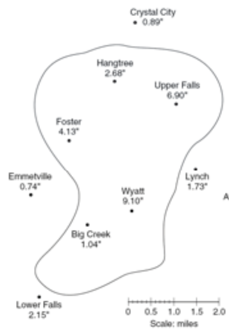


Other considerations

- In-splashing from area around the rain gage
- Obstructions
- Evaporation & wetting losses
- Instrument errors & observer errors
- Occult precipitation
- Low-intensity precipitation



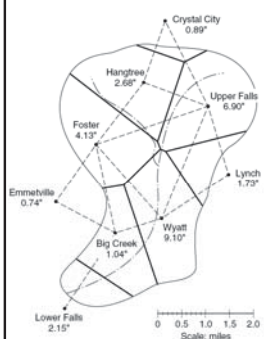
Areal average: arithmetic mean



$$\text{Average rainfall} = \frac{0.89 + 2.68 + 6.90 + 4.13 + 1.73 + 0.74 + 1.04 + 9.10 + 2.15}{9} = 3.26 \text{ in}$$

(*a*)

Areal average: Theissen method



(1) Station	(2) Recorded Rainfall Depth P (in)	(3) Area A Represented by Station (mi²)	(4) Rainfall Volume (mi²-in)
Crystal City	0.89	0.21	0.187
Hangtree	2.68	2.82	7.558
Upper Falls	6.90	3.00	20.700
Foster	4.13	2.64	10.903
Lynch	1.73	1.00	1.730
Emmetville	0.74	0	0
Wyatt	9.10	2.94	26.754
Big Creek	1.04	2.07	2.153
Lower Falls	2.15	0.82	1.763
	Totals	15.50	71.748

$$\text{Average rainfall} = \frac{71.748}{15.50} = 4.63 \text{ in}$$

(*b*)

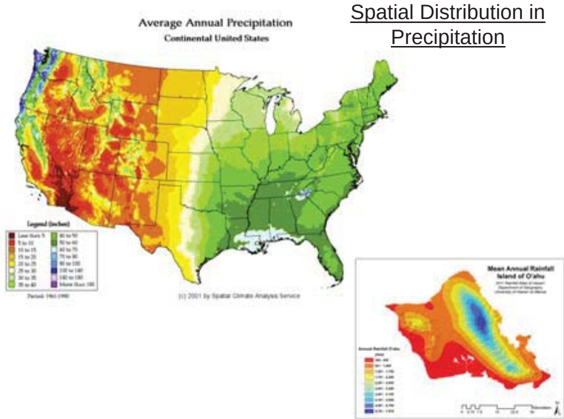
Example / Activity

Isohyetal Method

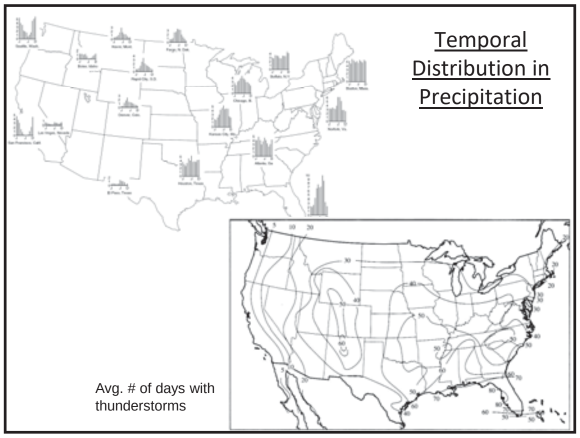
Rainfall Depth on Isohyet (in.)	Average Rainfall Depth (in.)	Area Between Isohyets (mi²)	Rainfall Volume (mi²-in.)
9.1			
8.0	8.55	0.407	3.480
6.0	7.0	1.412	9.884
5.0	5.5	0.841 + 1.375 = 2.216	1.219
4.0	4.5	0.592 + 1.697 = 2.289	10.300
3.0	3.5	3.122	10.927
2.0	2.5	2.599 + 0.431 = 3.030	7.575
	1.5	2.281	3.422
	1.0	0.05	0.050
1.0			
6.9			
6.0	6.45	0.693	4.470
	Totals	15.500	51.327

$$\text{Average rainfall} = \frac{51.327}{15.50} = 3.31 \text{ in.}$$

Spatial Distribution in Precipitation

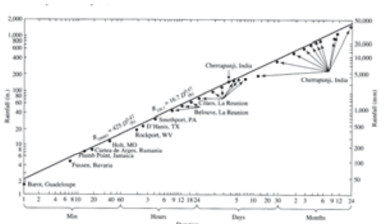


Temporal Distribution in Precipitation



Avg. # of days with thunderstorms

Maximum Precipitation



- Probable Maximum Precipitation (PMP) – theoretically the greatest depth of precipitation for a given duration that is physically possible over a given size of storm area at a particular geographical location at a certain time of year.

Probable Maximum Precipitation (PMP)

- Study of individual, extreme storms, their precipitation, and the area covered during the storm.

Table 3-4

MAXIMUM OBSERVED U. S. RAINFALL (in.)

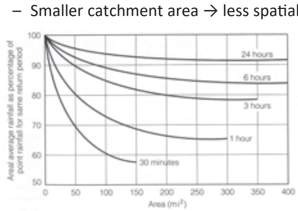
(Revised June 1960)

HMR41

Area (Square Miles)	Duration (hours) 6	12	18	24	36	48	72
10	24.7 a	29.8 b	36.3 c	38.7 c	41.8 c	43.1 c	45.2 c
100	19.6 b	26.3 c	32.5 c	35.2 c	37.9 c	38.9 c	40.6 c
200	17.9 b	25.6 c	31.4 c	34.2 c	36.7 c	37.7 c	39.2 c
500	15.4 b	24.6 c	29.7 c	32.7 c	35.0 c	36.0 c	37.3 c
1000	13.4 b	22.6 c	27.4 c	30.2 c	32.9 c	33.7 c	34.9 c
2000	11.2 b	17.7 c	22.5 c	24.8 c	27.3 c	28.4 c	29.7 c
5000	8.1 bj	11.1 b	14.1 b	15.5 c	18.7 d	20.7 d	24.4 d
10,000	5.7 j	7.9 k	10.1 e	12.1 e	15.1 d	17.4 d	21.3 d
20,000	4.0 j	6.0 k	7.9 e	9.6 e	11.6 d	13.8 d	17.6 d
50,000	2.5 eh	4.2 g	5.3 e	6.3 e	7.9 e	8.9 e	11.5 f
100,000	1.7 h	2.5 ih	3.5 e	4.3 e	5.6 e	6.6 f	8.9 f

Spatial Distribution

- Principle:
  - The “average” rainfall for a catchment is less than the rainfall at certain points
  - Longer storm → more averaging
  - Smaller catchment area → less spatial variation



F = areal-reduction factor (average rainfall : rain at a point)

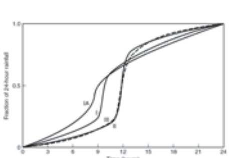
t_d = rainfall duration (hrs)

A = catchment area (miles^2)

$$F = 1 - \exp\left(-1.1 t_d^{\frac{1}{4}}\right) + \exp\left(-1.1 t_d^{\frac{1}{4}} - 0.01A\right)$$

Synthetic Storm Hyetograph: SCS Rainfall Distributions

- Types I and IA: Pacific maritime climate
  - *Wet winter, dry summer*
- Type II: Rest of United States
- Type III: Gulf of Mexico and Atlantic coastal areas
  - *Tropical storms dominate*



Using SCS Rainfall Distribution

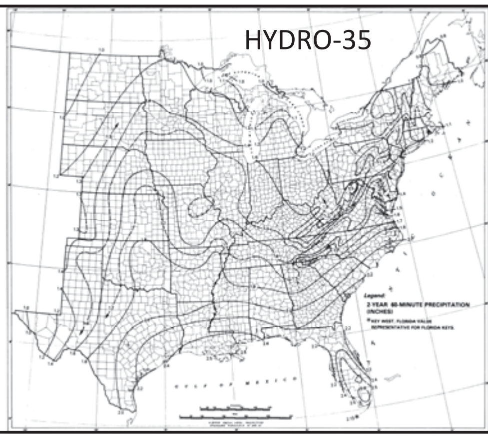
- Multiply the rainfall amount by the fraction given in the SCS Rainfall Distribution Table

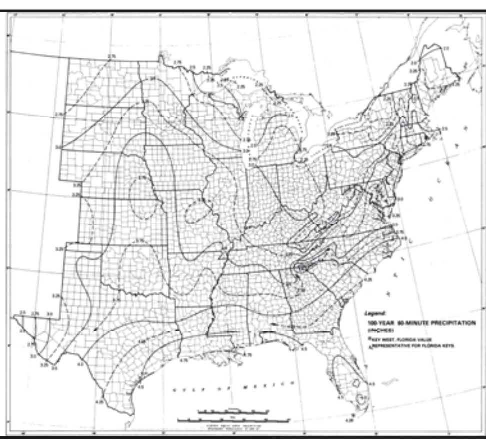
Table 7.2.2 SCS Rainfall Distributions

24-Hour Storm						6-Hour Storm		
		P_t/P_{24}						
Hour t	$t/24$	Type I	Type IA	Type II	Type III	Hour t	$t/6$	P_t/P_6
0	0	0	0	0	0	0	0	0
2.0	0.083	0.035	0.050	0.022	0.020	0.60	0.10	0.04
4.0	0.167	0.076	0.116	0.048	0.043	1.20	0.20	0.10
6.0	0.250	0.125	0.206	0.080	0.072	1.50	0.25	0.14
7.0	0.292	0.156	0.268	0.098	0.089	1.80	0.30	0.19
8.0	0.333	0.194	0.425	0.120	0.115	2.10	0.35	0.31
8.5	0.354	0.219	0.480	0.133	0.130	2.28	0.38	0.44
9.0	0.375	0.254	0.520	0.147	0.148	2.40	0.40	0.53
9.5	0.396	0.303	0.550	0.163	0.167	2.52	0.42	0.60
9.75	0.406	0.362	0.564	0.172	0.178	2.64	0.44	0.63
10.0	0.417	0.515	0.577	0.181	0.189	2.76	0.46	0.66
10.5	0.438	0.583	0.601	0.204	0.216	3.00	0.50	0.70
11.0	0.459	0.624	0.624	0.235	0.250	3.30	0.55	0.75
11.5	0.479	0.654	0.645	0.283	0.298	3.60	0.60	0.79
11.75	0.489	0.669	0.655	0.357	0.339	3.90	0.65	0.83
12.0	0.500	0.682	0.664	0.663	0.500	4.20	0.70	0.86
12.5	0.521	0.706	0.683	0.735	0.702	4.50	0.75	0.89
13.0	0.542	0.727	0.701	0.772	0.751	4.80	0.80	0.91
13.5	0.563	0.748	0.719	0.799	0.785	5.40	0.90	0.96
14.0	0.583	0.767	0.736	0.820	0.811	6.00	1.0	1.00
16.0	0.667	0.830	0.800	0.880	0.886			
20.0	0.833	0.926	0.906	0.952	0.957			
24.0	1.000	1.000	1.000	1.000	1.000			

Source: U.S. Dept. of Agriculture Soil Conservation Service (1973, 1986).

HYDRO-35





Design Depth Interpolation

$$P_{10\,\text{min}} = 0.41 P_{5\,\text{min}} + 0.59 P_{15\,\text{min}}$$

$$P_{30\,\text{min}} = 0.51 P_{15\,\text{min}} + 0.49 P_{60\,\text{min}}$$

For 2 or 100 year return period.

$$P_{T\,yr} = aP_{2\,yr} + bP_{100\,yr}$$

Table 7.2.1 Coefficients for Interpolating Design Precipitation Depths Using Equation (7.2.2)

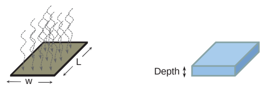
Return period *T* years	*a*	*b*
5	0.674	0.278
10	0.496	0.449
25	0.293	0.669
50	0.146	0.835

Source: Frederick, Myers, and Auciello (1997).

HYDRO-35 provides 5- 15- and 60-min durations and return periods of 2 and 100 years. All other data must be ***interpolated*** *using the above equations.*

Hydrology Concepts

- Rainfall amount: volume (m^3) vs. length (mm)
  - Depth of rainfall over an area



- Rainfall intensity vs. rainfall amount
  - Rate (mm/hr) vs. length (mm)
- Recurrence Interval
  - High intensity storms are rare, low probability
  - Size of storm can be described by how infrequently they return

Figure 4.1.1. Map of daily stations for NOAA Atlas 14 Volume 2.

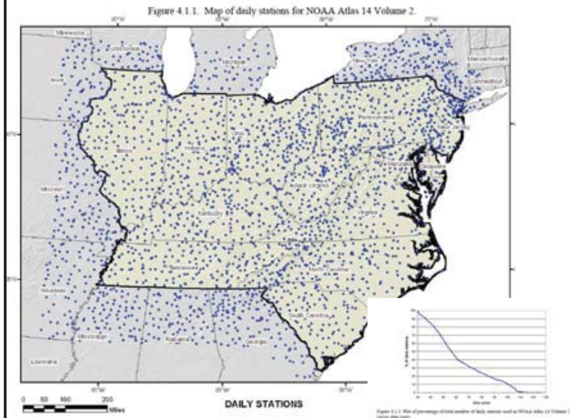
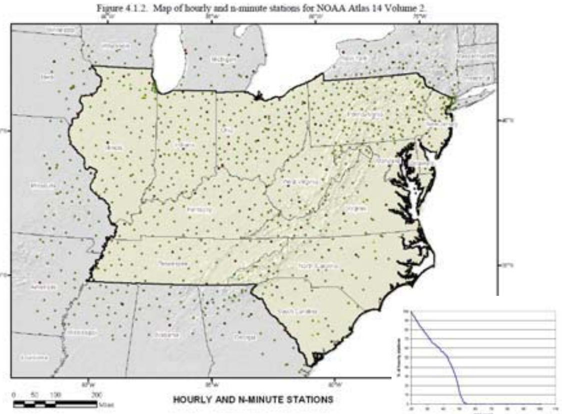


Figure 4.1.2. Map of hourly and n-minute stations for NOAA Atlas 14 Volume 2.



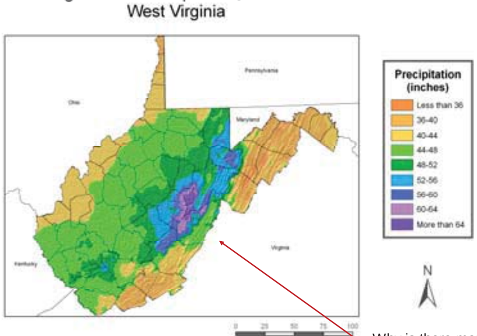
Huntington Airport

Precipitation Frequency Estimates

ARI* (years)	5 min	10 min	15 min	30 min	60 min	120 min	3 hr	6 hr	12 hr	24 hr	48 hr	4 day	7 day	10 day	20 day	30 day	45 day	60 day
1	0.36	0.55	0.68	0.90	1.09	1.26	1.32	1.57	1.84	2.23	2.66	3.07	3.66	4.21	5.84	7.28	9.24	11.11
2	0.42	0.66	0.81	1.08	1.33	1.52	1.60	1.88	2.19	2.66	3.16	3.64	4.32	4.96	6.85	8.50	10.76	12.89
5	0.51	0.79	0.97	1.32	1.66	1.90	1.99	2.32	2.68	3.21	3.78	4.32	5.07	5.75	7.83	9.62	12.03	14.30
10	0.57	0.88	1.08	1.50	1.91	2.19	2.30	2.67	3.08	3.67	4.29	4.86	5.64	6.35	8.56	10.44	12.97	15.33
25	0.65	0.99	1.23	1.73	2.25	2.59	2.72	3.17	3.64	4.30	4.97	5.58	6.39	7.13	9.48	11.45	14.12	16.57
50	0.71	1.08	1.33	1.90	2.51	2.90	3.06	3.57	4.11	4.82	5.53	6.14	6.96	7.71	10.16	12.19	14.93	17.44
100	0.77	1.15	1.43	2.07	2.77	3.22	3.41	3.99	4.59	5.35	6.09	6.70	7.52	8.27	10.79	12.86	15.65	18.21
200	0.82	1.23	1.53	2.23	3.03	3.55	3.76	4.42	5.09	5.90	6.66	7.26	8.06	8.80	11.38	13.48	16.32	18.91
500	0.90	1.32	1.64	2.43	3.37	3.99	4.25	5.02	5.80	6.67	7.45	8.01	8.76	9.48	12.11	14.22	17.09	19.70
1000	0.95	1.38	1.73	2.58	3.63	4.33	4.63	5.50	6.37	7.27	8.05	8.58	9.27	9.97	12.62	14.74	17.61	20.24

- Is this a table of ***amount*** or ***intensity***?
  - Look at the values for increasing duration: intensity will decrease, amount will increase by ever-smaller margins

Average Annual Precipitation, 1971-2000
West Virginia



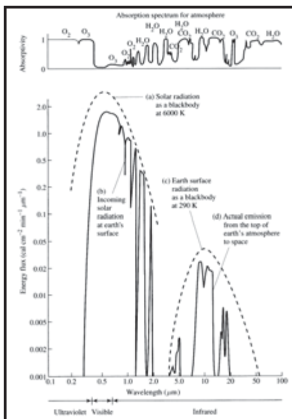
Map copyright (c) 2006 by the PRISM Group and Oregon Climate Service, Oregon State University.

Why is there more rain here?

What Factors Influence Evaporation Rate?

Evaporation Videos

- Time Lapse: http://www.youtube.com/watch?v=T5MtQ0H_tiY
- Leidenfrost Effect: http://www.youtube.com/watch?v=srAUFqEDvWU
- Canada: http://www.youtube.com/watch?v=ZGjwe-BCfms
- Vacuum: https://youtu.be/0x32Sw5ulVM?t=99

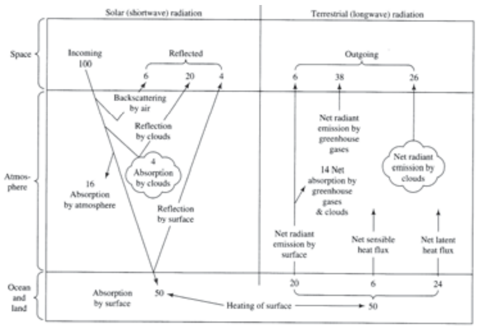


Energy Spectra & the Atmosphere

Barry and Chorley (1982) and Miller et al. (1983)

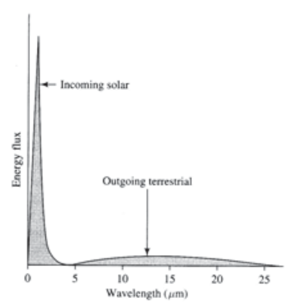
Average Global Energy Balance

(100 units = solar constant, 1367 W m^{-2}



Shuttleworth (1991) and Peixoto and Oort (1992)

Spectra of Incoming and Outgoing Terrestrial Radiation

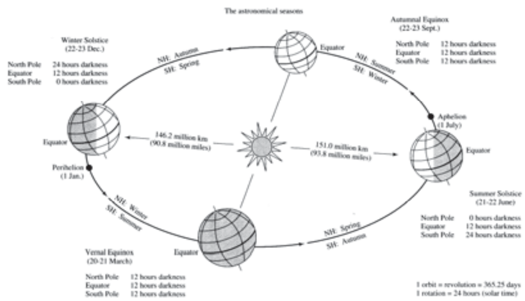


Barry and Chorley (1982)

Variation in Solar Radiation Intensity – Angle of Incidence

Day and Sternes (1970)

Astronomical Seasons



Oliver and Hidore (1984)

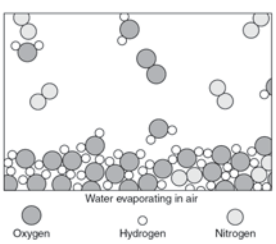
Humidity

http://www.shorstmeyer.com/wxfaqs/humidity/humidity.html

Water vapor exists as a gas when air temperature is below 100 °C because it has enough kinetic **energy** to exist as a gas

- Not all molecules have the same kinetic energy at a given temperature
  - There is a distribution of kinetic energies, related to molecule collisions
- Heat / energy from the sun keeps water vapor as a gas
  - There is constant exchange between liquid and gas phase

Evaporation at the molecular level



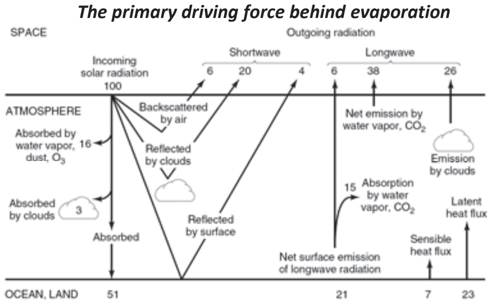
Temporal, Spatial average: 3 mm / day

- Consider
  - Quantity of gas molecules above liquid layer
    - *How is this measured?*
  - Quantity of water molecules, specifically
    - *How is this measured?*
  - What causes liquid water molecules to vaporize?

Latent heat of vaporization – energy required during vaporization of a liquid (water: $L_v = 2.501 \times 10^6 - 2370\ T$ (J per kg of water. T is in deg C)

Solar Radiation

The primary driving force behind evaporation

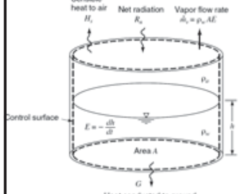


- *Why must incoming radiation = outgoing radiation?*

Evaporation Modeling:

Energy Balance Method ***liquid phase***

How much energy is available to provide the latent heat of vaporization?



Control surfaces that enclose an evaporation pan

Storage Transport

$$-\dot{m}_v = \frac{d}{dt}\int_{cv}\rho_w d\forall + \cancel{\sum_{cs}\rho_w \mathrm{V}\cdot \mathrm{A}}$$

Pan is impermeable

$$\frac{d}{dt}\int_{cv}\rho_w d\forall = \rho_w A\frac{dh}{dt}$$

Thus…

$$\dot{m}_v = \rho_w A\frac{-dh}{dt} = \rho_w AE$$

Evaporation: Energy Balance Method, cont.

Vapor Phase

$$\dot{m}_v = \frac{d}{dt}\int_{cv} q_v \rho_a d\forall + \sum_{cs} q_v \rho_a \mathrm{V}\cdot\mathrm{A}$$

q_v = specific humidity (mass of water / mass of air)

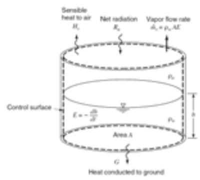
$$\frac{d}{dt}\int_{cv} q_v \rho_a d\forall_w = 0$$

Steady flow, water vapor in CV is constant

$$\rho_w AE = \sum_{cs} q_v \rho_a \mathrm{V}\cdot\mathrm{A}$$

or

$$E = \frac{1}{\rho_w A}\sum_{cs} q_v \rho_a \mathrm{V}\cdot\mathrm{A}$$



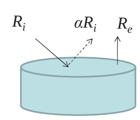
Evaporation: Energy Balance Method, cont.

Heat input

$$\frac{dH}{dt} = \frac{d}{dt}\int_{cv} e_u \rho_w d\forall = l_v \dot{m}_v$$

$$\frac{dH}{dt} = R_n - H_s - G$$

$$R_n = R_i(1-\alpha) - R_e$$



dH/dt = rate of heat input
e_u = specific internal heat energy of water
l_v = 2.501 x 10^6 – 2370T (°C) latent heat of vaporization (J/kg)
R_n = net radiation flux (W/m^2)
H_s = sensible heat flux to air by water
G = ground heat flux to ground by water

$$\frac{dH}{dt} = R_n - H_s - G$$

for $\dot{m}_v = \rho_w AE$
and assuming H_s and G are zero

$$E_r = \frac{R_n}{l_v \rho_w}$$

Evaporation Example (energy)

- Incident radiation at the Khaled Lagoon is 978 W/m^2 at noon on February 12th. Water temperature is 26.0 °C. Air temperature is 28.5°C, relative humidity is **75**%, and wind speed is **1.7** m/s at 2m.
  - Determine the open water evaporation rate in mm/d using the energy method

$$l_v = 2.501\times10^6 - 2370T$$

$$E_r = \frac{R_n}{l_v \rho_w}$$

$$R_n = R_i(1-\alpha) - R_e$$

$$R_e = e\sigma T_p^{\ 4}$$

Albedo, α = 0.35
Radiation emissivity of water, e = 0.995
Stefan-Boltzman constant, σ = 5.67 E^{-8} W/m^2 ·K^4
T_p = water temperature [K]

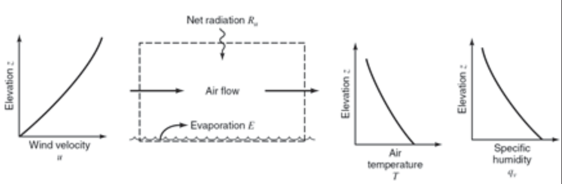
Evaporation: Review

- What is “latent heat of vaporization”?
- What is the name of the radiation emitted by the earth?
- What does the “energy method” estimate in order to predict evaporation rate?

Evaporation Modeling:

Aerodynamic Method

- *How quickly can water vapor be transported away from the water surface*



- ***Driving force****: <u>gradient</u> (difference) in amount of water in the air*
- *More wind = greater rate of vapor transport (provides unsaturated air)*
- *Large difference in temp = greater difference between sat. vapor pressure and ambient vapor pressure*
- *<u>Large difference in specific humidity = driving force</u>*

Evaporation Modeling:

Aerodynamic Method, *cont…*

$$E_a = B\left(e_{as} - e_a\right)$$

$$B = \frac{0.102 u_2}{\left[\ln\left(z_2 / z_0\right)\right]^2}$$

$$e_{as} = 611 \exp\left(\frac{17.27 T_a}{237.3 + T_a}\right)$$

$$e_a = R_h e_{as}$$

E_a = evaporation rate (aerodynamic)
B = vapor transfer coefficient (mm/d·Pa)
e_{as} = saturation vapor pressure (Pa)
e_a = ambient vapor pressure (Pa)
R_h = relative humidity
u_2 = wind velocity (m/s) at height z_2 (cm)
z_0 = water surface roughness height (cm), typically 0.01 – 0.06 cm
T_a = air temp (°C)

Evaporation Example (aerodynamic)

- Net radiation at the Khaled Lagoon is 185 W/m^2 at noon on February 12th. Air temperature is 28.5°C, relative humidity is **75**%, and wind speed is **1.7** m/s at 2m.
  - Determine the open water evaporation rate in mm/d using the aerodynamic method, with z_0 = 0.03 cm

$$e_{as} = 611\exp\left(\frac{17.27T_{air}}{237.3+T_{air}}\right)$$

$$e_a = R_h e_{as}$$

$$B = \frac{0.102u_2}{\left[\ln(z_2/z_0)\right]^2}$$

$$E_a = B(e_{as} - e_a)$$

Evaporation Modeling:

The Combined Method

- Non-limiting energy supply → use aerodynamic method
- Non-limiting vapor transport → use energy balance method
- Either case is rare
  - A combined method is required

$$E = \left(\frac{\Delta}{\Delta+\gamma}\right)E_r + \left(\frac{\gamma}{\Delta+\gamma}\right)E_a$$

Available energy   aerodynamic

Priestley-Taylor

$$\approx 1.3\left(\frac{\Delta}{\Delta+\gamma}\right)E_r$$

$$\Delta = \frac{4098e_{as}}{(237.3+T_a)^2} \qquad \gamma = \frac{(c_p)_{air}P}{l_v MW_{ratio}} = 66.8\ \text{Pa}/^\circ\text{C}$$

Gradient of saturated vapor pressure curve   *Psychrometric constant*

Evaporation Example (combined)

- Net radiation at the Khaled Lagoon is 185 W/m^2 at noon on February 12th. Air temperature is 28.5°C, relative humidity is 75%, and wind speed is 1.7 m/s at 2m.
  - Determine the open water evaporation rate in mm/d using the **combined** method and **Priestley-Taylor** method

$$\Delta = \frac{4098e_{as}}{(237.3+T_a)^2}$$

$$E = \left(\frac{\Delta}{\Delta+\gamma}\right)E_r + \left(\frac{\gamma}{\Delta+\gamma}\right)E_a$$

$$\approx 1.3\left(\frac{\Delta}{\Delta+\gamma}\right)E_r \quad \text{(P-T)}$$

Evaporation Pans

- Directly measure amount of evaporation
  - Used to estimate crop evaporation, ET_0
  - Utilize pan coefficients that depend on conditions
  - Considers solar radiation, wind, temperature, humidity


Wind	Case A: Pan surrounded by short green crop				Case B: Pan surrounded by dry, bare area			
		Mean relative humidity, %				Mean relative humidity, %		
	Upwind fetch of green crop, m	Low <40	Med 40–70	High >70	Upwind fetch of dry fallow, m	Low <40	Med 40–70	High >70
Light (<2 m/s)	1	0.55	0.65	0.75	1	0.70	0.80	0.85
	10	0.65	0.75	0.85	10	0.60	0.70	0.80
	100	0.70	0.80	0.85	100	0.55	0.65	0.75
	1000	0.75	0.85	0.85	1000	0.50	0.60	0.70
Moderate (2–5 m/s)	1	0.50	0.60	0.65	1	0.65	0.75	0.80
	10	0.60	0.70	0.75	10	0.55	0.65	0.70
	100	0.65	0.75	0.80	100	0.50	0.60	0.65
	1000	0.70	0.80	0.80	1000	0.45	0.55	0.60
Strong (5–8 m/s)	1	0.45	0.50	0.60	1	0.60	0.65	0.70
	10	0.55	0.60	0.65	10	0.50	0.55	0.65
	100	0.60	0.65	0.70	100	0.45	0.50	0.60
	1000	0.65	0.70	0.75	1000	0.40	0.45	0.55
Very strong (>8 m/s)	1	0.40	0.45	0.50	1	0.50	0.60	0.65
	10	0.45	0.55	0.60	10	0.45	0.50	0.55
	100	0.50	0.60	0.65	100	0.40	0.45	0.50
	1000	0.55	0.60	0.65	1000	0.35	0.40	0.45

Source: Doorenbos and Pruitt (1977).

Evapotranspiration

$$ET_0 = k_p E_p$$

Identify conditions
- Wind speed
- Relative humidity
- Upwind fetch

Select Pan Coeff.

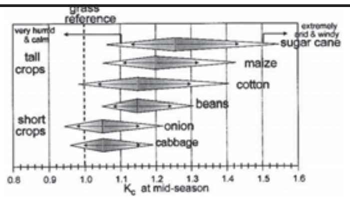
Apply Equation

Discuss Trend of ET_0 vs k_p : (1) Wind speed, (2) Upwind fetch, (3) Relative Humidity

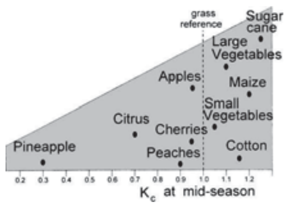
Evaporation Pan Example

- Average wind speed in Northeast Ohio is 2.7 m/s and the mean relative humidity is 65%. If an evaporation pan (surrounded by 100 m of dry fallow on all sides) measures 4.2 mm of evaporation per day:
  - What is the monthly reference evapotranspiration for short, irrigated grass turf?
  - How much irrigation should farmers provide?
    - Will evapotranspiration be more or less for corn, compared to grass?


$$ET_0 = k_p E_p$$



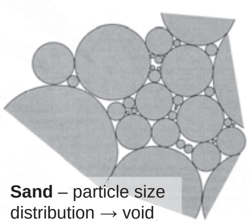
Water demands of other crops relative to a grass reference



Clay – bound by inter-grain electrostatic forces

Soil Particle Aggregates - Conceptual Diagrams

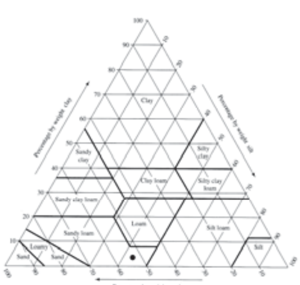
How do soil properties influence the behavior of water?



Sand – particle size distribution → void size distribution

Soil-texture triangle

*(Soil is a **mixture** of components)*



Particle Size Classification

Clay < 0.002 mm

0.002 mm < Silt < 0.05 mm

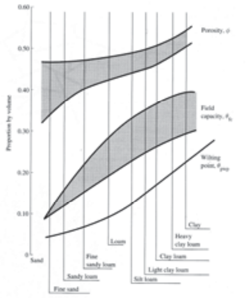
0.05 mm < Sand < 2 mm

2 mm < Gravel

Example

% > 2 mm	25%
% Sand	40%
% Silt	33%
% Clay	2%

Soil Property Ranges



Porosity – pore space / total volume.

Field Capacity – moisture content in soil after draining excess water. Usually 2-3 days after precipitation.

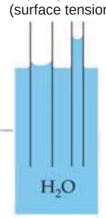
Wilting point – minimum soil moisture required for plants not to wilt.

Interpretation: moisture 'moves' more easily in sand than in clay

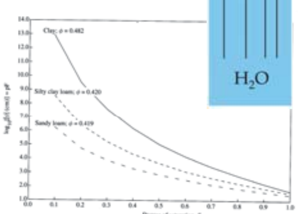
Soil-water pressure (tension)

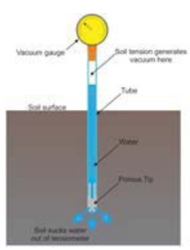
Suction (tension) in the unsaturated zone

Capillary effect
(surface tension)

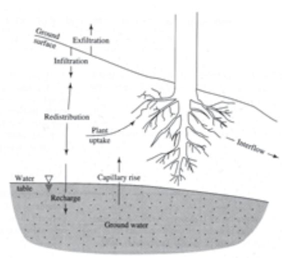


Tension is much higher in finer-grained than in coarser-grained soils





Water Movement in **Unsaturated** Zone



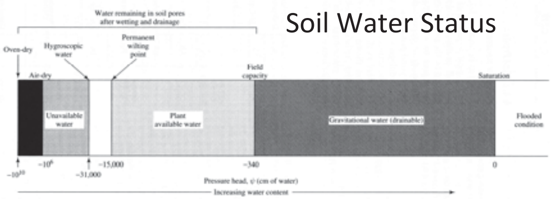
76% of land-area precipitation infiltrates.

Provides water for natural and cultivated plants.

Responsible for recharge of ground-water reservoirs.

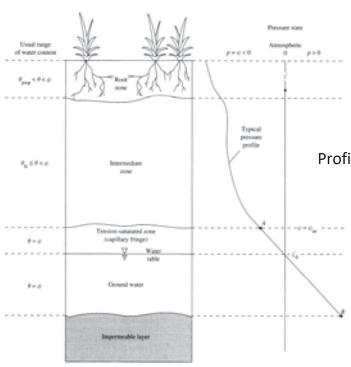
Water that does not infiltrate becomes **overland flow.**

Soil Water Status



- **Field capacity** – minimum soil water content after indefinite gravitational drainage
- **Permanent wilting point** – natural vegetation cannot remove enough water to match moisture **loss to atmosphere**
- **Hygroscopic water** – water forms thin layers around soil particles. Tightly held, not available to plants.

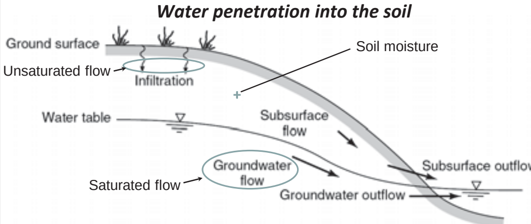
Soil Profile Horizons



Profile varies during infiltration event.

Infiltration

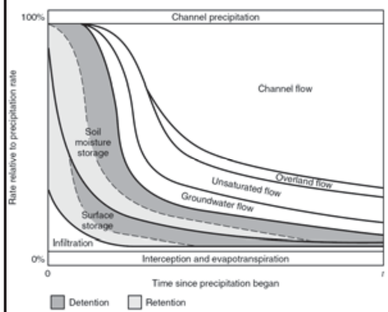
Water penetration into the soil



<u>Rate of infiltration depends on</u>

- Condition of soil surface
- Vegetative cover
- Soil properties: porosity, hydraulic conductivity, moisture content

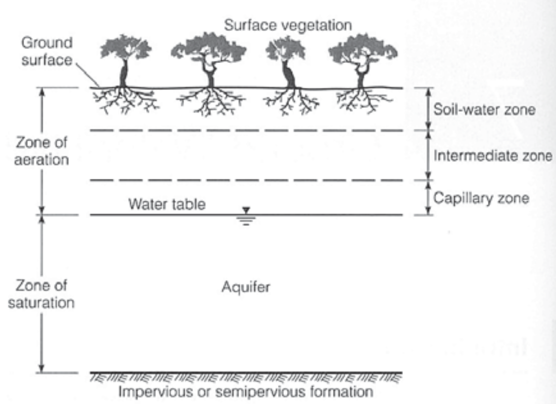
Rainfall and Watershed Response

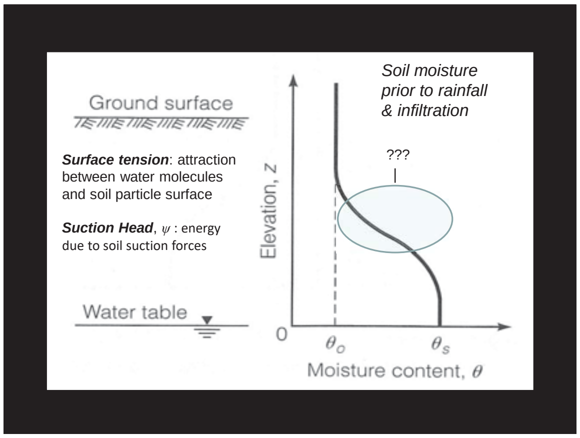


- ***Retention***: water kept for a long period of time, removed by evaporation
- ***Detention***: water kept for a short period, depleted by outflow

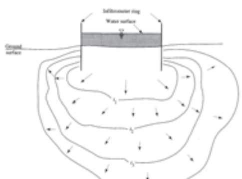
Important Terms

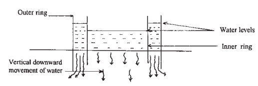
- ***Zone of saturation***: region where soil void spaces are completely filled with water
- ***Zone of aeration***: region where void spaces are not filled with water, and where atmospheric gasses can circulate
  - ***Soil-water zone***: where vegetation roots are found, water capacity limited by gravity / maximum moisture content in soil
  - ***Intermediate zone***: between soil-water and capillary zone
  - ***Capillary zone***: where additional moisture is present in soil due to capillary forces





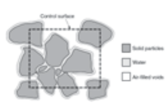
Infiltrometer test





Subsurface Flow: Important Definitions

porosity $$\eta = \frac{\text{volume of voids}}{\text{total volume}}$$



→ *porosity varies from 0.25 to 0.40*

soil moisture content $$\theta = \frac{\text{volume of water}}{\text{total volume}}$$

→ *soil moisture varies from 0 to η (saturated soil: $\theta = \eta$)*
→ *the amount of soil moisture gained during infiltration, as θ increases from θ_i to θ_s is $\Delta\theta$*
→ *after soil is thoroughly drained, it still has* ***residual moisture content***, θ_r

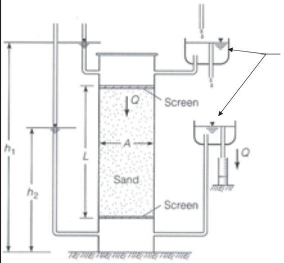
effective saturation $$s_e = \frac{\theta - \theta_r}{\eta - \theta_r} \qquad \frac{\text{available moisture (at a given time)}}{\text{effective porosity, } \theta_e}$$

Darcy's Law

- Studying the performance of sand filters in treating drinking water, Darcy measured the flowrate of water through sand.

Hydraulic Conductivity, K, key parameter dictating flow rate *(m/s)*

Constant water surface elevations



$$Q = KA\frac{h_1 - h_2}{L}$$

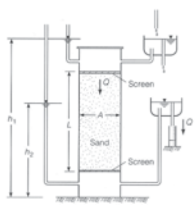
$$J = \frac{h_2 - h_1}{L} \qquad q = \frac{Q}{A}$$

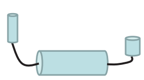
$$\boxed{q = -KJ}$$ *Darcy Flux*

Darcy Example

$$Q = KA\frac{h_1 - h_2}{L}$$

- *A "fine sand" has hydraulic conductivity of 3 m/d. What flow rate would be expected through a 1 m long, 25 cm diameter column of soil where the head differential is 35 mm?*

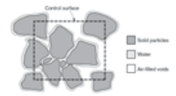




- Water movement in soil:
- https://www.youtube.com/watch?v=ego2FkuQwxci

Subsurface Flow: Important Definitions

porosity $\eta = \dfrac{\text{volume of voids}}{\text{total volume}}$



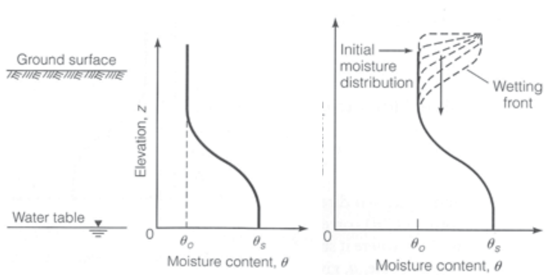
→ *porosity varies from 0.25 to 0.40*

soil moisture content $\theta = \dfrac{\text{volume of water}}{\text{total volume}}$

→ *soil moisture varies from 0 to η (saturated soil: $\theta = \eta$)*
→ *the amount of soil moisture gained during infiltration, as θ increases from θ_i to θ_s is $\Delta\theta$*
→ *after soil is thoroughly drained, it still has **residual moisture content,** θ_r*

effective saturation $s_e = \dfrac{\theta - \theta_r}{\eta - \theta_r}$ $\dfrac{\text{available moisture (at a given time)}}{\text{effective porosity, } \theta_e}$

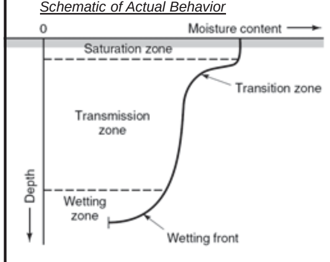
Soil Water



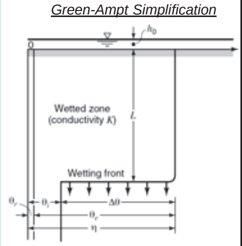
During a rainfall event, a soil's capacity to absorb water decreases. During a storm, *<u>infiltration rate decreases with time.</u>*

Moisture Zones **During** Infiltration

Schematic of Actual Behavior



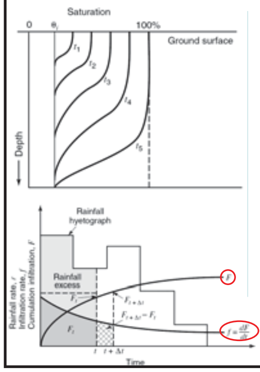
Green-Ampt Simplification



$$Q = KA\frac{h_1 - h_2}{L} \quad \longrightarrow \quad f = K\,\frac{h_0 - (-\psi - L)}{L} \approx K\left[\frac{\psi + L}{L}\right]$$

Q [=] m³/s f = infiltration rate (cm/s) ψ = *wetting front soil suction head*

Cumulative Infiltration, F



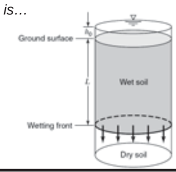
$$F(t) = \int_0^t f(\tau)d\tau$$

f = infiltration rate

During infiltration through a column of soil, moisture content increases from θ_i to η

$$F(t) = L(\eta - \theta_i)$$

So the question is… what is L at t?



Green-Ampt Equation

For cumulative infiltration and infiltration rate

$$F(t) = Kt + \psi\Delta\theta \ln\left(1 + \frac{F(t)}{\psi\Delta\theta}\right) \qquad f(t) = K\left[\frac{\psi\Delta\theta}{F(t)} + 1\right]$$

$F(t)$ = cumulative infiltration from time 0 until time t
$f(t)$ = infiltration rate at time t
ψ = suction head
$\Delta\theta$ = increase in soil moisture during infiltration
K = hydraulic conductivity
t = time period during which infiltration occurs
s_e = effective saturation
θ_e = effective porosity

<u>*Notes:*</u>

$$\Delta\theta = (1 - s_e)\theta_e$$

Green-Ampt assumes continuous ponding

<u>Method:</u>

- Given K, t, ψ and $\Delta\theta$
- Substitute a "trial" value of F(t) on RHS
  - Good first try: $F(t) = Kt$
- Calculated value of $F(t)$ on LHS is substituted into RHS
- Iterate until convergence

Table 7.4.1 Green-Ampt Infiltration Parameters for Various Soil Classes*

Soil class	Porosity η	Effective Porosity θ_e	Wetting Front Soil Suction Head ψ (cm)	Hydraulic Conductivity K (cm/h)
Sand	0.437 (0.374–0.500)	0.417 (0.354–0.480)	4.95 (0.97–25.36)	11.78
Loamy sand	0.437 (0.363–0.506)	0.401 (0.329–0.473)	6.13 (1.35–27.94)	2.99
Sandy loam	0.453 (0.351–0.555)	0.412 (0.283–0.541)	11.01 (2.67–45.47)	1.09
Loam	0.463 (0.375–0.551)	0.434 (0.334–0.534)	8.89 (1.33–59.38)	0.34
Silt loam	0.501 (0.420–0.582)	0.486 (0.394–0.578)	16.68 (2.92–95.39)	0.65
Sandy clay loam	0.398 (0.332–0.464)	0.330 (0.235–0.425)	21.85 (4.42–108.0)	0.15
Clay loam	0.464 (0.409–0.519)	0.309 (0.279–0.501)	20.88 (4.79–91.10)	0.10
Silty clay loam	0.471 (0.418–0.524)	0.432 (0.347–0.517)	27.30 (5.67–131.50)	0.10
Sandy clay	0.430 (0.370–0.490)	0.321 (0.207–0.435)	23.90 (4.08–140.2)	0.06
Silty clay	0.479 (0.425–0.533)	0.423 (0.334–0.512)	29.22 (6.13–139.4)	0.05
Clay	0.475 (0.427–0.523)	0.385 (0.269–0.501)	31.63 (6.39–156.5)	0.03

*The numbers in parentheses below each parameter are one standard deviation around the parameter value given.

Hydraulic conductivity **decreases** from sand → clay

Soil Suction head **increases** from sand → clay

Why is effective porosity closer to porosity for sand than it is for clay?

$$F(t) = Kt + \psi\Delta\theta \ln\left(1 + \frac{F(t)}{\psi\Delta\theta}\right)$$

Green-Ampt Example

- A silty clay soil has the characteristics shown below. Find the infiltration depth and infiltration rate after 0.1 hour and 0.2 hour assuming initial effective saturation of 45% and continuous ponding (use Solver, not Goal-Seek)

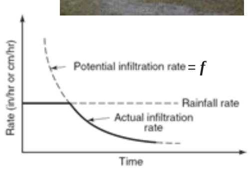
$$\Delta\theta = (1 - s_e)\theta_e$$

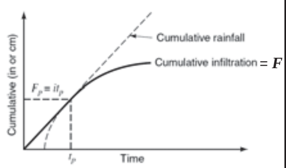
Parameter	Value
θ_e (effective porosity)	0.423
ψ (Soil suction head)	29.22 cm
K (hydraulic conductivity)	0.05 cm/hr

$$F(t) = Kt + \psi\Delta\theta \ln\left(1 + \frac{F(t)}{\psi\Delta\theta}\right)$$

$$f(t) = K\left[\frac{\psi\Delta\theta}{F(t)} + 1\right]$$

Ponding Time





$$t_p = \frac{K\psi\Delta\theta}{i(i-K)}$$

i = rainfall intensity
ψ = suction head
$\Delta\theta$ = increase in soil moisture during infiltration
K = hydraulic conductivity
t_p = time to ponding

Ponding Time Example

- The soil characterized below has an initial effective saturation of 45%.
  a) For a constant rainfall intensity of 1.5 cm/hr, how long until ponding occurs?
  b) What rainfall intensity will cause ponding after 20 minutes?
  c) How much cumulative infiltration during 0 to 0.156 hr?

Parameter	Value
θ_e (effective porosity)	0.423
ψ (Soil suction head)	29.22 cm
K (hydraulic conductivity)	0.05 cm/hr

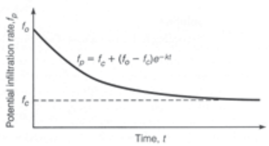
$$t_p = \frac{K\psi\Delta\theta}{i(i-K)}$$

Horton Model (of declining potential infiltration rate)

Assumes continuous ponding above soil column.

Rate: $$f_p = f_c + (f_o - f_c)e^{-kt}$$

Soil type	f_o (mm/h)	f_c (mm/h)	k (min^{-1})
Alphalpha loamy sand	483	36	0.64
Carnegie sandy loam	375	45	0.33
Dothan loamy sand	88	67	0.02
Fuquay pebbly loamy sand	158	61	0.08
Leefield loamy sand	288	44	0.13
Tooup sand	584	46	0.55



f_p = potential infiltration rate
f_o = initial infiltration rate
f_c = minimum infiltration rate
k = infiltration constant
t = time (min)

Horton Model: Infiltration depth (cumulative)

$$F_t = f_c t + \frac{(f_o - f_c)}{k}\left(1 - e^{-kt}\right)$$

Horton Example

- Calculate the infiltration rate as a function of time for a Leefield loamy sand.

$$f_p = f_c + (f_o - f_c)e^{-kt}$$

Soil type	f_o (mm/h)	f_c (mm/h)	k (min^{-1})
Alphalpha loamy sand	483	36	0.64
Carnegie sandy loam	375	45	0.33
Dothan loamy sand	88	67	0.02
Fuquay pebbly loamy sand	158	61	0.08
Leefield loamy sand	288	44	0.13
Tooup sand	584	46	0.55

  - What is the infiltration rate after 15 minutes of 300 mm/hr rain?
    - What happens if the rainfall is < f_0?

Large Scale Hydrologic Model

Water: Where it is coming from, where is it going, and how much of both?

$$Q_{out} = Q_{in} + PR - ET - GR - \Delta S - LQ - AG$$

Q_{out} = Stream discharge from watershed
Q_{in} = Water in from upstream
PR = Precipitation
ET = Evapotranspiration
GR = Groundwater recharge (+/-)
ΔS = Surface water storage recharge (+/-)
LQ = Large Quantity user water consumption
AG = Agricultural user water consumption

Abstraction

The difference between observed precipitation and rainfall excess.

- The process of the quantity (or timing) rainfall being *changed* prior to water entry into a discharge system
  - Delay, and routing effects
  - Quantity reduction

- Design implications:
  - Conveyance network sizing
    - Peak storm intensity delayed by abstraction
  - Detention / retention pond sizing
  - Treatment process parameters and sizing
  - Channel capacity and sizing

Interception

- Amount of rainfall being collected by vegetation (and buildings) before it can reach the ground
- Heavy vegetation intercepts more water

Cover type	Season	Interception (%)	Reference
Conifers			
Picea abies	Year	48	Leyton et al. (1967)
Tsuga canadensis	Summer	33	Voigt (1960)
Pseudotsuga	Year	36	Aussenac and Boulangeat (1980)
Pseudotsuga	Summer	24	Rothacher (1963)
	Winter	14	
Pinus caribaea	Year	18	Waterloo et al. (1999)
Pinus radiata	Year	26	Feller (1981)
Pinus radiata	Year	19	Smith (1974)
Pinus resinosa	Summer	19	Voigt (1960)
Pinus strobus	Year	16	Helvey (1967)
Pinus taeda	Year	14	Swank et al. (1972)
Evergreen hardwoods			
Notofagus sp.	Year	33	Aldridge and Jackson (1973)
Notofagus/Podocarpus	Summer	30	Rowe (1979)
	Winter	21	
Acacia	Year	19	Beard (1962)
Eucalyptus regnans	Year	19	Feller (1981)
Melaleuca quinquenervia	Summer	19	Woodall (1984)
Moist tropical forest	Summer	16	Jackson (1971)
Mixed eucalypts	Year	11	Smith (1974)
Deciduous hardwoods			
Carpinus sp.	Year	36	Leyton et al. (1967)
Fagus grandifolia	Summer	25	Voigt (1960)
Fagus silvatica	Summer	21	Aussenac and Boulangeat (1980)
	Winter	6	
Liriodendron	Year	10	Helvey (1964)
Grasses			
Themeda sp.	Year	13	Beard (1962)
Cymbopogon sp.	Year	13	Beard (1962)
Soil cover			
Hardwood litter	Year	3	Helvey (1964)
Pinus strobus litter	Year	3	Helvey (1967)
Oak litter	Year	2	Blow (1955)
Pinus caribaea litter	Year	8	Waterloo et al. (1999)
Pinus taeda litter	Year	4	Swank et al. (1972)

Actual amount of rainfall intercepted can be affected by:

- Storm characteristics (intensity, duration, temporal distribution)
- Local climate (humidity, evaporation)
- Density of vegetation
- Age, size, health of vegetation

Calculating Interception

- Account for
  - vegetative storage, *S* (mm)
  - amount of rainfall, *P* (mm)
  - leaf area index (leaf area: projected ground area), *K*
  - evaporation rate during the storm, *E* (mm/hr)
  - storm duration, *t* (hr)

Vegetation	Storage (mm)
Pine trees	3 – 4
Spruce, fir, hemlock	7
Hardwood (leafed)	3
Bare hardwood	1

$$I = S\left(1 - e^{-\frac{P}{S}}\right) + KEt$$

Example: Interception

- During a 1.5 hour long storm, 3.8 cm of precipitation falls. Evaporation during the storm is 0.3 mm/hr.
  - For spruce trees with a leaf area index of 6.5, how much precipitation is available for runoff & infiltration?

Vegetation	Storage (mm)
Pine trees	3 – 4
Spruce, fir, hemlock	7
Hardwood (leafed)	3
Bare hardwood	1

$$I = S\left(1 - e^{-\frac{P}{S}}\right) + KEt$$

Depression Storage

Some of the precipitation does not immediately infiltrate or runoff.

- Water accumulation in surface depressions (puddles)
- Due to topography, not subject to transport
- Water in depression storage will eventually infiltrate or evaporate

Typical Depression Storage Quantities

For moderate slope. Flatter slope → more depression storage.

Surface Type	Depression storage (mm)	Reference
Pavement:		
Steep	0.5	Pecher (1969), Viessman et al. (1977)
Flat	1.5, 3.5	Pecher (1969), Viessman et al. (1977)
Impervious areas	1.3–2.5	Tholin and Kiefer (1960)
Lawns	2.5–5.1	Hicks (1944)
Pasture	5.1	ASCE (1992)
Flat roofs	2.5–7.5	Butler and Davies (2000)
Forest litter	7.6	ASCE (1992)

- Additional Factors:
  - Slope
  - Specific surface area (surface area / plan-view area… porosity)
  - Water affinity of material
  - Previous, recent rainfall events (depression storage still wet / already full)

Motivations for Studying **Stream Response**

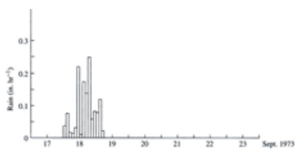
- Water supply (quantity)

- Flood Prediction and Forecasting

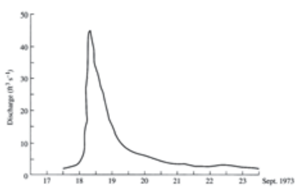
- Water Quality

Stream Response

- ***Hyetograph*** – graph of water input vs. time

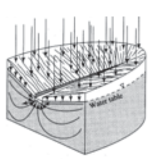


- ***Streamflow hydrograph*** – graph of stream discharge vs. time

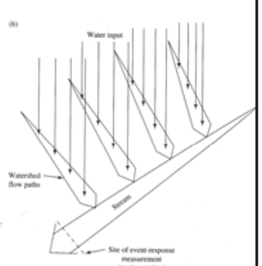


Factors that Influence Response

- Precipitation characteristics
- Watershed characteristics

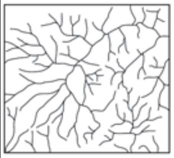


Flow network & path



Flow with lateral inflows

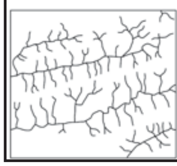
Drainage Basin: topographic area that collects and discharges surface streamflow through one outlet or mouth



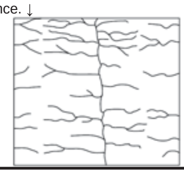
Rectangular → : preferential flow in fractured rock & fault lines

↑ **Dendritic**: uniform erosion resistance

Trellis – mature coastal plain: unequal erosion resistance. ↓

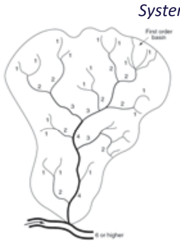


←**Trellis** - folded: unequal resistance to erosion. Tributaries extend in lest resistant areas.



Stream Ordering

System to classify network hierarchy



- ***First order*** – a non-branching channel segment
- ***Second order*** – receives only first-order segments
- When lower-order joins higher-order, classification retains higher order

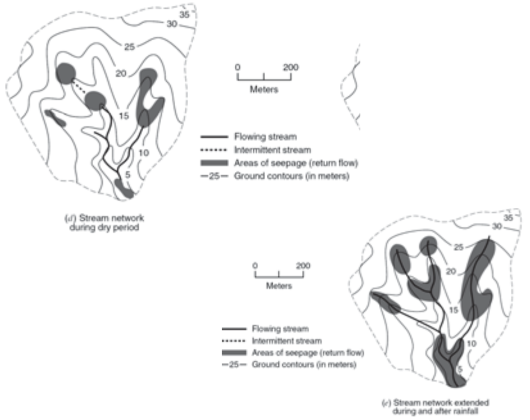
---

- ***Perennial streams***– continuous flow, well defined channel
- ***Intermittent Streams*** – only flow during wet season (<50%)
- ***Ephemeral Streams*** – flow only during or immediately after storms

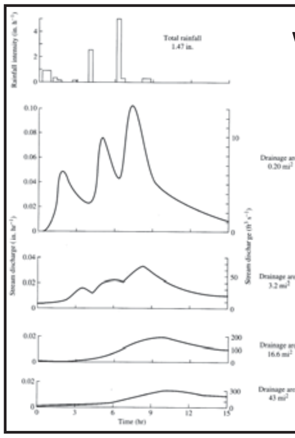
Perennial stream ↑

Intermittent stream ↑

Ephemeral stream →



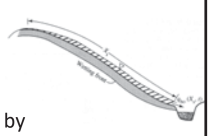
Watershed area and stream response



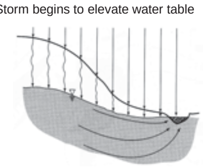
Flow through the stream network attenuates the peaks of a runoff hydrograph.

Flow Mechanisms, cont.

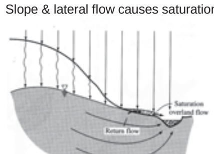
- Overland flow
  - *Hortonion Overland Flow*: Caused by saturation from above.
  - *Saturation Overland Flow*: Caused by saturation from below (e.g., groundwater movement from upslope).



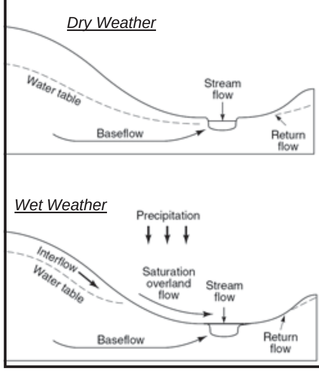
Storm begins to elevate water table



Slope & lateral flow causes saturation



Channel Water Sources

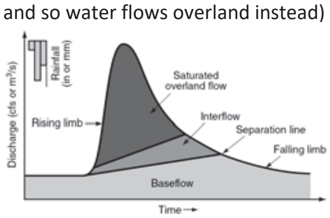


- ***Baseflow*** – groundwater that enters the channel
  - Typically present even during dry weather
- ***Return flow*** – infiltrated water that re-emerges at the surface and enters the channel
- ***Overland flow*** – surface flow that enters the stream

Hydrograph

graphical representation of streamflow over time

- ***Interflow***: lateral motion of water in the vadose zone until it reaches a stream
- ***Rising limb***: discharge increasing over time
- ***Saturated overland flow***: water that is the result of rainfall onto soil in excess of potential infiltration (soil is saturated, and so water flows overland instead)



Hydrograph

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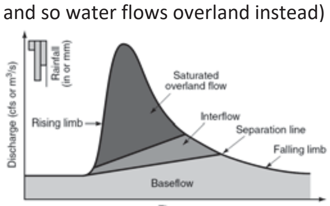
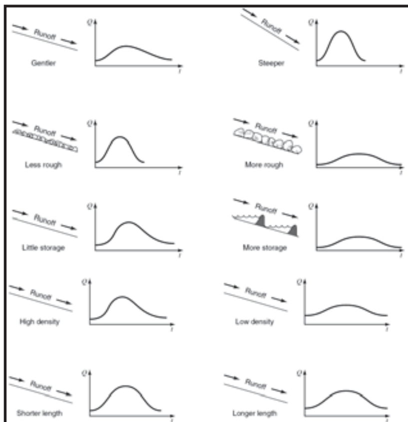


Hydrograph Shape

- *"When the local **abstractions** have been accomplished for a small area of a watershed, water begins to flow overland as overland flow, and eventually into a drainage channel (in a gulley or stream valley)."*

- Factors:
  - Drainage area
  - Channel slope
  - Hydraulic roughness
  - Natural and channel storage
  - Stream length
  - Channel density
  - Antecedent moisture conditions
  - Other: vegetation, channel modifications, etc.



Slope

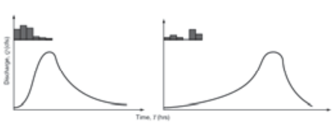
Hydraulic Roughness

Storage

Drainage Density

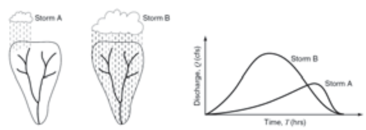
Channel Length

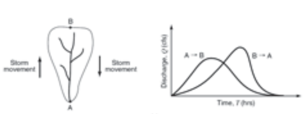
Hydrograph Shape, cont…



Temporal distribution of rainfall

Geographic size of storm / spatial distribution

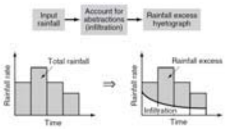




Storm direction & Movement

Rainfall Excess

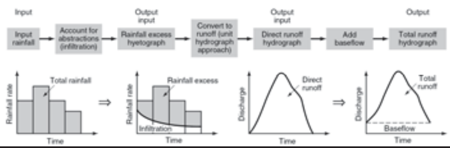
Rain that is neither retained on the surface nor infiltrated into soil.



Why is infiltration decreasing over time?

Hyetograph vs hydrograph: ***hyetograph*** – bar graph of rainfall vs time. ***Hydrograph*** – graph of some property of a stream over time (flow, stage, velocity, etc.)

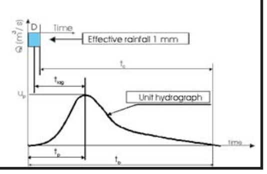
Analytical steps – rainfall to runoff



Unit Hydrograph

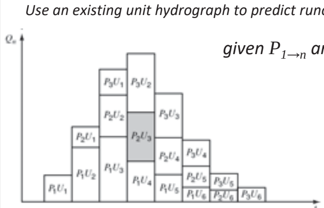
A simple linear model of rainfall excess and catchment hydrograph

- The amount of runoff resulting from 1 unit (inch, cm, etc.) of rainfall excess
- Principle: once you know a watershed's response to one storm, you can predict what its response for another storm will look like
- Assumes
  - Constant intensity
  - Uniformly distributed
  - Time increment is constant
  - Watershed is not changing



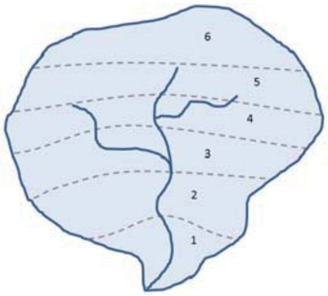
Multiple Unit Hydrographs

Use an existing unit hydrograph to predict runoff during a non-unit rainfall event



given $P_{1\to n}$ and $U_{1\to n}$ find $Q_{1\to n}$

For multiple "pulses" of precipitation, combine responses to each individual segment of precipitation.



Response to 1 in of
Rainfall Excess

Time (hr)	Flow (cfs)
1	10
2	100
3	200
4	150
5	100
6	50

Time (h)	1	2	3	4
Precipitation (in)	0.5	1.0	1.5	0.5

Unit Hydrograph Example

- One inch of rainfall excess falls onto a watershed in one hour, and yields the following "unit hydrograph"
  - What is the hydrograph if a precipitation event yields the rainfall excess shown below? (**Assume abstractions of .3 inches per hour**)

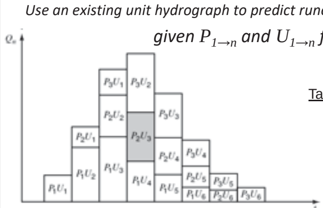
Time (hr)	Flow (cfs)
1	10
2	100
3	200
4	150
5	100
6	50

Time (h)	1	2	3	4
Precipitation (in)	0.5	1.0	1.5	0.5

Unit Hydrograph

Use an existing unit hydrograph to predict runoff during a non-unit rainfall event

given $P_{1\rightarrow n}$ *and* $U_{1\rightarrow n}$ *find* $Q_{1\rightarrow n}$



Conceptual figure of runoff
(there are FOUR rainfall excess periods)

Table of "U"

Time (hr)	Flow (cfs)
1	10
2	100
3	200
4	150
5	100
6	50

Table of "P"

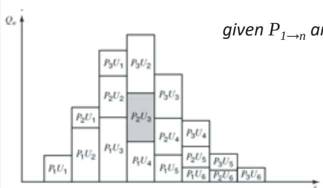
Time (h)	1	2	3	4
Precipitation (in)	0.5	1.0	1.5	0.5
Rainfall Excess (in)	0.2	0.7	1.2	0.2

Spreadsheet Example

Q_1 =	P_1U_1	0	0	0	0	0	0	0	0	0	0
Q_2 =	P_2U_1 +	P_1U_2	0	0	0	0	0	0	0	0	0
Q_3 =	P_3U_1 +	P_2U_2 +	P_1U_3	0	0	0	0	0	0	0	0
Q_4 =	P_4U_1 +	P_3U_2 +	P_2U_3 +	P_1U_4	0	0	0	0	0	0	0
Q_5 =	0 +	P_4U_2 +	P_3U_3 +	P_2U_4 +	P_1U_5	0	0	0	0	0	0
Q_6 =	0 +	0 +	P_4U_3 +	P_3U_4 +	P_2U_5 +	P_1U_6	0	0	0	0	0
Q_7 =	0 +	0 +	0 +	P_4U_4 +	P_3U_5 +	P_2U_6 +	P_1U_7	0	0	0	0
Q_8 =	0 +	0 +	0 +	0 +	P_4U_5 +	P_3U_6 +	P_2U_7 +	P_1U_8	0	0	0
Q_9 =	0 +	0 +	0 +	0 +	0 +	P_4U_6 +	P_3U_7 +	P_3U_8 +	P_1U_9 +	0	0
Q_{10} =	0 +	0 +	0 +	0 +	0 +	0 +	P_4U_7 +	P_3U_8 +	P_2U_9 +	P_1U_{10}	0
Q_{11} =	0 +	0 +	0 +	0 +	0 +	0 +	0 +	P_4U_8 +	P_3U_9 +	P_2U_{10} +	P_1U_{11}

Unit Hydrograph

Use an existing unit hydrograph to predict runoff during a non-unit rainfall event



given $P_{1\to n}$ and $U_{1\to n}$ find $Q_{1\to n}$

Table of "U"

Time (h)	1	2	3	4	5	6
Flow (cfs)	10	100	200	150	100	50

- What if…
  - Given P
  - Given Q
  - **Need to find U**

Table of "P"

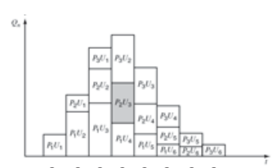
Time (h)	1	2	3	4
Precipitation (in)	0.5	1.0	1.5	0.5

Deconvolution: developing a unit hydrograph

$$Q_n = \sum_{1}^{n \le m} P_m U_{n-m+1}$$

n = runoff hydrograph time interval
m = precipitation time interval

- See spreadsheet -



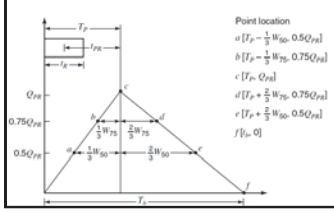
Synthetic Unit Hydrographs

- Sometimes rainfall-runoff data is not available to make a unit hydrograph
  - Even when it is, a unit hydrograph is only valid for the watershed where the data was collected, and only for the location where streamflow data were measured

- ***Synthetic hydrographs*** – use geometric or statistical procedures to interpolate a unit hydrographs where actual data is not available

Snyder's Synthetic Unit Hydrograph

- Driving principal: the time lag between the middle of the rainfall and the peak of runoff



Example: Snyder's Synthetic Unit Hydrograph

Watershed area, A = 5.42 mi^2

Main channel length, L = 4.45 mi

Distance from outlet to watershed centroid, L_c = 2.0 mi

Regional parameters, C_t = 2.0, C_p= 0.625

- Find the "standard duration", t_r

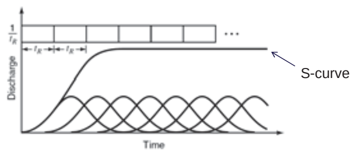
a) Find the synthetic unit hydrograph for a desired rainfall excess duration (t_R) of 60 min

b) Find the synthetic unit hydrograph for a desired rainfall excess duration (t_R) of 30 min

S-hydrographs

A method for changing a unit hydrograph from one duration to another

- Given: a unit hydrograph that corresponds to some rainfall excess duration, t_R (e.g., 2 hr)
- Wanted: a unit hydrograph that corresponds to a different rainfall excess duration, t'_R (e.g., 4 hr)
- Method depends on an "S-Curve"



The S-curve is made by lagging the unit hydrograph by t_R an infinite number of times, and summing the result

Excel Example: S-Curve

- One inch of rain falls during 2 hours (t_R), and yields the following hydrograph:

Time Hrs	2-hr Unit Hydrograph (cfs/in)
0	0
2	69
4	143
6	328
8	389
10	352
12	266
14	192
16	123
18	84
20	49
22	20
24	0
26	0

Question: What is the hydrograph if one inch of rain falls during 4 hours (t'_R)?

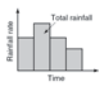
Procedure:
1. Create the S-Curve
2. Lag by t'_R
3. Subtract the lagged S-Curve from the original S-Curve
4. Divide the result by t'_R/t_R

What is the "big question" of this course?

NRCS Approach: Conceptually

A Watershed Model Works to Define…

Rainfall (Temporal Distribution) → **Runoff** (Temporal Distribution)

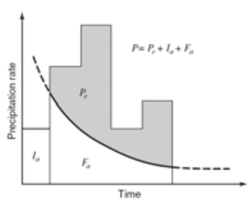


<u>Influencing Factors:</u>
- Soil properties
- Land cover
- Abstractions (interception, surface wetting, minor ponding)
- Ground slope
- Stream characteristics
- Watershed geometry (size, shape, stream density)

<u>NRCS Approach</u>
- Define soil & land characteristics
- Estimate distribution of initial abstraction, retention, and runoff, in terms of overall **depth** during the event
- Use a unit hydrograph to translate runoff depth into runoff *flow*

SCS / NRCS Curve Number Model

$$\frac{F_a}{S} = \frac{P_e}{P - I_a} \qquad \frac{\text{Actual amount stored}}{\text{Potential amount stored}}$$



F_a = retention; water reaching ground that is retained by catchment. Mainly infiltrated water.

S = potential maximum retention; related to retention capacity of soil

I_a = initial abstraction; rainfall stored in catchment before runoff begins.

P_e = rainfall excess, runoff.

P = precipitation.

During a rainfall event, the portion of the available storage (S) that gets filled (F) is the available rainfall (P-I_a) that appears as direct runoff (P_e).

$I_a = 0.2S$ (Empirical approximation)

Mass Balance and the NRCS Method

IN (Rainfall) → Watershed
- Initial Abstraction
- Retention

→ OUT (Runoff)

Accumulation

Soil storage and Runoff Volume

- Calculate soil storage

$$S = \left(\frac{1000}{CN} - 10\right)$$

- Calculate runoff depth

P>0.2S $\quad P_e = \dfrac{(P - 0.2S)^2}{P + 0.8S}$ $\qquad$ $P_e = 0$ $\quad$ P<0.2S

Example: NRCS Method

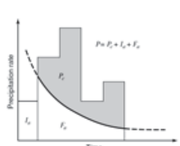
$$S = \left(\frac{1000}{CN} - 10\right) \qquad P_e = \frac{(P - 0.2S)^2}{P + 0.8S}$$

$$I_a = 0.2S \qquad \frac{F_a}{S} = \frac{P_e}{P - I_a}$$

- What is the rainfall excess depth for a watershed (CN = 70) that experiences:
  a) 0.7 inches of rainfall
  b) 3.5 inches of rainfall
    - In this case, 'where is the water?'

Rainfall-Runoff

$$\frac{F_a}{S} = \frac{P_e}{P - I_a}$$



$$S = \left(\frac{1000}{CN} - 10\right)$$

$$P_e = \frac{(P - 0.2S)^2}{P + 0.8S}$$

- For HW **8**, Problem 3, use cumulative P up to a certain time, and…

$$F_{a,t} = \frac{S(P_t - I_a)}{P_t - I_a + S}$$

Curve Number Estimation

Soil Group Classification

- **Group A**: deep sand, deep loess (wind-blown granular silt), aggregated silts
- **Group B**: shallow loess, sandy loam (mix of sand, clay, and decaying organics)
- **Group C**: clay loams, shallow sandy loam, soils low in organic content, soils usually high in clay
- **Group D**: soils that swell when wet, heavy plastic clays, certain saline soils

Group	Minimum Infiltration Rate (in/hr)
A	0.30 – 0.45
B	0.15 – 0.30
C	0 – 0.05

Land Use Description	Average % impervious[b]	Curve Numbers for Hydrologic Soil Group A	B	C	D
Fully developed urban areas[a] (vegetation established)					
Lawns, open spaces, parks, golf courses, cemeteries, etc.					
Good condition; grass cover on 75% or more of the area		39	61	74	80
Fair condition; grass cover on 50% to 75% of the area		49	69	79	84
Poor condition; grass cover on 50% or less of the area		68	79	86	89
Paved parking lots, roofs, driveways, etc.		98	98	98	98
Streets and roads					
Paved with curbs and storm sewers		98	98	98	98
Gravel		76	85	89	91
Dirt		72	82	87	89
Paved with open ditches		83	89	92	93
Commercial and business areas	85	89	92	94	95
Industrial districts	72	81	88	91	93
Row houses, town houses, and residential with lot sizes 1/8 acre or less	65	77	85	90	92
Residential: average lot size					
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84
2 acre	12	46	65	77	82
Developing urban areas[c] (no vegetation established)					
Newly graded area		77	86	91	94

Cover: Land Use	Treatment of Practice	Hydrologic Condition[d]	A	B	C	D
Cultivated agricultural land						
Fallow	Straight row		77	86	91	94
	Conservation tillage	Poor	76	85	90	93
	Conservation tillage	Good	74	83	88	90
Row crops	Straight row	Poor	72	81	88	91
	Straight row	Good	67	78	85	89
	Conservation tillage	Poor	71	80	87	90

Table 8.7.3 Runoff Curve Numbers (Average Watershed Condition, $I_a = 0.2S$)

Land Use Description		Curve Numbers for Hydrologic Soil Group A	B	C	D
Meadow	—	30	58	71	78
Forestland—grass or	Poor	55	73	82	86
orchards—evergreen or	Fair	44	65	76	82
deciduous	Good	32	58	72	79
Brush	Poor	48	67	77	83
	Good	20	48	65	73
Woods	Poor	45	66	77	83
	Fair	36	60	73	79
	Good	25	55	70	77
Farmsteads	—	59	74	82	86
Forest–range					
Herbaceous	Poor		79	86	92
	Fair		71	80	89
	Good		61	74	84
Oak–aspen	Poor		65	74	
	Fair		47	57	
	Good		30	41	
Juniper–grass	Poor		72	83	
	Fair		58	73	
	Good		41	61	
Sage–grass	Poor		67	80	
	Fair		50	63	
	Good		35	48	

Condition: depends on the density of ground cover. (e.g., "fair" hydrologic condition for noncultivated agricultural land is 25 – 50% cover density)

The Geography of Recession

- https://worldview.stratfor.com/article/geography-recession

The Geography of Recession
By Peter Zeihan, Stratfor

Volume 5 - Special Edition
June 4, 2009

The United States and the Free Market

The most important aspect of the United States is not simply its sheer size, but the size of its usable land. Russia and China may both be similar-sized in absolute terms, but the vast majority of Russian and Chinese land is useless for agriculture, habitation or development. In contrast, courtesy of the Midwest, the United States boasts the world's largest contiguous mass of arable land — and that mass does not include the hardly inconsequential chunks of usable territory on both the West and East coasts.

Second is the American maritime transport system. The Mississippi River, linked as it is to the Red, Missouri, Ohio and Tennessee rivers, comprises the largest interconnected network of navigable rivers in the world. In the San Francisco Bay, Chesapeake Bay and Long Island Sound/New York Bay, the United States has three of the world's largest and best natural harbors. The series of barrier islands a few miles off the shores of Texas and the East Coast form a water-based highway — an Intercoastal Waterway — that shields American coastal shipping from all but the worst that the elements can throw at ships and ports.

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	Fair		50	63	
	Good		35	48	

Condition: depends on the density of ground cover. (e.g., “fair” hydrologic condition for noncultivated agricultural land is 25 – 50% cover density)

Curve Number Estimation

Antecedent Moisture Classes (AMC)

AMC Group	Total 5-Day Antecedent Rainfall (in) Dormant Season	Growing Season
I	Less than 0.5	Less than 1.4
II	0.5 to 1.1	1.4 to 2.1
III	Over 1.1	over 2.1

Source: U.S. Department of Agriculture Soil Conservation Service (1972).

$$CN(\mathrm{I}) = \frac{4.2CN(\mathrm{II})}{10 - 0.058CN(\mathrm{II})}$$

$$CN(\mathrm{III}) = \frac{23CN(\mathrm{II})}{10 + 0.13CN(\mathrm{II})}$$

Example: A residential ¼ acre lot on class "B" soil has a curve number of 75 under AMC group II conditions.

•*What would be the curve number if there had been no rain in the past five days?*

•*What would be the curve number if, in July, it had rained 3 inches in the past five days?*

Composite Curve Numbers

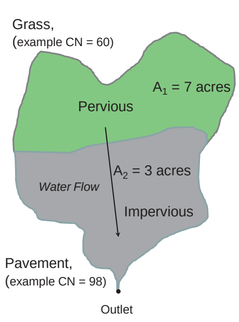
- For watersheds of several subcatchments with different CNs, compute the area-averaged CN
- ***Example***: For the watershed summarized in the table below, what is the **rainfall excess** for a rainfall of 6 inches?

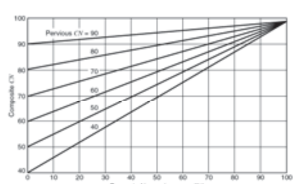
Land Use (%)	Soil Group	Curve Number
40	C	83
25	D	80
20	C	94
15	D	93

$$S = \left(\frac{1000}{CN} - 10\right)$$

$$\mathrm{P}_e = \frac{(P - 0.2S)^2}{P + 0.8S}$$

Composite CN: Connected Impervious Areas

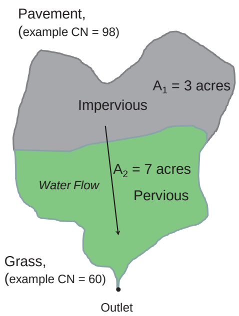


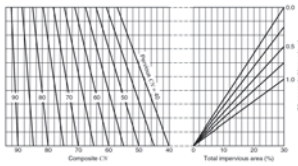


Example: Runoff from 7 acres of grass flows over and joins runoff from 3 acres of pavement before reaching the outlet.

What is the Composite Curve Number for this catchment? (Ans. 72)

Composite CN: Unconnected Impervious Areas

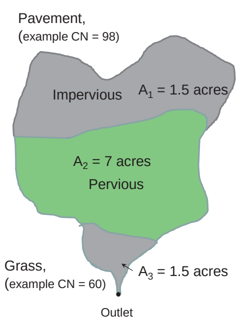


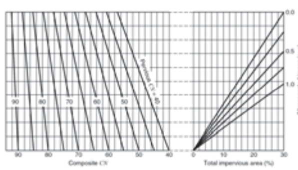


Example: Runoff from 3 acres of pavement flows over and joins runoff from 7 acres of grass before reaching the outlet.

What is the Composite Curve Number for this catchment? (Ans. 65)

Composite CN: Connected & Unconnected Impervious Areas





Example: Runoff from 1.5 acres of pavement flows over and joins runoff from 7 acres of grass, all of which flows over and joins runoff from 1.5 acres of pavement before reaching the outlet.

What is the Composite Curve Number for this catchment? (Ans. 68)

Demo: Geospatial Data

Google Earth Pro

https://www.google.com/earth/download/gep/agree.html

- Enable/disable terrain and other layers
- Measure area
- Import Shapefiles

Soil Type: STATSGO (low-res) and SSURGO (high-res)

http://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx

- Define Area of Interest (AOI)
- Browse soil classifications and characteristics (Soil Map)
- Soil Data Explorer: (a) Suitabilities (Forest Prod), (b) Soil Properties & Qualities, Soil Qualifies & Features, Hydrologic Soil Group
- Download Soils Data

Demo: Geospatial Data, continued

National Land Cover Database

https://www.mrlc.gov/nlcd11_data.php

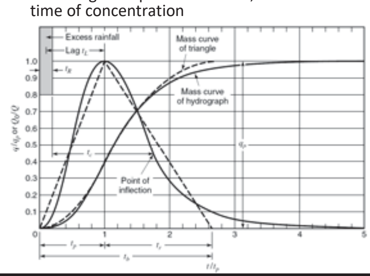
- Entire NLCD raster (USA)

https://viewer.nationalmap.gov/basic/

-Download individual states

SCS Unit Hydrograph Method

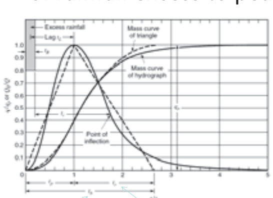
- Similar in background and approach to Snyder's synthetic unit hydrograph
  - Find runoff hydrograph by knowing some geographic parameters about the watershed to define *"lag time"*
  - Advantage: shape is curvilinear; can use SCS-derived runoff quantities & time of concentration



Time of Concentration

For use in SCS unit hydrograph

- ***Time Lag*** (t_L) time in hours from center of mass of rainfall excess to peak discharge



$$t_b = 2.67t_p \qquad t_r = 1.67t_p$$

$$t_L = \frac{L^{0.8}(S+1)^{0.7}}{1900Y^{0.5}}$$

Y = slope (%)
L = hydraulic length (ft)
S = potential maximum retention (in)

$$t_c = \frac{5}{3}t_L$$

Time to Peak and Peak Discharge

$$t_p = 0.67 t_c \qquad P_e [=] Q \qquad q_p = \frac{484AQ}{t_p}$$

A= watershed area (mi^2)
Q = amount of direct runoff (in) - for a 'unit hydrograph' Q = 1 inch
V = velocity (ft/s)
q_p = peak discharge for a unit hydrograph (ft^3/s)

General Description	Peaking Factor	Limb Ratio (Recession to Rising)
Urban areas; steep slopes	575	1.25
Typical SCS	**484**	1.67
Mixed urban/rural	400	2.25
Rural, rolling hills	300	3.33
Rural, slight slopes	200	5.5
Rural, very flat	100	12.0

SCS Unit Hydrograph **Example**

- For a 3.0 mi^2 watershed of CN 86, find the **unit** hydrograph peak discharge (given: 3% slope and 1.2 mile hydraulic length)

1. Find time of concentration $\quad t_L = \frac{L^{0.8}(S+1)^{0.7}}{1900Y^{0.5}} \qquad t_c = \frac{5}{3} t_L$
2. Find time to peak $\quad t_p = 0.67 t_c$
3. Find peak discharge $\quad q_p = \frac{484AQ}{t_p}$

- *What is the flow rate at t = 87 min?*

$$S = \left(\frac{1000}{CN} - 10\right)$$

Time Ratios (t/t_p)	Discharge Ratios (q/q_p)	Mass Curve Ratios (Q_a/Q)
0.0	0.000	0.000
0.1	0.030	0.001
0.2	0.100	0.006
0.3	0.190	0.012
0.4	0.310	0.035
0.5	0.470	0.065
0.6	0.660	0.107
0.7	0.820	0.163
0.8	0.930	0.228
0.9	0.990	0.300
1.0	1.000	0.375
1.1	0.990	0.450
1.2	0.930	0.522
1.3	0.860	0.589
1.4	0.780	0.650
1.5	0.680	0.700
1.6	0.560	0.751
1.7	0.460	0.790
1.8	0.390	0.822
1.9	0.330	0.849
2.0	0.280	0.871
2.2	0.207	0.908
2.4	0.147	0.934
2.6	0.107	0.953
2.8	0.077	0.967
3.0	0.055	0.977
3.2	0.040	0.984
3.4	0.029	0.989
3.6	0.021	0.993
3.8	0.015	0.995
4.0	0.011	0.997
4.5	0.005	0.999
5.0	0.000	1.000

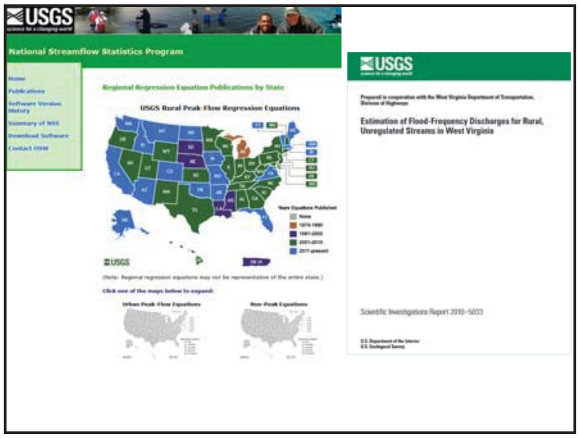
Physical Measurement of Lag Time

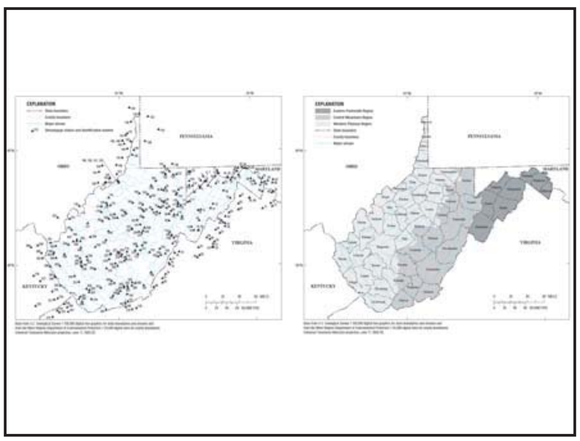
WMS Program Outline

- Pre- / Post-Processor for Hydrologic Models
  - **GUI** for models that were previously command-line (text) driven
  - Read (& obtain) **GIS data** to compute parameters
  - **Calculator** for parameters based on GIS data
  - Generate reports & model **outputs** (e.g., hydrographs)
- Integration with hydraulic / water quality models
  - HEC-RAS
  - HY8
  - CE-Qual-W2

WMS Demo – Program Tour, Basic Modeling

- Delineate watershed: Ona, WV
  - Images, identification, elevation, delineation (TOPAZ)
- Activity 1: Images
- Activity 2: DEMs and Watersheds


USGS
science for a changing world
National Streamflow Statistics Program
Home
Publications
Software Version History
Summary of NSS
Download Software
Contact OSW
Regional Regression Equation Publications by State
USGS Rural Peak-Flow Regression Equations
Years Equations Published
None
(Note: Regional regression equations may not be representative of the entire state.)
Click one of the maps below to expand:
Urban Peak-Flow Equations
Non-Peak Equations
USGS
science for a changing world
Prepared in cooperation with the West Virginia Department of Transportation, Division of Highways
Estimation of Flood-Frequency Discharges for Rural, Unregulated Streams in West Virginia
Scientific Investigations Report 2010–5033
U.S. Department of the Interior
U.S. Geological Survey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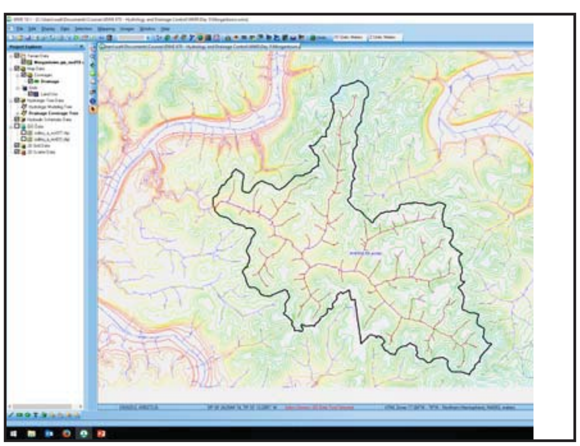
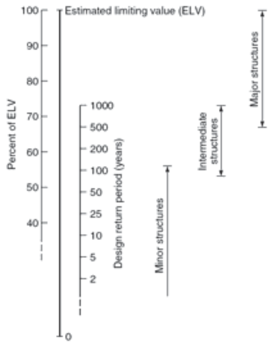


Hydrologic Design Scale

- Primary hydrologic design factors that must be considered
  - Cost and safety
  - Optimal magnitude for design balances these
- *Estimated limiting value (ELV)* – largest possible magnitude for a hydrologic event at a given location



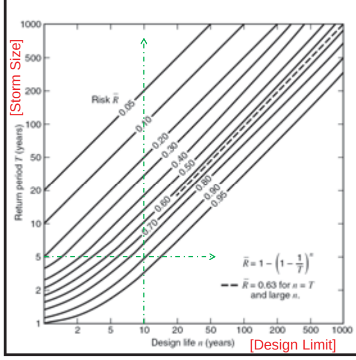
Type of Structure	Return Period (Years)	ELV
Highway culverts		
Low traffic	5–10	—
Intermediate traffic	10–25	—
High traffic	50–100	—
Highway bridges		
Secondary system	10–50	—
Primary system	50–100	—
Farm drainage		
Culverts	5–50	—
Ditches	5–50	—
Urban drainage		
Storm sewers in small cities	2–25	—
Storm sewers in large cities	25–50	—
Airfields		
Low traffic	5–10	—
Intermediate traffic	10–25	—
High traffic	50–100	—
Levees		
On farms	2–50	—
Around cities	50–200	—
Dams with no likelihood of loss of life (low hazard)		
Small dams	50–100	—
Intermediate dams	100 +	—
Large dams	—	50–100%
Dams with probable loss of life (significant hazard)		
Small dams	100 +	50%
Intermediate dams	—	50–100%
Large dams	—	100%
Dams with high likelihood of considerable loss of life (high hazard)		
Small dams	—	50–100%
Intermediate dams	—	100%
Large dams	—	100%

Source: Chow et al. (1988)

Guiding Principles

- Cost of damage upon failure
  - Temporary inconvenience
  - Cleanup
  - Structure replacement only?
  - Other damage
- Risk of loss of life upon failure

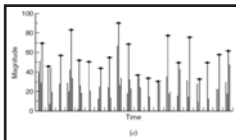
Risk of ***at least one*** event that exceeds design limits during expected life…



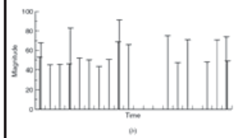
For 10 year design life…
- 90% risk of 5 year storm or larger.
- 63% risk of 10 year storm or larger.
  - *Why isn't it a 50% risk?*

Question:
For a 20 year design life, what storm size has only a 5% risk of at least one event?

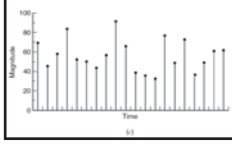
Rainfall data over 20 years



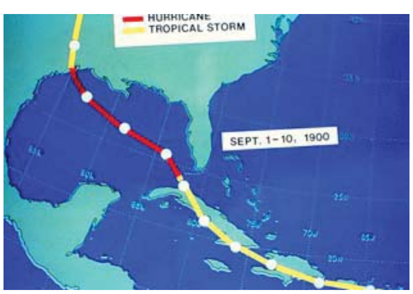
Complete Duration Series



Annual Exceedance Series

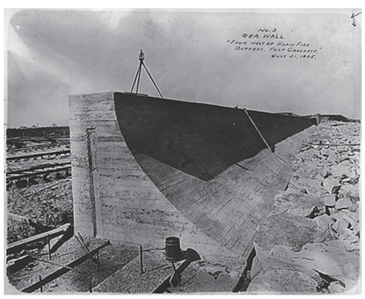


Annual Maxima



145 mph winds, 8000 dead,

Galveston, 1900: highest point 8.7 ft, storm surge 15 ft.



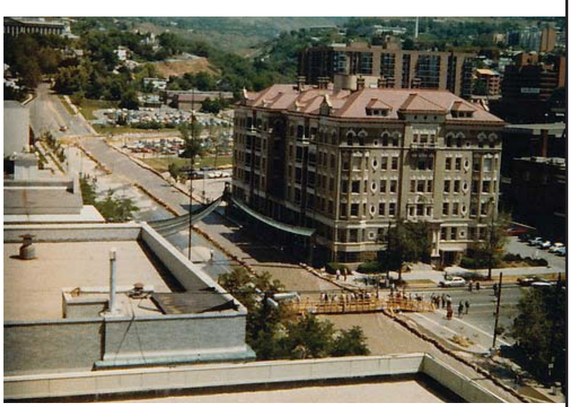
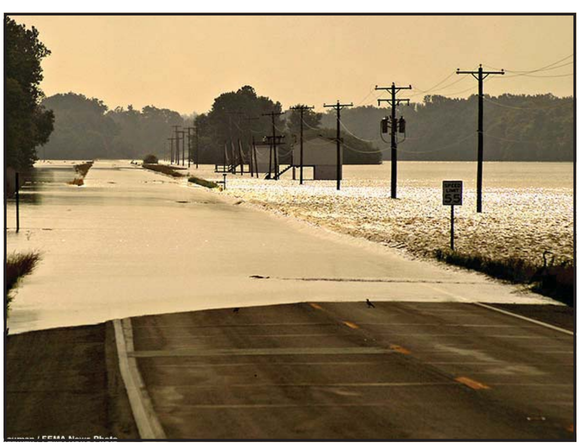
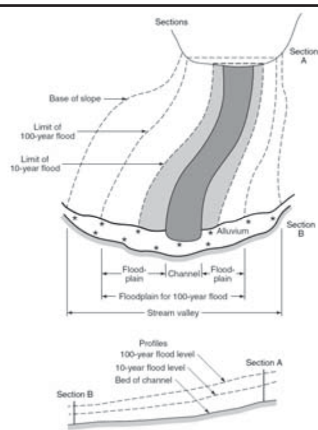



Photo by Jocelyn Augustino/FEM

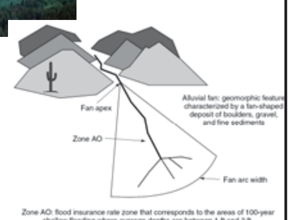

Photo by Andrea Booher/FE



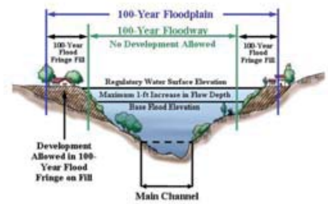
- Flood Locations:
  - Along rivers, streams, and lakes
  - In coastal areas
  - On Alluvial fans
  - In ground-failure areas (subsidence)
  - In areas influenced by structural measures
  - In areas with surface runoff and inadequate drainage
- *Floodplain*: flat, normally dry area adjoining rivers, streams lakes, bays, or oceans



Alluvial Fan



- ***Encroachment*** – development on floodplains that reduces flood-carrying capacity and increases flood height and hazard
- ***Floodway*** – stream channel plus the adjacent floodplains that must be kept clear to limit 100-year flood height increase to 1.0 foot or less
- ***Floodway fringe*** – floodplain section that could be completely obstructed and still limit water surface elevation increase to 1.0 foot or less



Floodplain Management

1. Reduce flood susceptibility
2. Modify the flood
3. Assist individuals and communities in responding to floods

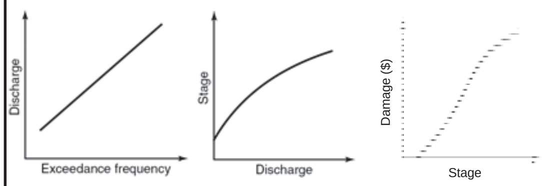
National Flood Insurance Program (NFIP)

- Encourage responsible development of floodplain areas by managing (subsidizing) pooled flood insurance

NFIP Standards & Requirements

- Require **permits** for development in flood-hazard areas (i.e., the 100-year floodplain)
- Ensure **flood-resistant materials** and methods are used (e.g., elevate lowest finished floor above base flood elevation)
- Assure that proposed development is consistent with need to **minimize damage**
- **Regulation** of watercourses & alterations / relocations
- **Prohibit encroachments**

Flood Assessment Relationships



Hydrologic analysis – create a rainfall/runoff model considering the watershed characteristics and expected meteorological event

Hydraulic analysis – based on the flow rates identified in the hydrologic analysis, determine the related water depth once the runoff enters the channel

Economic analysis – calculation of the amount of damage expected at various water depths

Question*: Think of a modification that could alter each of the above relationships.*

Flood Control Alternatives

Objective: reduce or alleviate the consequences of flooding

- ***Structural Measures*** – flood-control facilities such as reservoirs, diversions, levees or dikes, and channel modification
- ***Non-structural measures*** – techniques designed to modify the damage susceptibility of floodplains

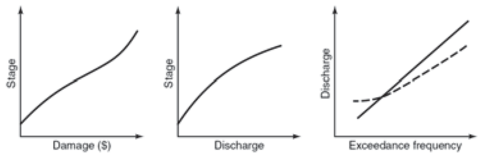
- Decision: whether to undertake structural measures, non-structural measures, both, or none

Learn with your hands…

- For each of the following structural measures, prepare a conceptual ‘sketch’ showing how it will work.

Flood Control Reservoirs

- Used to store flood water until after flood event
  - Reduces peak discharge magnitude



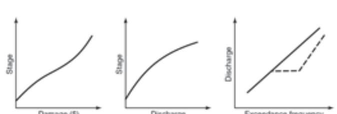
- Stage-Discharge can be altered by erosion / sediment deposition
- Stage-Damage can be altered by subsequent development

Reservoir Suitability

1. Damageable property is spread over a **large geographic area**
2. **High degree of protection** is desired
3. **Variety of property types** to be protected (e.g., agricultural, structures, infrastructure, etc.)
4. Water impounded can be **used for other purposes**
5. **Land area is available** for reservoir construction
6. Economic value of damageable property **justifies construction costs**

Diversions

- Used to reroute or bypass flood flows away from damage centers

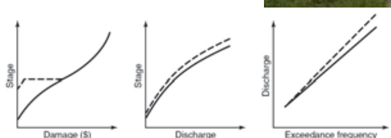


Diversion Suitability

1. Damageable property spread over large geographic area
2. High degree of protection is desired
3. Variety of property types to be protected (e.g., agricultural, structures, infrastructure, etc.)
4. Land area is available for diversion channel and/or tunnel
5. Economic value of damageable property justifies construction costs

Levees and Floodwalls

- Modifies all three functional relationships
  - Stage-Damage
  - Stage-Discharge
  - Discharge – Exceedance frequency



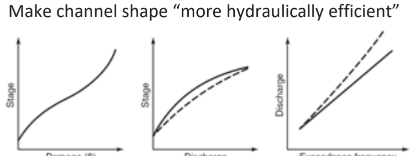
Increases peak discharges downstream by reducing the natural storage of a floodwave

Flow is excluded from floodplain outside the levee – constricts flow to a smaller conveyance area

Channel Modifications

Channel Modifications

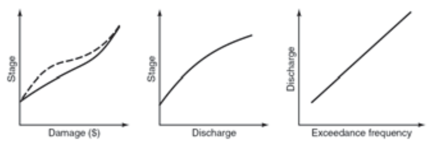
- Improve the conveyance characteristics of a stream channel
  - Reduce channel roughness
  - Increase channel slope
  - Reduce channel length
  - Make channel shape “more hydraulically efficient”



Decreases local storage.

Non-structural measures (Flood Proofing)

- Waterproofing exterior walls
- Small walls or levees
- Raising in-place
- Flood warning systems



Web Resources

Precipitation and River Depth Data
http://water.weather.gov/

Floodplain Mapping
http://msc.fema.gov/

Flood Damage Relationships

- ***Direct damage*** – property loss directly attributable to contact with flood water
- ***Indirect damage*** – lost business and services, cost of alleviating hardship, rerouting traffic
- ***Secondary damage*** – adverse effects by those who depend on output from the damaged property or hindered services
- ***Intangible damage*** – environmental quality, social well being, aesthetic values
- ***Uncertainty damage*** – failure to develop (economically) because of the threat of flooding

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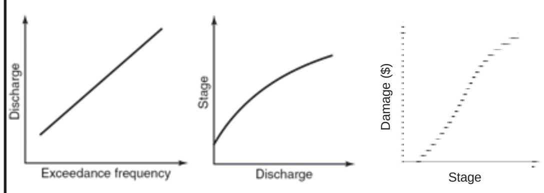
Review: Flood Assessment Relationships

For each model, consider the *independent* and *dependent* variables.



Hydrologic analysis –
Input: return period
Output: flow rate

Hydraulic analysis –
Input: flow rate
Output: water depth

Economic analysis –
Input: water depth
Output: damage cost

Evaluating Flood Control Alternatives

- Calculate the "Damage Reduction" each alternative offers compared to the existing (no action) condition
- For each alternative, compute how much "Damage Savings" will occur on an annual basis
  - ***Incremental probability*** (ΔF) difference in exceedance probability between two consecutive rows/ 100
  - ***Damage Reduction*** (ΔD) average damage reduction between two consecutive rows
  - ***Annual expected flood reduction***, $\Sigma(\Delta D \cdot \Delta F)$ the sum of all annualized flood damage savings

Expected Flood Damage: Example

	Damage *(millions of dollars)*				
Exceedance Probability %	Existing (Do Nothing)	Dike	Diversion	Channel Modification	Reservoir
20	0	0	0	0	0
10	6	0	0	0	0
7	10	0	0	0	0
5	13	13	2	4	3
2	22	22	10	12	10
1	30	30	20	18	12
0.5	40	40	30	27	21
0.2	50	50	43	40	35
0.1	54	54	47	43	45
0.05	57	57	55	50	56

*For the four alternatives of a certain size (Dike, Diversion, Channel Modification, or Reservoir) what is the **expected annualized benefit** of each?*

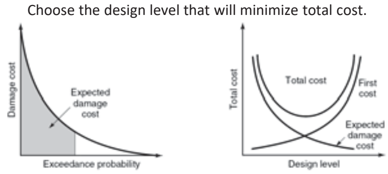
Step 1: Assemble 'Expected Damage Cost' vs Exceedance Probability Data. (Here: given.)
*Step 2: Calculate 'Damage **Reduction**' vs Exceedance Probability for each alternative.*
Step 3: Calculate Incremental Probability, Incremental Damage Reduction, and accumulate.

Maximizing Annual Benefit

- Compute "Total" annual cost
  - Annual damage + annual cost
  - *Identify which level of protection has the lowest total cost*
- Calculate annual benefit
  - How much less the annual damage is compared to the "baseline" case
- Calculate the net benefit
  - Annual benefit – Annual cost
  - Identify which level of protection has the highest Annual ***Net*** Benefit

Risk-Based Design

Cost comes from (1) flood damage, and (2) flood prevention.
Choose the design level that will minimize total cost.



- *Expected damage cost* – a high 'exceedance probability' is an event that happens regularly
  - Cost of damage is low for frequently-occurring events
- *Total cost* – the sum of construction costs for damage prevention, and expected damage costs that still occur even after structural measures are put into place

Maximizing Annual Benefit of Flood Control

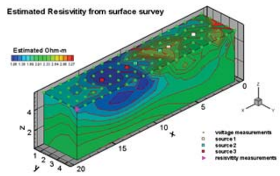
T (yr)	Annual Damage ($M/yr)	Annual Cost ($M/yr)
5	1.94475	-
10	1.64475	0.2
20	1.17475	0.6
50	0.64975	1
100	0.38975	1.4
200	0.21475	1.8
500	0.07975	2.1
1000	0.02775	2.3
2000	0.00000	2.5

You currently have protection in place against the 5 year storm (i.e., no new spending required to get this protection). On average, the annual damage is $1.94475M. By spending $0.2M/year, you can protect against the 10 year storm, and the annual damage experienced will go down to $1.64475/year.

- A dike system could be built to provide varying levels of protection, corresponding to differing return periods.
  - *Calculate "Total Cost" ($M/yr) for varying levels of protection*
  - *Calculate "Benefit" ($M/yr) – reduced damage compared to the current annual damage with the existing protection*
  - *Calculate "Net Benefit" ($M/yr): Benefit – Annual Cost*

Ground-water hydrology

- Studies several parameters for water below the surface of the earth:
  - quantity
  - quality
  - distribution
  - movement



- Other issues include:
  - contaminant transport and remediation
  - engineered storage systems (of surface water)
  - lowering groundwater table for agricultural needs

Quantity of Water Available on Earth

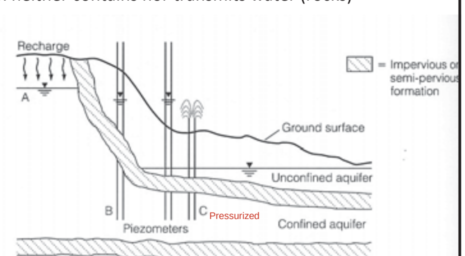
Location	%	Volume
Oceans	**97.02%**	1.35 * 10^18 cubic meters
Icecaps and Glaciers	2.09%	
Groundwater less than 1 km	**0.3**	this is, by inference, our largest source of fresh water on Earth!
Groundwater greater than 1 km	0.3	
Freshwater Lakes	0.009	
Saline Lakes and Inland Seas	0.007	
Soil Water	0.005	
Atmospheric Water	0.0009	
Biomass Water	0.0002	

Ogallala Aquifer Video   Groundwater Recharge Video

Aquifer

- ***Aquifer***: geologic formation where water can be withdrawn in significant amounts (sand, gravel, fractured rocks)
- ***Aquiclude***: contains water, but cannot transmit (clays)
- ***Aquifuge***: neither contains nor transmits water (rocks)

$$\phi = \frac{p}{\gamma} + z$$

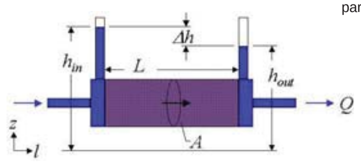


Additional Terms

- ***Artesian aquifer**:* aquifer under such pressure that flowing water is produced at ground level when penetrated by a well
- ***Aquitard**:* a soil or rock formation that slows water flow in an aquifer
- ***Leaky aquifer**:* an aquifer bound by a semi-pervious later
  - *Leaky unconfined aquifer*
  - *Leaky confined aquifer*

Darcy's Law

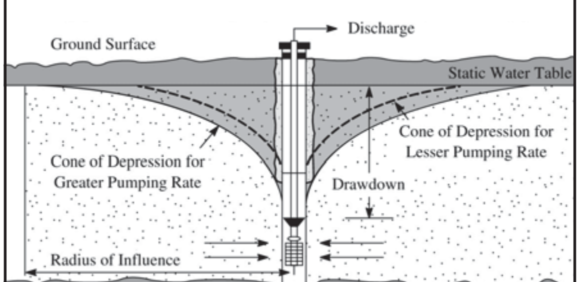
- Studying the performance of sand filters in treating drinking water, Darcy measured the flowrate of water through sand.



Hydraulic Conductivity, K, key parameter dictating flow rate

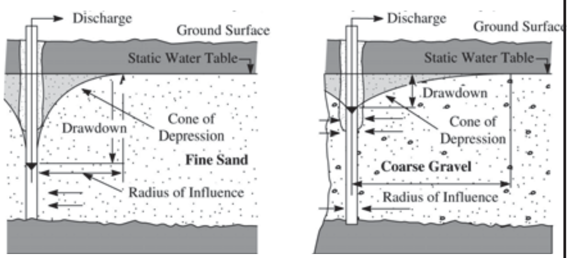
$$Q = KA\frac{\Delta h}{L}$$

Pumping and Cone of Depression

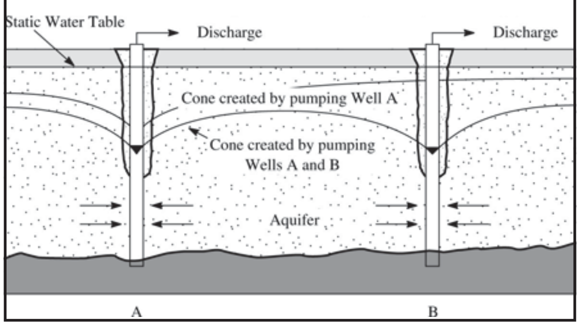


Cone of Depression surface comes into equilibrium during steady-state pumping. (Over-pumping can exhaust an aquifer.)

Aquifer Material & Cone of Depression



Effect of Overlapping Cones of Depression



Well Terms

- Fully penetrating
- “Screen” depth (or location)
- Well radius

- ***Transmissivity***: a measure of an aquifer’s ability to transmit fluid flow, on a unit width basis.

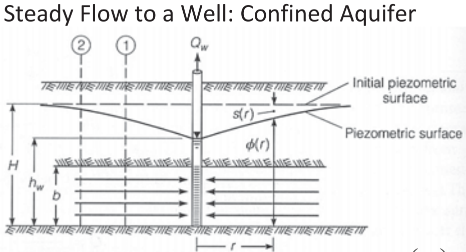
  T=Kb (confined aquifer)

  T=KH (unconfined aquifer)

Terms

- *Hydraulic Conductivity, K:* derived from Darcy's law, is a function of fluid and soil properties. Measures ability of fluid to flow through soil. [L/T]
- *Aquifer Thickness, b:* Vertical distance through which water flows through the soil. Often the distance from a lower confining layer to an upper confining layer (or to groundwater table elevation). [L]
- *Transmissivity, T:* function of aquifer conductivity and thickness, T=Kb. [L^2/T]
- *Piezometric head, φ:* Sum of pressure and elevation heads for some location, $\varphi = P/\gamma + z$
- *Effective Porosity, n:* That portion of the soil porosity that is available for fluid flow.

Steady Flow to a Well: Confined Aquifer



r_w = radius of well

b = height of aquifer

h_w = depth of water in the well

H = Initial piezometric surface

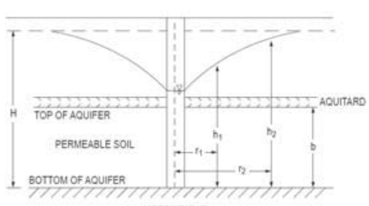
s(r) = drawdown at some radius, r

φ (r) = piezometric head at some radius, r

$$\phi(r) = h_w + \frac{Q_w}{2\pi Kb}\ln\left(\frac{r}{r_w}\right)$$

$$Q_w = \frac{2\pi T(h_2 - h_1)}{\ln\left(\frac{r_2}{r_1}\right)}$$

Steady Flow to a Well: **Confined Aquifer**



Theim Equation

$$Q = \frac{2\pi T(h_2 - h_1)}{\ln\left(\frac{r_2}{r_1}\right)}, \text{ where}$$

T = Kb = transmissivity (ft²/sec)

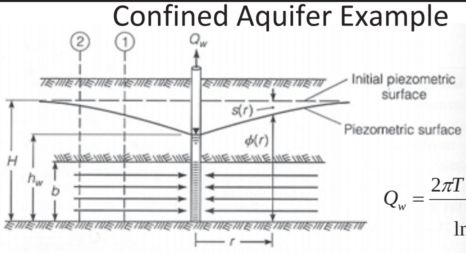
b = thickness of confined aquifer (ft)

h_1, h_2 = heights of piezometric surface above bottom of aquifer (ft)

r_1, r_2 = radii from pumping well (ft)

ln = natural logarithm

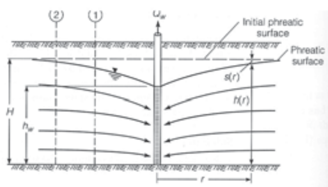
Confined Aquifer Example



$$Q_w = \frac{2\pi T(h_2 - h_1)}{\ln\left(\frac{r_2}{r_1}\right)}$$

- A confined aquifer has hydraulic conductivity of 20 m/d, thickness of 6.6 m, and initial piezometric surface of 14.53 m above the lower confining layer.
  - What flowrate will cause the piezometric surface to be 13.85 m at a radius of 40 m and 14.31 at a radius of 85 m?
  - What is the water depth at the well if the well diameter is 0.50 m?

Steady Well Flow: Unconfined Aquifer



r_w = radius of well

H = height of aquifer

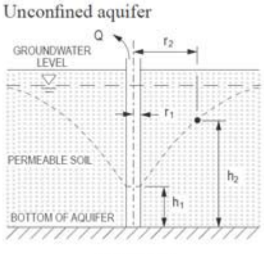
h_w = depth of water in the well

H = Initial phreatic surface

s(r) = drawdown at some radius, r

$$Q_w = \frac{\pi K(h_2{}^2 - h_1{}^2)}{\ln\left(\frac{r_2}{r_1}\right)}$$

Unconfined aquifer



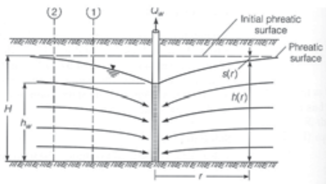
Q = flow rate of water drawn from well (cfs)
K = coefficient of permeability of soil
= hydraulic conductivity (ft/sec)
h_1 = height of water surface above bottom of aquifer at perimeter of well (ft)
h_2 = height of water surface above bottom of aquifer at distance r_2 from well centerline (ft)
r_1 = radius to water surface at perimeter of well, i.e., radius of well (ft)
r_2 = radius to water surface whose height is h_2 above bottom of aquifer (ft)
ln = natural logarithm
Q/D_w = specific capacity
D_w = well drawdown (ft)

Dupuit's Formula

$$Q = \frac{\pi K\left(h_2^2 - h_1^2\right)}{\ln\left(\frac{r_2}{r_1}\right)}, \text{where}$$

Example – Unconfined Aquifer

- A well pumps 0.4 m^3/s from an unconfined aquifer whose saturated thickness is 24 m. If the drawdown 50 m from the well is 1m and the drawdown 100 m from the well is 0.5 m, then:
  - **(a) calculate the hydraulic conductivity** of the aquifer.
  - (b) Determine the expected **drawdown** 5 m from the well.



$$Q_w = \frac{\pi K (h_2^{\ 2} - h_1^{\ 2})}{\ln\left(\frac{r_2}{r_1}\right)}$$