http://www.jimstonefreelance.com/weather.htm

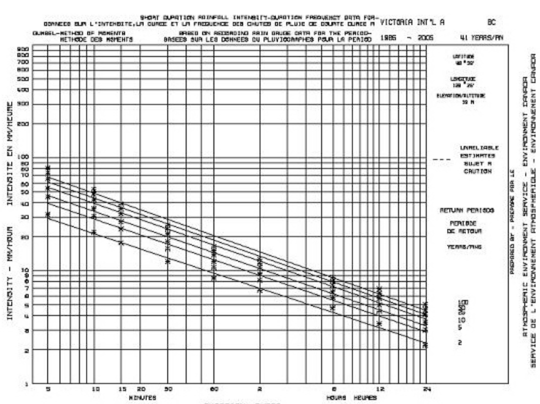
Civ E 321: Principles of Environmental Modelling and Risk

WEEK 2: PRECIPITATION

Most information in Topic 3 is from pages 23-35 *of* ***Bedient et al. (2019)*** *and from* ***Ponce (1989)***

http://www.goshido.com/author/ger/

http://garrettalloway.files.wordpress.com/2010/06/you-were-born-in-a-rain-drop.jpg



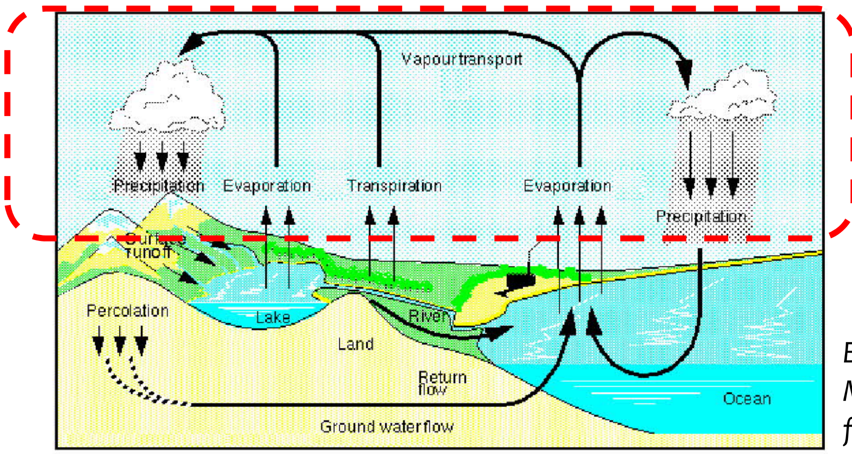
http://www.idfcurve.org/

Section overview

- The atmosphere and clouds
- Intro and point measures
- Areal precipitation
- Storm analysis
- IDF curves
- Design hyetographs

1. THE ATMOSPHERE

- The atmosphere is the **major hydrological link** between oceans and continents



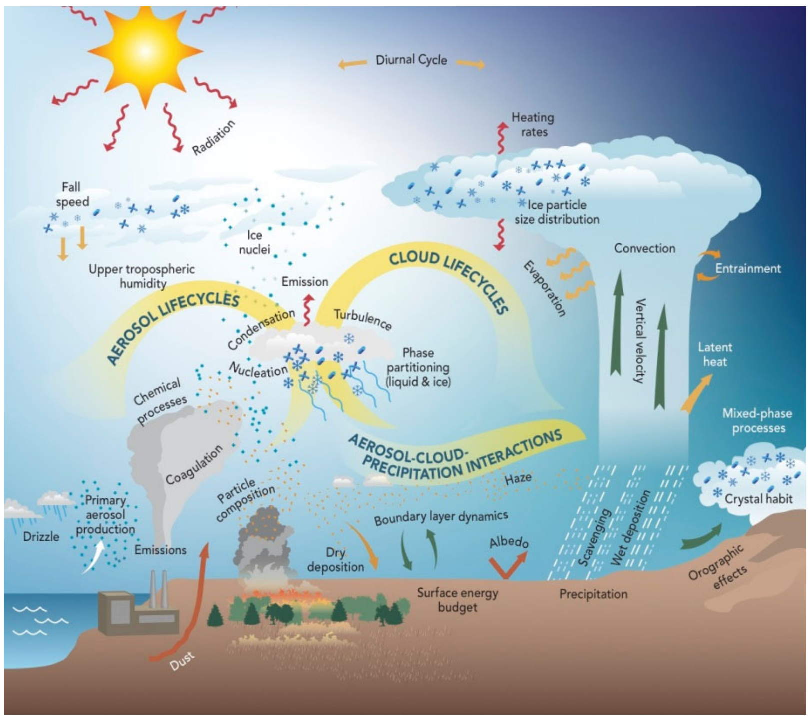
Erich Roeckner, Max Planck Inst. for Meteorology

- Key point: The hydrological cycle is shaped by atmospheric conditions, **with precipitation as the major input to cycle**
- **Water vapour content** of atmosphere is a major component of the atmospheric processes that create weather in the lower atmosphere

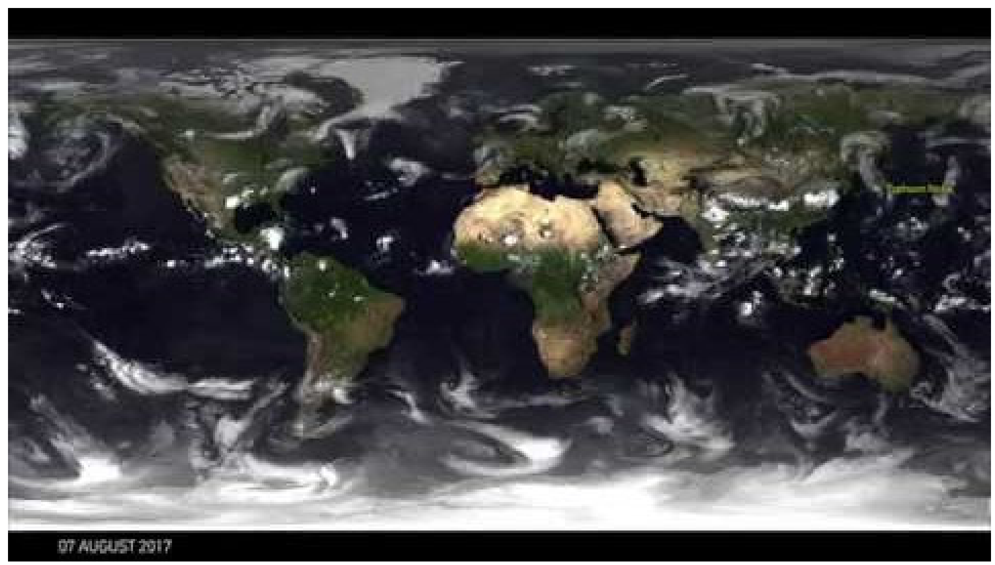
Bedient et al. (2019)

The Atmosphere

"**Atmospheric weather systems** are fueled by solar input, and characterized by air masses in motion, circulating winds, cloud generation, and changes in temperature and pressure…"



 http://asr.science.energy.gov/images/cms/scienceplan.jpg



Global Weather, August 2017 - EUMETSAT
https://youtu.be/QFZZJF8djJA

Bedient et al. (2019: 10)

ATMOSPHERIC PARAMETERS

- Key atmospheric parameters include,
  - Pressure
  - Density, temperature
  - Humidity and vapour pressure
  - Latent heat

Atmospheric pressure

- *Force per unit area exerted on a surface* (N/m^2)
- **Atmospheric pressure** measures the weight of air per unit area
  - *At sea level*, average air pressure is ~1 atmosphere
  - 1 atm = 101.3 kPa, 1013 millibars (mb), or 760 mm-Hg
  - Atmospheric pressure decreases with altitude, because the density of air molecules decreases
- Horizontal and vertical pressure changes in atmosphere produce **wind**, which drives most of our weather

Bedient et al. (2019)

Pressure, density, temperature

- **Ideal gas law,**

$$P = \rho RT$$

  - P is pressure, ρ is density, R is gas constant, T is absolute temperature
- Implications:
  - At constant density, $P \propto T$, so an increase in temperature causes an increase in pressure
  - Also, $P \propto \rho$, so for a fixed pressure, a decrease in temperature causes an increase in density
    - Cold air masses usually associated with higher *P*

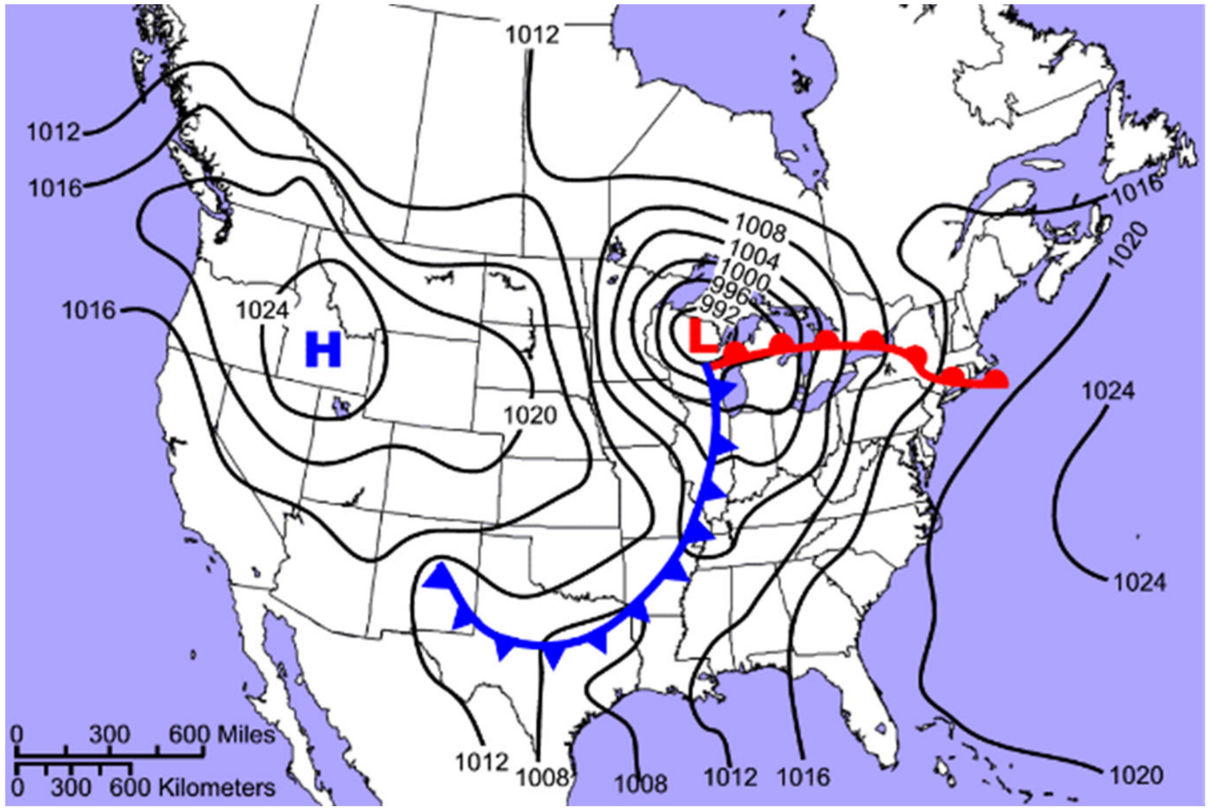
Bedient et al. (2019)

Pressure and weather fronts

Pressures in millibars (1 mb = 100 Pa)

‘H’ = High pressure

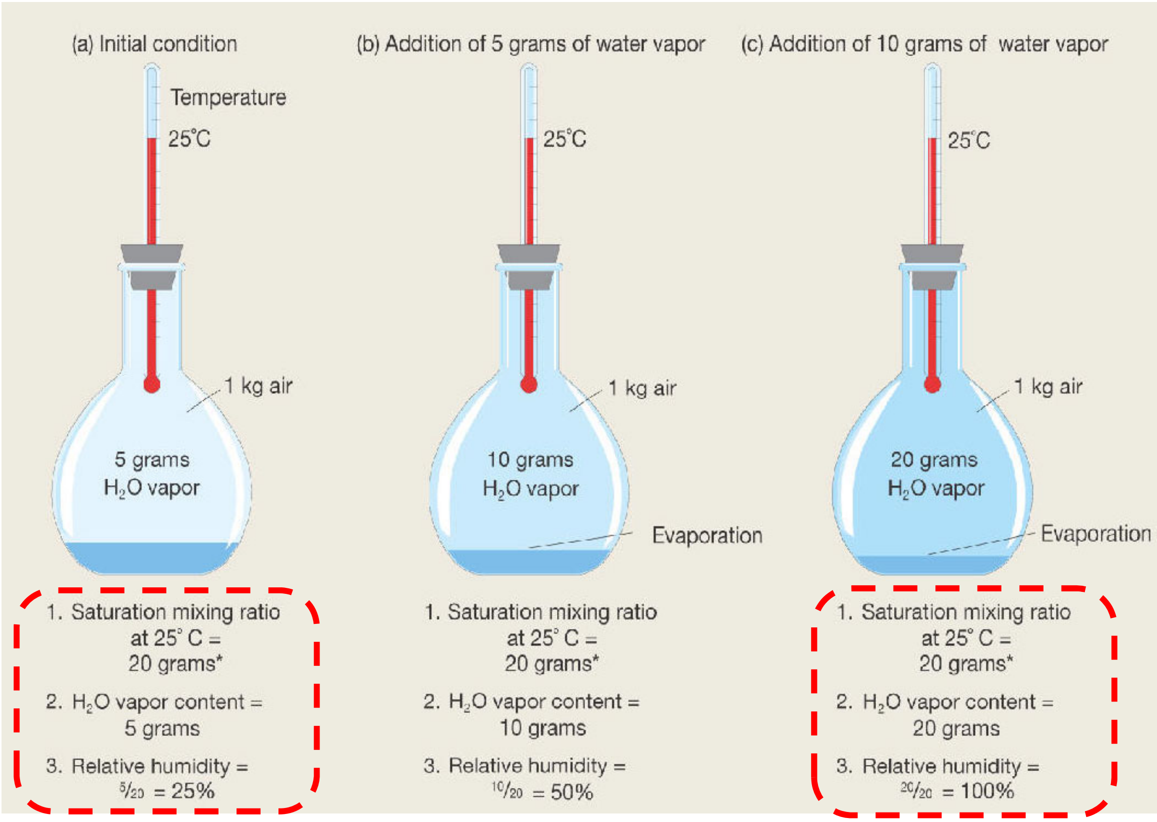
‘L’ = Low pressure



http://www.sercc.com/education_files/wxmap/wxmap.html

Humidity

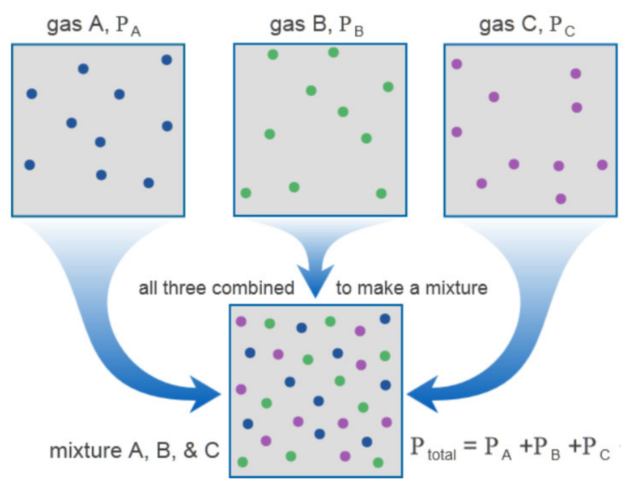
- Mixture of gases in atmosphere includes **water vapour**
- ***Humidity:*** *"Measure of the amount of water vapour…"*
- **Relative humidity: ratio** of air's actual water content to the amount at saturation for a given air temperature



Bedient et al. (2019)

Vapour pressure

- **Partial pressure:** pressure on surface of a container from a particular gas in a mixture,



http://ch301.cm.utexas.edu/gases/mixtures/mixtures-all.php

- **Vapour pressure:** the partial pressure exerted by *water vapour*
- **Saturation vapour pressure:** the pressure of water vapour at its maximum capacity in atmosphere
  - *Try at home: Saturation vapour pressure example, with ice and boiling water, at* https://youtu.be/i0Frx_bPsT8 (Dr. David Naylor, Ryerson)

Bedient et al. (2019)

Vapour pressure

- Vapour pressure and temperature effects
  - *Vapour pressure is dependent on temperature*
  - As air lifts and cools, relative humidity increases to *saturation point*
    - Vapour can then begin to **condense** into liquid water
    - **Dew point temperature** is temperature to which a sample of air must be cooled to reach saturation point
    - *Try at home: How dew forms* https://youtu.be/Bosp9ZTLuBM

Bedient et al. (2019)

Equations: Saturation vapour pressure

- **Vapour pressure** is normally written as *e*
- At **saturation vapour pressure**, *e* is written as e_s, and can be found as,

$$e_s = 2.7489 \times 10^8 \times exp\left(-\frac{4278.6}{T + 242.79}\right)$$

  - Where,
    - e_s is in mb,
    - *T* is temperature *in Celsius*
  - Used to find saturation vapour pressure over water, and accurate to 0.5% for 0°C to 40°C

Bedient et al. (2019)

Equations: Humidity

- **Relative humidity** is ratio of current water vapour pressure to saturated water pressure,

$$RH = 100\left({}^{e}/_{e_s}\right)$$

  - Sample typical (high and low) relative humidities:
    - Houston (89, 67); Chicago (80, 64); New York (72, 56); Denver (67, 40); Las Vegas (40, 21)
  - *See how to measure RH with a* ***psychrometer****, using "dry bulb" vs. "wet bulb" temperatures, at* https://youtu.be/OZh9ksAy9kc

http://metronews.ca/news/toronto/50095/its-not-the-heat-its-the-humidity/

http://environment.nationalgeographic.com/environment/photos/climate-change/

Bedient et al. (2019)

Equations: Humidity

- **Specific humidity** is mass of water vapour in a unit mass of moist air (g/g) → shows as a *fraction*
  - Equal to ratio of densities, ρ_w / ρ_m
    - ρ_w is vapour density, ρ_m is density of moist air

- First, solve for ρ_m as,

$$\rho_m = \frac{(P - e) + 0.622e}{RT} = \frac{P}{RT}(1 - 0.378e/P)$$

- (Note that the equation shows moist air is ***lighter*** than dry air!)

Bedient et al. (2019)

Equations: Humidity

- Rearranging slightly from ρ_m, and writing the ***specific humidity*** as q,

$$q = \frac{\rho_w}{\rho_m} = \frac{0.622e}{P - 0.378e}$$

  – Where,
    - q is the specific humidity (g/g)
    - e is the vapour pressure (mb)
    - P is total atmospheric pressure (mb)
    - ρ_w is vapour density or absolute humidity (g/cm^3)
    - ρ_m is density of the mixture of dry and moist air (g/cm^3)

Bedient et al. (2019)

Changes of state

- Water can change state (solid, liquid, gas) under normal atmospheric conditions
- This phase change absorbs/releases energy:
  - Melting/freezing, evaporating/condensing

http://www.123rf.com/photo_7903255_melting-ice-cubes-on-a-metal-tabletop.html

http://laura-no-iken.blogspot.ca/2007_11_01_archive.html

http://en.wikipedia.org/wiki/Condensation

Bedient et al. (2019)

Latent heat

- For vapour to condense to water, a quantity of heat called **latent heat** (L_c) must be removed from the moist air
  - Note: *latent heat of condensation* (L_c) = *latent heat of evaporation* (L_e), the amount of heat added to turn water into vapour at same temperature

- With *T* measured in Celsius and *L* in cal/g,

(1 cal = 4.18 J)

$$L_e = -L_c = 597.3 - 0.57 \cdot T$$

- For melting and freezing, also with *L* in cal/g,

$$L_m = -L_f = 79.7$$

- So, it takes about **7.5 times** the energy to evaporate a gram of water compared to melting a gram of ice

Bedient et al. (2019)

Ex 1: Atmospheric parameters

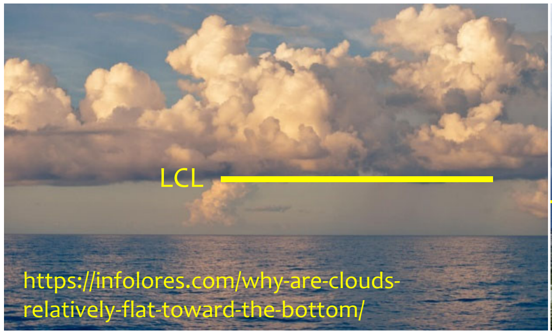
At the airport, a weather specialist measures the air pressure as 124.3 kPa, the air temperature as 28°C, and the *dew point* temperature as 20°C.

Calculate the corresponding a) vapour pressure, b) relative humidity, and c) specific humidity.

Example 1-1 in Bedient et al. (2019)

The atmosphere and clouds

- Air circulates (horiz., vertically) in the atmosphere → **wind**
- Rising moist, unsaturated air begins to cool (lower pressure causes it to expand and its density to decrease), and…
  - The **relative humidity** increases, until…
  - At some altitude, air reaches saturation (RH = 100%)
  - Any further cooling causes the **moisture in the air to condense**
    - Occurs at altitude called the "lifting condensation level" (LCL)
  - Leads to **cloud formation!**
- Further, when moisture condenses, the *latent heat of condensation* is released and the air warms!
  - This latent heat exchange is the **major energy source** that fuels tropical cyclones and hurricanes, thunder storms, etc.



Bedient et al. (2019)

Amount of cooling?

- How quickly does this *air cooling* occur?
- Rate of temperature change with elevation in the atmosphere called **adiabatic lapse rate**
  - Dry adiabatic lapse rate is 9.8°C/km and assumes no phase changes of water
  - Average ambient lapse rate is about 6.5°C/km

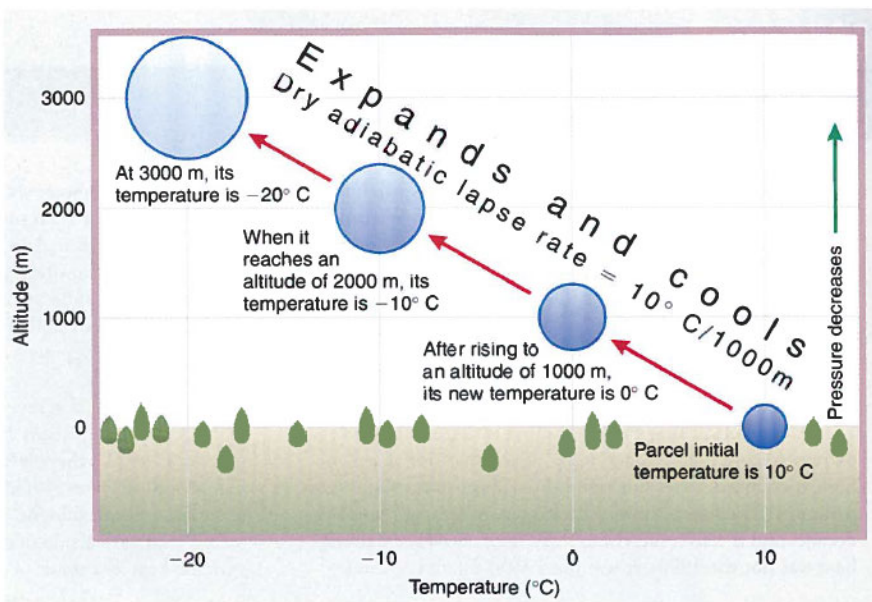


Fig. 3-17 in Ackerman and Knox (2007)

Bedient et al. (2019)

The atmosphere and clouds

- **Horizontal variations** in atmos. pressure cause air to move from higher to lower pressure
  - These produce **wind!**
- **Vertical displacement** causes air to move too, but far more slowly
  - This movement and lifting of air produces **clouds**, collections of small water droplets or tiny ice crystals

University at Albany, 2017. https://youtu.be/TgYCtOpbLSo

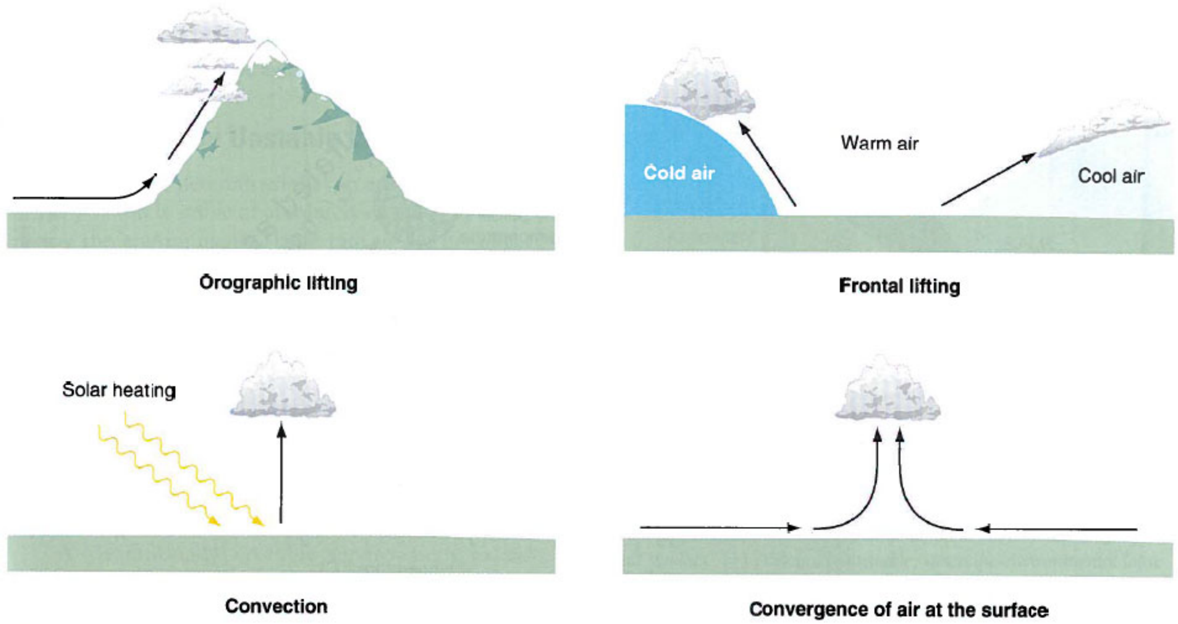
M. Descombes, 2015. https://youtu.be/0YatiDf9A8A

- **Lifting mechanisms** required for moist air masses to cool and approach saturation conditions
  - In presence of small nuclei (*typically "aerosols": salt, dust, pollen, etc.*), condensation droplets grow and produce clouds, precipitation

Bedient et al. (2019)

Cloud formation

- Lifting mechanisms that produce clouds:



- In each example, rising air creates updraft that keeps cloud particles suspended in mid-air despite force of gravity

Fig. 4-13 in Ackerman and Knox (2007)

2.1 Introduction to Precipitation

"Precipitation is the primary input to the hydrological cycle – as rain, snow, or hail – and is generally derived from atmospheric moisture" (Bedient et al. 2019: 20)

Further, *"Because precipitation is the input to the land phase of the hydrological cycle, its accurate measurement is the essential foundation for quantitative hydrological analyses"* (Dingman 2002: 105)

For precipitation to occur,

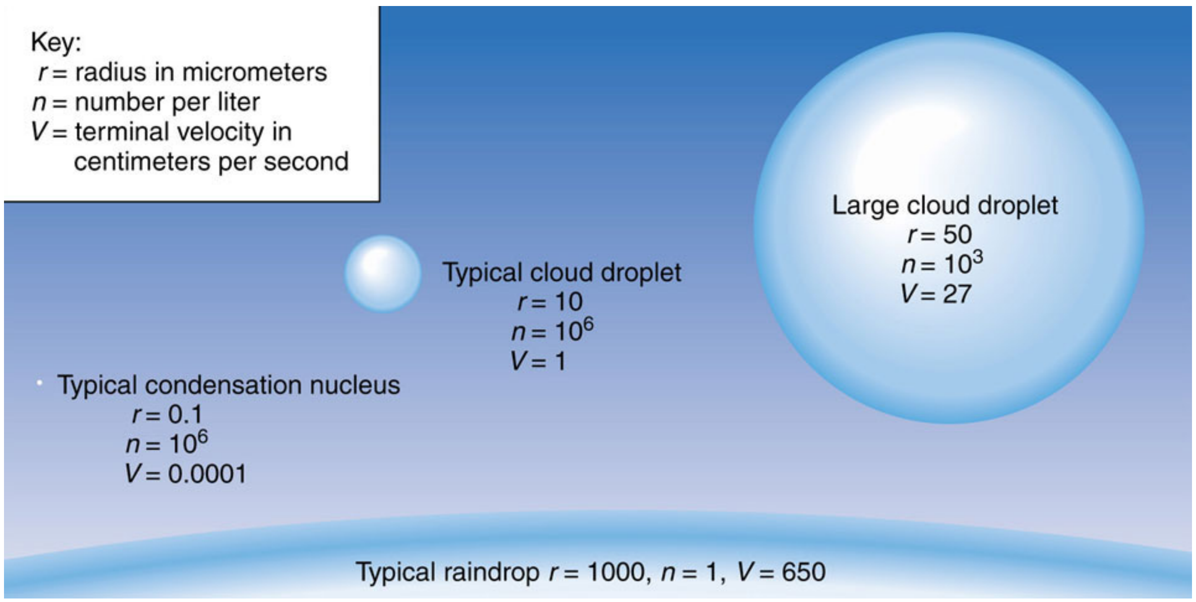
1. A moisture source must be available
2. Moist air must undergo lifting and cooling
3. Phase change must occur, and condensation onto small nuclei in air must occur
4. Droplets must grow large enough to overcome drag and evaporation to reach ground…

See NOVA (PBS, 2013) video for a good recap: https://youtu.be/UZEETyzql0Q

Bedient et al. (2019)

Precipitation formation

- Condensation at altitude cannot produce precipitation alone… *the cloud particles are too small*!
  - Average about 0.01 mm in diameter; must exceed 0.5 mm for significant precipitation to occur
  - *See UK Met Service on cloud formation*: https://youtu.be/q87Ekar3emA



http://www.geog.ucsb.edu/~joel/g110_w08/lecture_notes/precip_processes/precip_processes.html

Bedient et al. (2019)

Precipitation formation

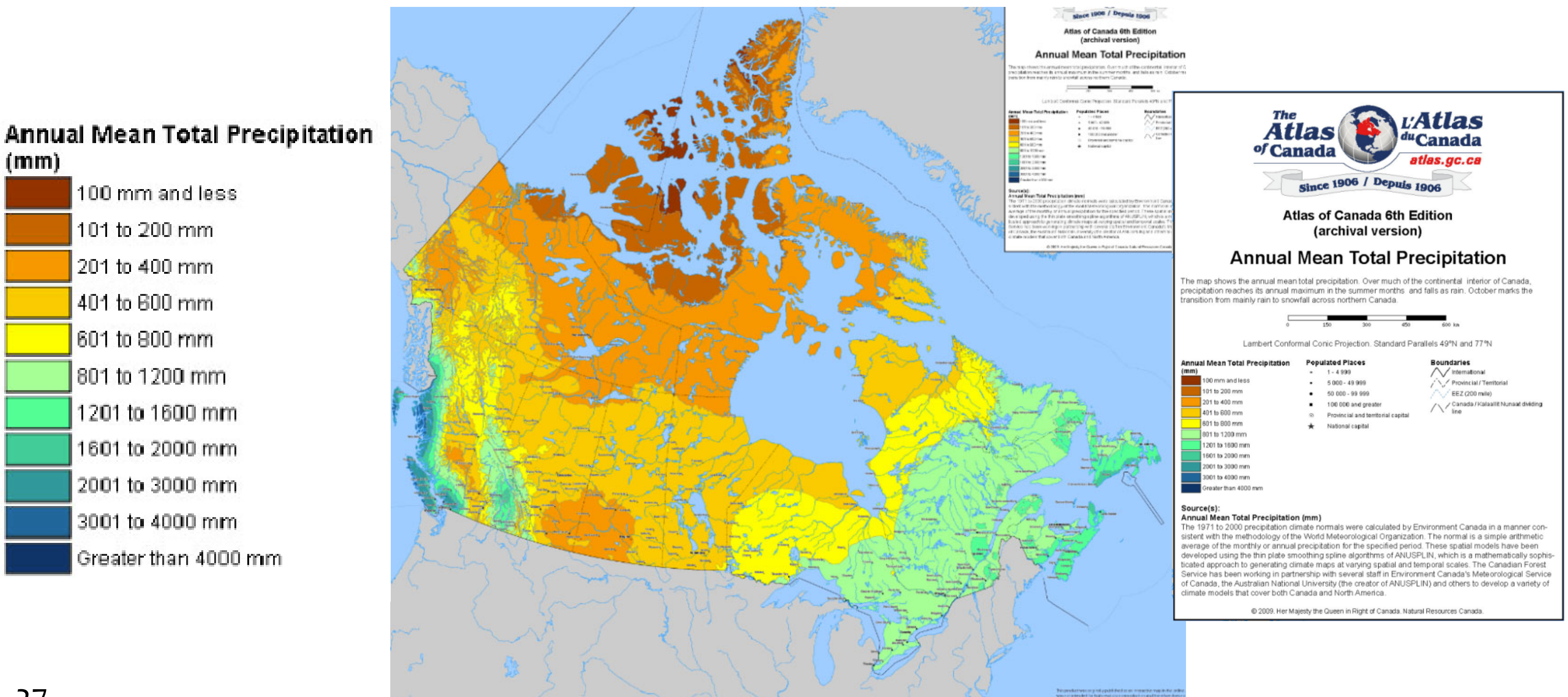
- If cloud particles are too small…
- *Droplets must condense onto "condensation nuclei"*
  - Droplets grow through condensation onto active nuclei through diffusion down a vapour pressure gradient toward droplet surface
  - Growing droplets begin to move relative to overall cloud
  - Droplets heavy enough to fall grow through "coalescence" → larger falling drops overtake smaller, droplets grow through collisions

http://lewlew.wordpress.com/2008/06/10/597/

Bedient et al. (2019)

Precipitation patterns

- Main source of moisture for annual rainfall is evaporation from oceans
  - Precipitation heavier near coastlines
  - Distortion due to orographic effects (mountains)
    - More rainfall on windward side of mountain ranges



Precipitation patterns

- Precipitation can vary annually and intra-annually (monthly)
  - Time variation of precipitation occurs seasonally
  - Variation even within a single storm type
  - Prevailing winds, relative land temperature, proximity of ocean can all affect precipitation

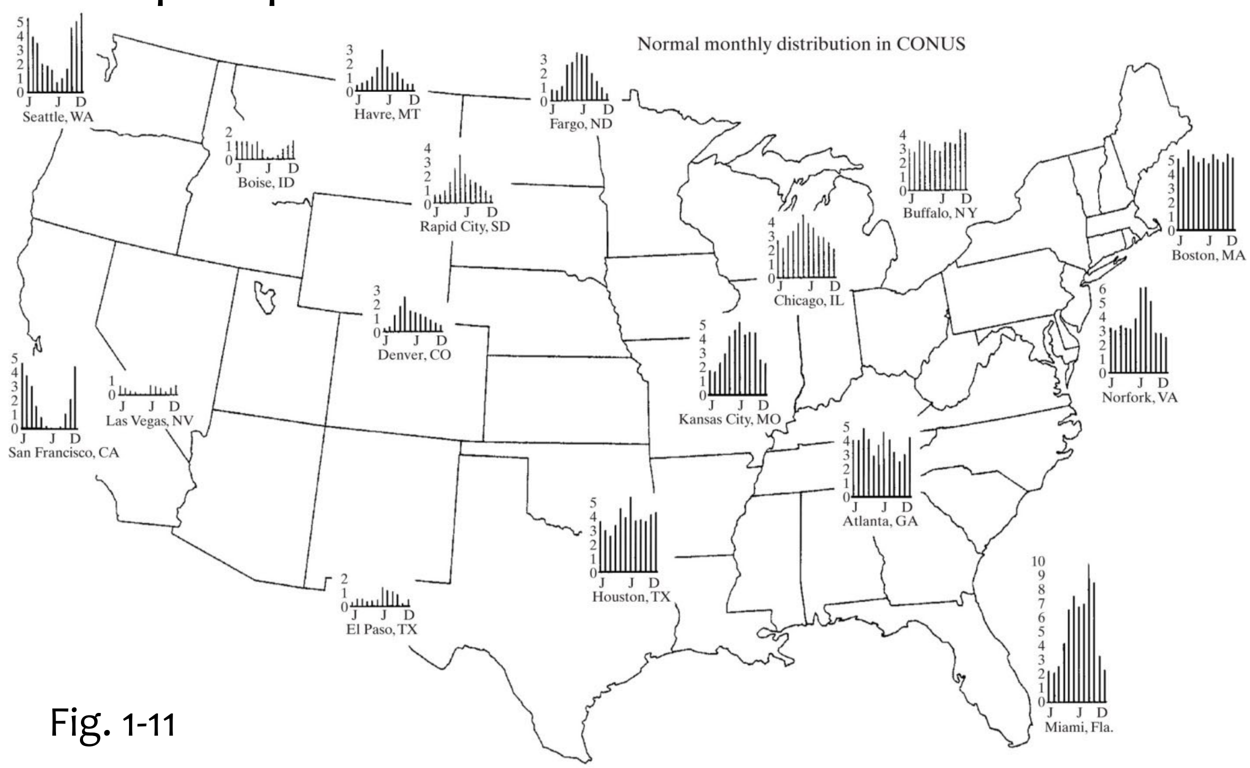
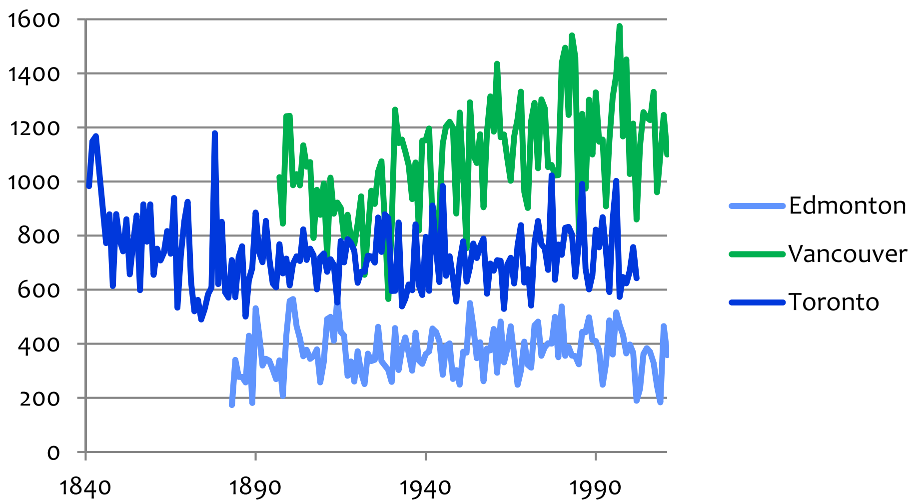


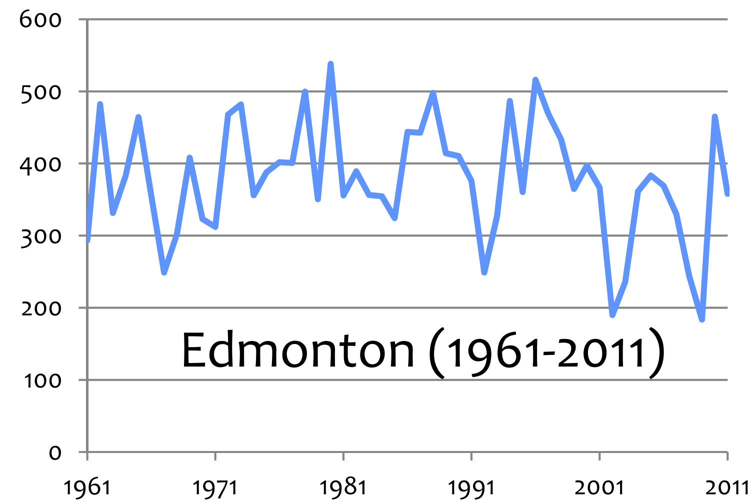
Fig. 1-11

Bedient et al. (2019)

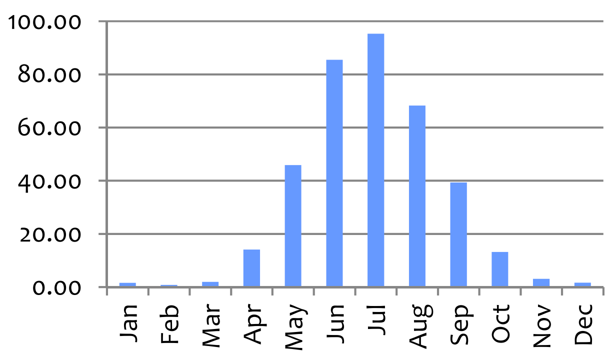
Canadian precipitation patterns

Average annual rainfall (mm) for three Canadian cities:

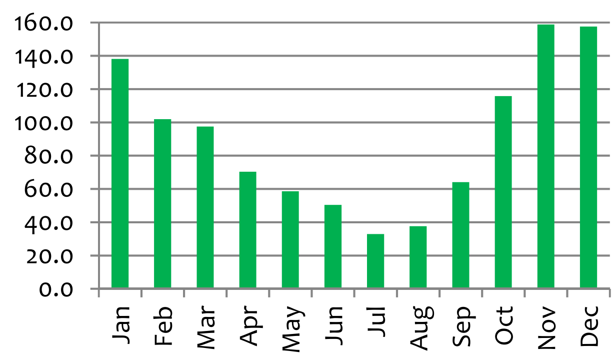




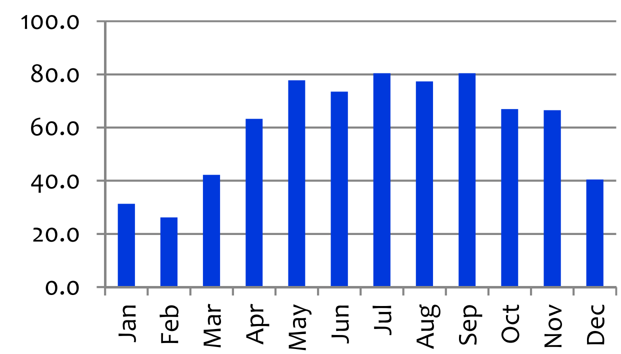
Average monthly rainfall (mm) for three Canadian cities:



Edmonton (1883-2011)



Vancouver (1897-2011)



Toronto (1841-2002)

All data from http://ec.gc.ca/dccha-ahccd/default.asp?lang=en&n=2E5F8A39-1

2.2 POINT MEASUREMENTS

- From precipitation data at single points,
  - Can look at **longer term patterns**,
    - Rainfall data collected over long term
  - Can also examine **single rainfall events**
    - An interesting statistic is the **maximum recorded rainfall** at a single gauge

.2 **Greatest known observed point rainfall** From Brutsaert (2005)

Duration	(mm)	Location	Date
1 min	38	Barot, Guadeloupe	Nov. 26, 1970
5 min	63	Haynes Camp, California	Feb. 2, 1976
8 min	126	Fussen, Bavaria	May 25, 1920
15 min	198	Plumb Point, Jamaica	May 12, 1916
20 min	206	Curtea-de-Arges, Roumania	Jul. 7, 1889
30 min	280	Sikeshugou, Hebei	Jul. 3, 1974
42 min	305	Holt, Missouri	Jun. 22, 1947
60 min	401	Shangdi, Inner Mongolia	Jul. 3, 1975
1 h 12 min	440	Gaoj, Gansu	Aug. 12, 1985
2 h 30 min	550	Bainaobao, Hebei	Jun. 25, 1972
2 h 45 min	559	D'Hanis, Texas (17 miles NNW)	May 31, 1935
3 h	600	Duan Jiazhuang, Hebei	Jun. 28, 1973
4 h 30 min	782	Smethport, Pennsylvania	Jul. 18, 1942
6 h	840	Muduocaidang, Inner Mongolia	Aug. 1, 1977
10 h	1400	Muduocaidang, Inner Mongolia	Aug. 1, 1977
18 h	1589	Foc Foc, Reunion	Jan. 7–8, 1966
24 h	1825	Foc Foc, Reunion	Jan. 7–8, 1966
2 d	2467	Aurere, Reunion	Apr. 8–10, 1958
3 d	3240	Grand Ilet, Reunion	Jan. 24–27, 1980
4 d	3721	Cherrapunji, Meghalaya	Sep. 12–15, 1974
5 d	3951	Commerson, Reunion	Jan. 23–27, 1980
7 d	4653	Commerson, Reunion	Jan. 21–27, 1980
10 d	5678	Commerson, Reunion	Jan. 18–27, 1980
15 d	6083	Commerson, Reunion	Jan. 14–28, 1980
31 d	9300	Cherrapunji, Meghalaya	Jul. 1–31, 1861
2 mon	12767	Cherrapunji, Meghalaya	Jun.–Jul. 1861
4 mon	18738	Cherrapunji, Meghalaya	Apr.–Jul. 1861
6 mon	22454	Cherrapunji, Meghalaya	Apr.–Sep. 1861
1 y	26461	Cherrapunji, Meghalaya	Aug. 1860–Jul. 1861
2 y	40768	Cherrapunji, Meghalaya	1860–1861

Source: World Meteorological Organization (1986).

Bedient et al. (2019)

Rain gauges

- *How do we collect such rainfall data?*
- Quite simple answer, conceptually:
  - Place vessel open to air at point of observation
  - *i*) Periodically measure, or *ii*) continuously record, quantity of water collected
  - Divide volume collected by area of opening to get **depth** of precipitation (mm)

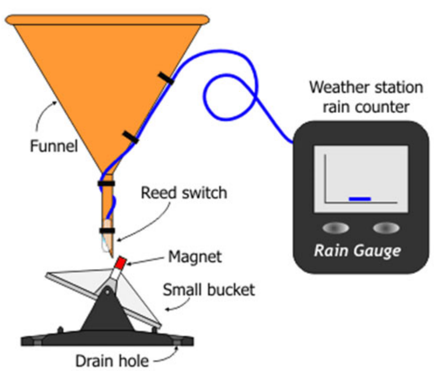
- *Note:* ***snow gauges*** *are more complicated because of wind effects and other factors…*

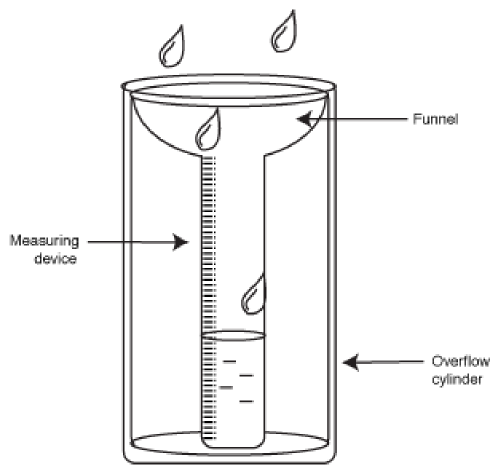
Dingman (2002)

Rain gauges

- **Rainfall gauges** come in two types:
  - Non-recording: cumulative volume only
  - Recording: uses a data logger
  - *See examples of rain gauges used by UK Met Service*: https://youtu.be/JVOxLrMaWA8

http://www.kifissiameteo.gr/Lesson08_Instrument_RainGauge.html





http://www.infoplease.com/cig/weather/measuring-rain.html

http://ec.gc.ca/meteoaloeil-skywatchers/default.asp?lang=En&n=7EF00E34-1

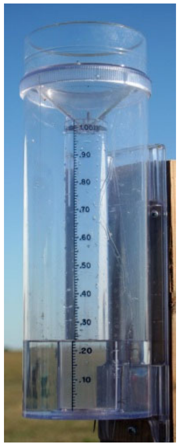
Bedient et al. (2019)

Non-recording gauge

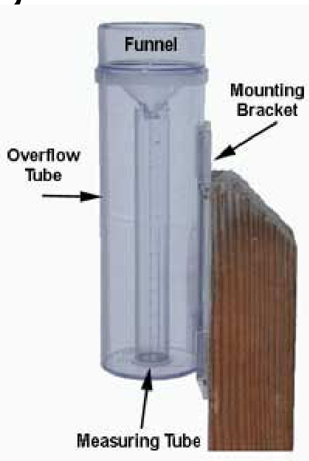
- Observers usually report 12-hr or daily amounts
  - Provide little information on intensity (mm/hr)
- Gauges typically either simple, straight-sided cylinders, or more elaborate devices with funnels and collecting vessels
- These are simple, inexpensive, and easy to use

http://www.crh.noaa.gov/ind/?n=standardgage

http://www.hubbardbrook.org/w6_tour/rain-gauge-stop/precipitation.htm



http://www.kcare.ksu.edu/p.aspx?tabid=885



http://www.cocorahs.org/Content.aspx?page=measurerain

Bedient et al. (2019); Dingman (2002)

Recording gauge

- **Recording gauge** required for time-distribution of rainfall
  - Useful for urban drainage or flood control works
  - Data can be shown as a,
    - **Cumulative mass curve** → *data given as cumulative reading*
    - **Rainfall intensity** graph → *"hyetograph", often input to a computer model*
- Two common types of gauge:
  - **Tipping-bucket gauge** fills small buckets on a fulcrum (slide 11) one at a time → records each time it tips. See https://youtu.be/ygLJV8upFQ4
  - **Weighing-recording gauge** introduces collected water to vessel on scale → records accumulated weight

http://www.munroinstruments.co.uk/Meteorological/contents/en-us/d53_Recording_Rain_Gauges.html

http://www.belfortinstrument.com/products/universal-rain-gauge

Bedient et al. (2019); Dingman (2002)

Sample rainfall graphs

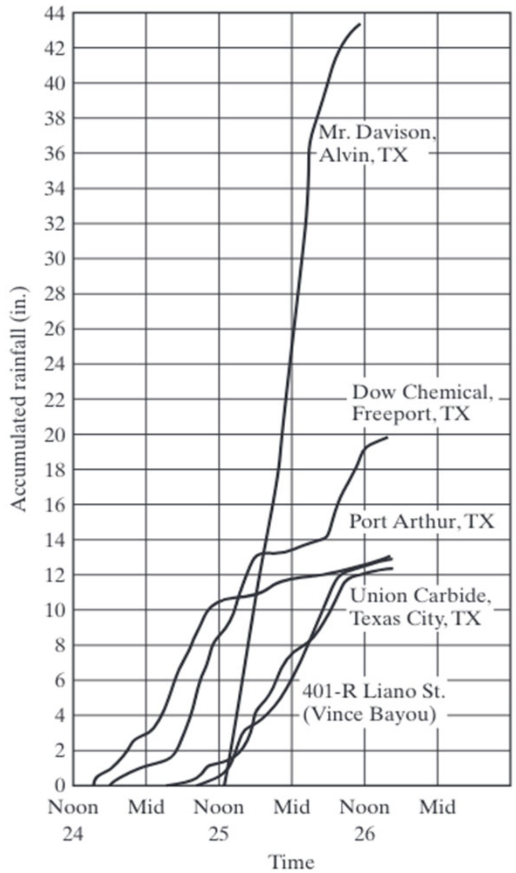
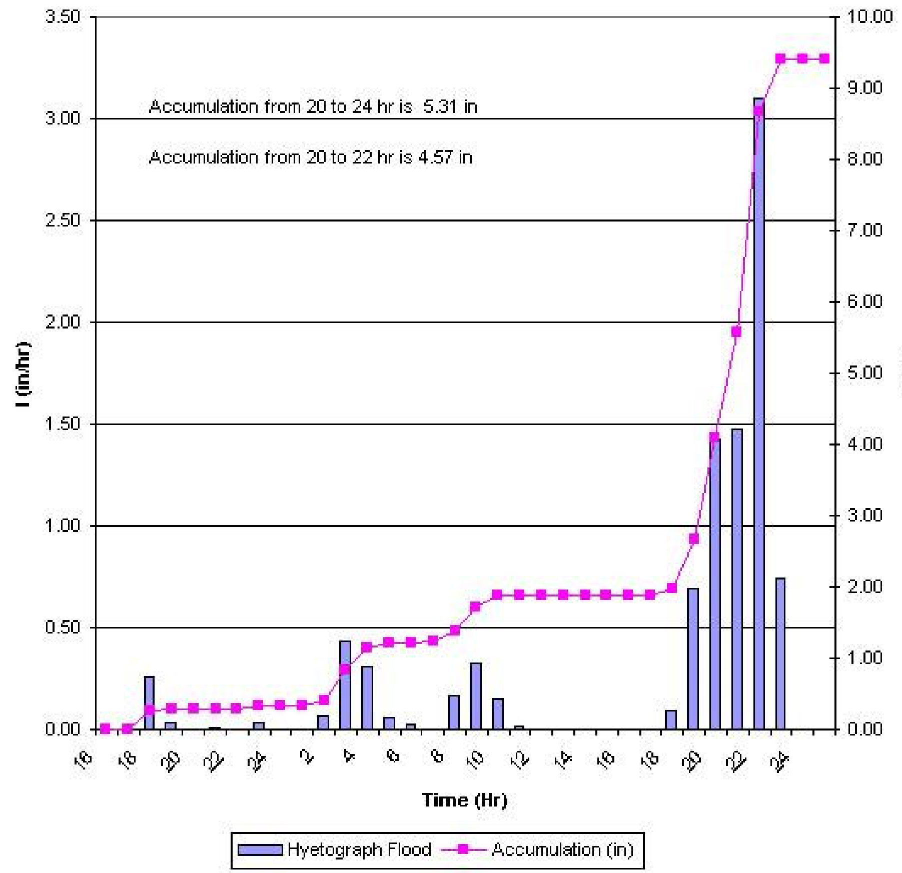


Figure 1–12
Accumulated rainfall for the July 1979 storm event near Houston, TX.

Cumulative mass curve
Fig. 1-12(b) in Bedient et al. (2013)



Cumulative mass curve
and **Hyetograph**
http://wwweng.uwyo.edu/civil/faculty/ogden-files/FortCollins/hyetogra.html

Problems with gauges

- For conventional gauges, there can be uncertainty about the fraction of the precipitation that enters the gauge
- Problems can be associated with,
  - Size of the orifice
  - Orientation of the plane of the orifice
  - Height of gauge above ground surface
  - Whether or not a wind shield used
  - Distance of gauge from other objects
  - Splashing in/out of water
  - Evaporative losses of collected water

Dingman (2002)

Missing data?

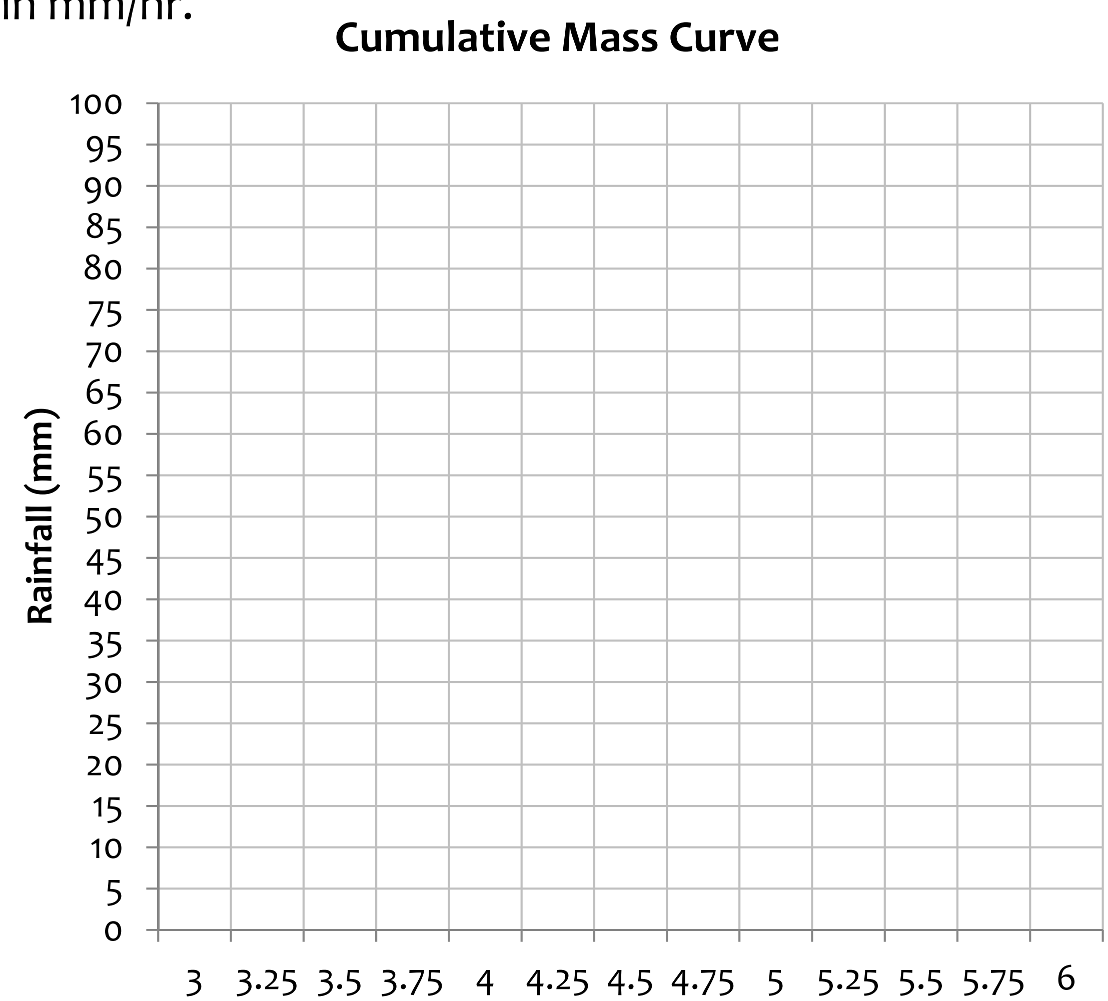
- *Finally, sometimes necessary to estimate point rainfall at a given location from recorded values at surrounding sites*
- Many ways available (see Dingman, 2002), but a simple way is based on **weighted average of surrounding values,**
  - Weights are reciprocals of sums of squares of distances D, measured from point of interest
  - For four rain gauges, where one broke and did not record rainfall,
    1. Estimate distances from non-functional gauge (for which we want P_1) to functional gauges. Distances called D_2, D_3, D_4
    2. Estimate for P_1 based on measured values P_2, P_3, P_4
    3. Equations: $D^2 = x^2 + y^2$, weight = $W = 1/D^2$, and rainfall estimate = $\sum_i P_i W / \sum_i W_i$

Bedient et al. (2019)

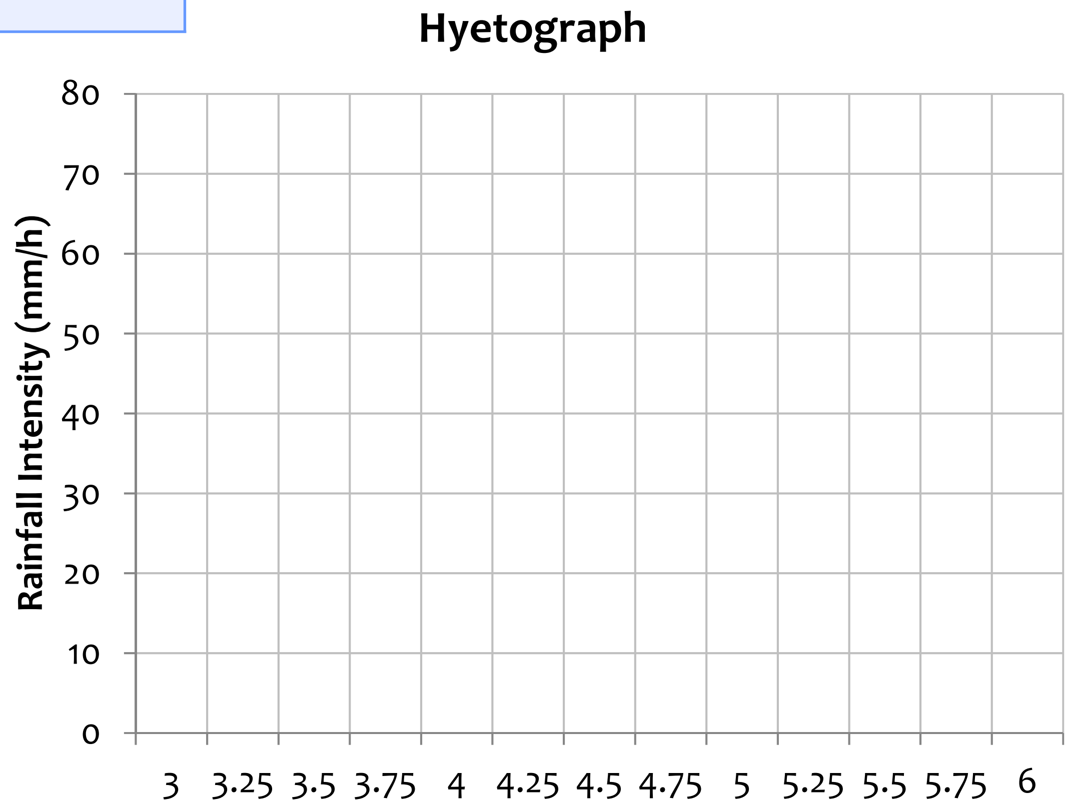
Ex 2: A hyetograph

The table below is a section of a record of precipitation from a recording gauge for a storm in Texas, for the period between 3 am and 6 am in increments of 0.25 hr. For the data given, develop the mass curve and rainfall hyetograph. Find the maximum-intensity rainfall for the gauge in mm/hr.

Time	Rainfall (mm)
3	27.9
3.25	37.3
3.5	47.5
3.75	58.9
4	78.7
4.25	86.4
4.5	88.4
4.75	89.9
5	91.9
5.25	93.5
5.5	94.5
5.75	96.0
6	97.5

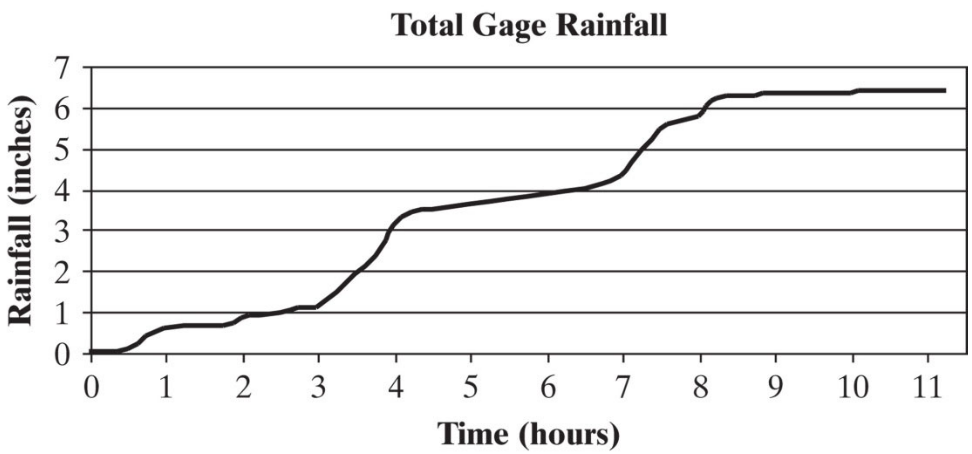


Time	Rainfall (mm)		
3	27.9		
3.25	37.3		
3.5	47.5		
3.75	58.9		
4	78.7		
4.25	86.4		
4.5	88.4		
4.75	89.9		
5	91.9		
5.25	93.5		
5.5	94.5		
5.75	96.0		
6	97.5		

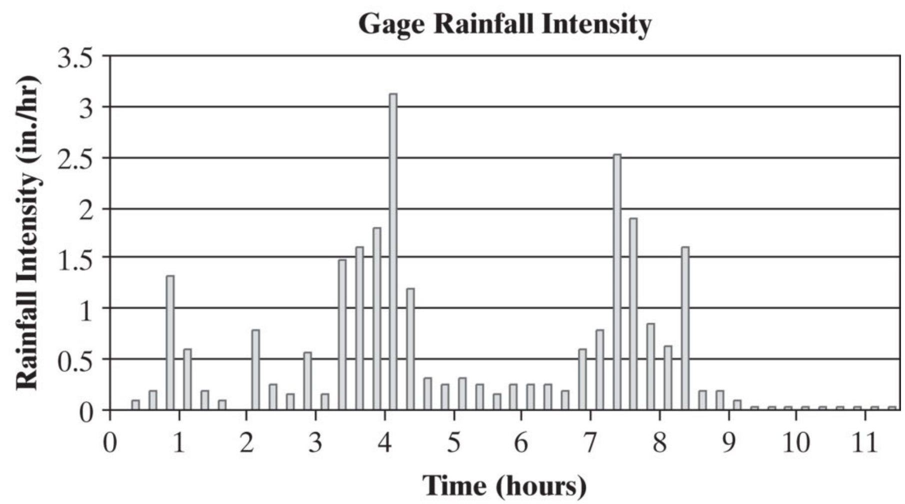


Solutions

- *Note: the solutions below show a longer timespan for the data, from midnight to 11:15 am. Units are **inches***



(a)



(b)

Bedient et al. (2019)

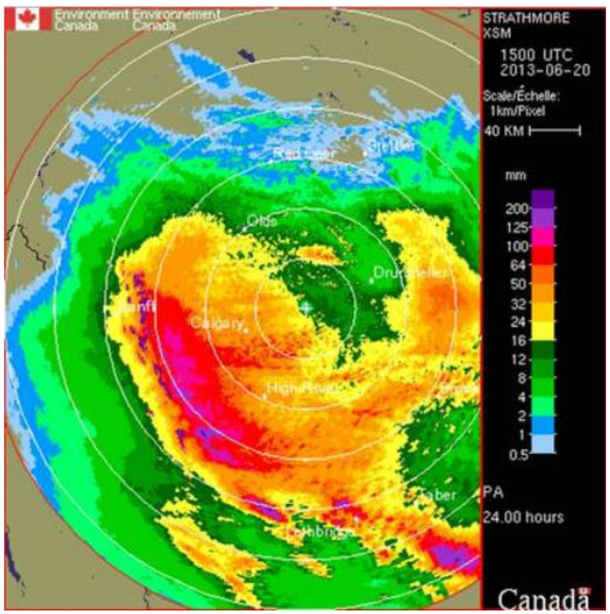
2.3 Areal Precipitation

- Predicting watershed response to a precipitation event requires knowledge of average rainfall that occurs over watershed in specified duration
  - *The key question: If several gauges in watershed record different depths, what value best represents the average rainfall depth?*

Rainfall data for S. Alberta floods, June 2013

24 h rainfall amounts

Watershed average?



Calgary flooding, 2013, from CBC: https://youtu.be/Ej1Z2KRz3gw
See also video footage of Canmore, Bragg Creek, High River at https://youtu.be/ptpPrzHg4qk (*Do NOT drive into flood waters!*)

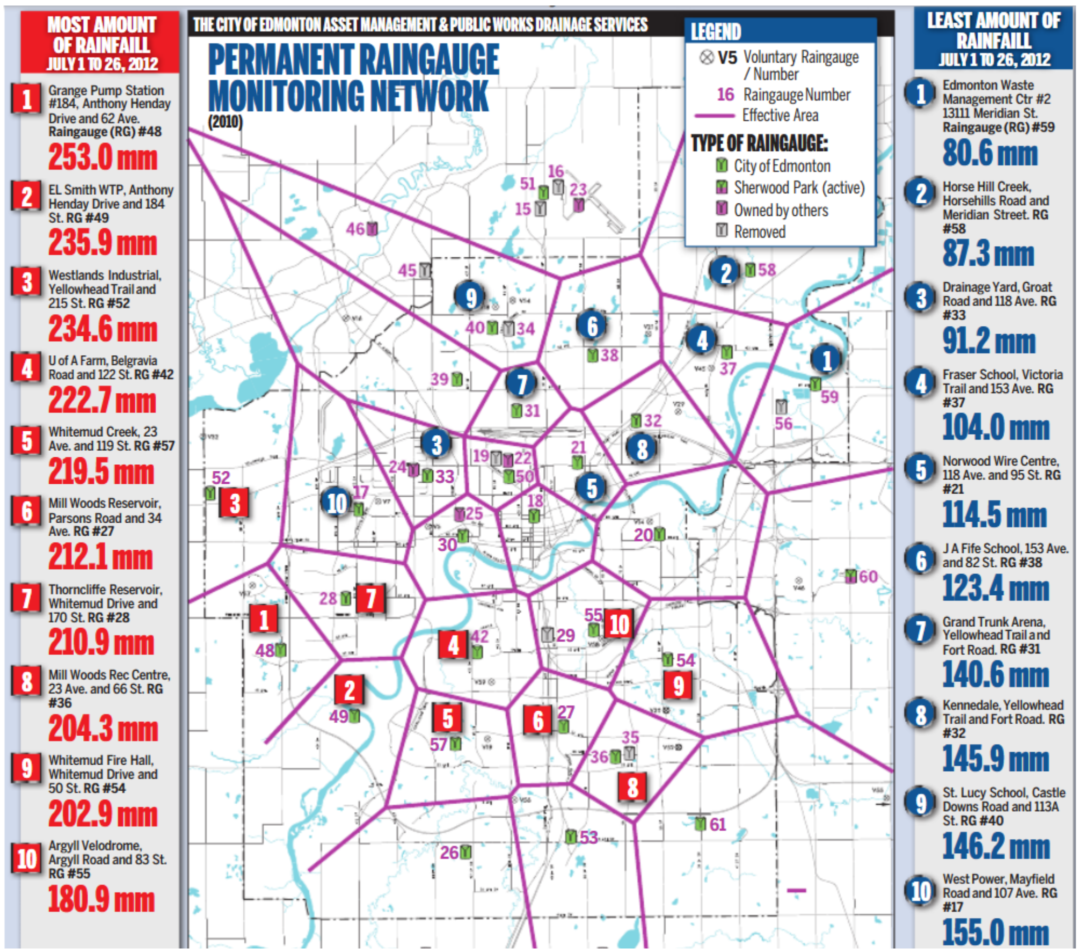
Bedient et al. (2019)

Areal rainfall data

- Note: Areal rainfall data available only from sophisticated **rainfall recording networks**
  - Typically located in larger urban areas, along major river basins

Edmonton rainfall gauge network, July 2012 rainfall

Source: Edmonton Sun Online July, 2012



Bedient et al. (2019)

Areal averaging methods

- Three basic methods are available for calculating watershed-average rainfall
  1. Arithmetic mean
  2. Thiessen polygon method
  3. Isohyetal method

- See Dingman (2002) for more complex alternatives
  - *Table reproduced on next page*

Bedient et al. (2019)

Areal precipitation methods

TABLE 4-5
Classification of Methods for Estimating Areal Precipitation from Point Measurements.

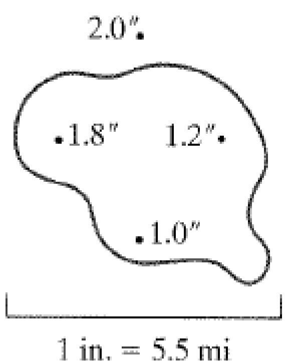
Method	Classification	Computational Complexity	Source for Full Description
Arithmetic average	Direct	Very low	This text
Thiessen polygons	Direct	Low	This text
Bethlahmy's two-axis	Direct	Low	This text
Eyeball isohyetal	Surface-fitting Deterministic Smoothing	Low to moderate	This text
Polynomial surface	Surface-fitting Deterministic Smoothing	Moderate	Tabios & Salas (1985)
Lagrange polynomial surface	Surface-fitting Deterministic Smoothing	Moderate to high	Tabios & Salas (1985)
Spline surface	Surface-fitting Deterministic Interpolation	Moderate to high	Creutin & Obled (1982) Lebel et al. (1987)
Inverse-distance interpolation	Surface-fitting Deterministic Interpolation	Moderate to high	Tabios & Salas (1985)
Multiquadric interpolation	Surface-fitting Deterministic Interpolation	Moderate to high	Shaw (1988) Creutin & Obled (1982)
Optimal interpolation/kriging	Surface-fitting Statistical Interpolation	High	Creutin & Obled (1982) Tabios & Salas (1985) Lebel et al. (1986)
Empirical orthogonal functions	Surface-fitting Statistical Interpolation	High	Creutin & Obled (1982)
Hypsometric	Surface-fitting Deterministic Smoothing	Low to moderate	This text i.e. Dingman (2002)

Dingman (2002)

Dingman (2002)

Arithmetic mean

- Simplest method for estimating average areal rainfall
  - Simply take **arithmetic mean** of point rainfalls from available gauges
  - Approach satisfactory if,
    1. Gauges uniformly distributed, and
    2. Individual variations from mean are low
  - Not very accurate for larger watersheds with variable rainfall



$$\frac{1.8 + 1.2 + 1.0}{3} = 1.33 \text{ in.}$$

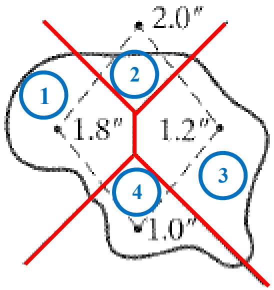
(a) Arithmetic mean

Bedient et al. (2019)

Thiessen polygons

- More complicated method, allows for areal weighting of rainfall from each gauge
- Probably most widely used approach
- Does not allow for orographic effects

- Produces a polygon around each gauge
  - Each polygon is the locus of points closer to the given gauge than any other



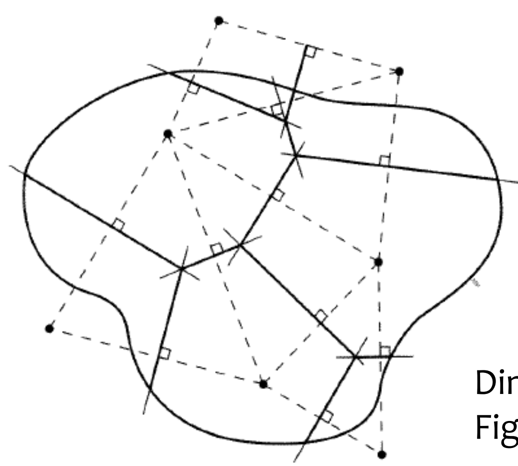
P_i (in.)	A_i (mi^2)	A_i/A_r	$(P_i)(A_i/A_r)$ (in.)	
2.0	1.5	0.064	0.13	2
1.8	7.2	0.305	0.55	1
1.2	5.1	0.216	0.26	3
1.0	9.8	0.415	0.42	4
$\Sigma =$	23.6	1.000	1.35 in.	

(b) Thiessen polygon method

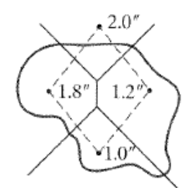
Bedient et al. (2019)

Thiessen polygons

- Method: Using map of all gauges,
  1. Draw connecting lines between stations → Triangles
  2. Draw perpendicular bisectors for each connecting line (*dotted lines* in figure)
  3. Use bisector lines (*solid lines* in figure) to form polygon around each gauge
  4. Ratio of area of each polygon, A_i, within watershed boundary to total watershed area, A_T, is used to weight each station's rainfall



Dingman (2002), Fig. 4-23



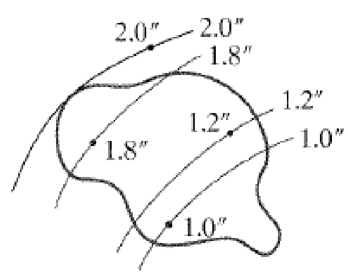
P_i (in.)	A_i (mi^2)	A_i/A_T	$(P_i)(A_i/A_T)$ (in.)
2.0	1.5	0.064	0.13
1.8	7.2	0.305	0.55
1.2	5.1	0.216	0.26
1.0	9.8	0.415	0.42
Σ =	23.6	1.000	1.35 in.

(b) Thiessen polygon method

Bedient et al. (2019)

Isohyetal approach

- Contours of equal precipitation (*isohyets*) are drawn
- Most accurate approach, but extensive gauge network required for accurate drawing of isohyets
- Can include orographic effects, storm morphology
- Calculation involves,
  1. Finding average rainfall between each pair of contours
  2. Multiplying by area between the contours
  3. Totalling the products
  4. Dividing by total area



Isohyet (in.)	A (mi^2)	P_{av} (in.)	V (in.–mi^2)
2.0	5.1	1.9	9.69
1.8	9.8	1.5	14.7
1.2	3.1	1.1	3.41
1.0	5.6	0.5*	2.8
	23.6		30.6

Average rainfall = 30.6/23.6 = 1.30 in.

* Estimated

(c) Isohyetal method

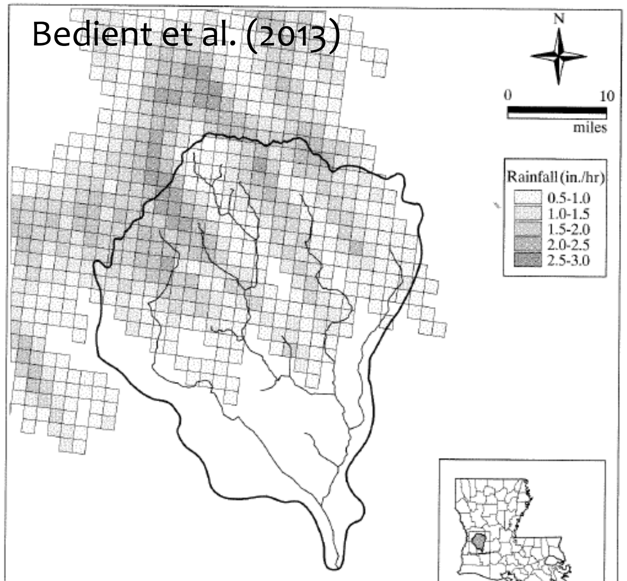
Bedient et al. (2019)

Radar-based measurement

- Advances in weather radar in early 1990s greatly improved ability to determine rainfall rates over watersheds →
  NEXRAD = next-generation radar
  - Until development of NEXRAD, gauging stations were only source of rainfall data
- NEXRAD reflects off raindrops in atmosphere to estimate rainfall rates in time and space
  - Uses 1 mm to 10-cm-wavelength radar
  - Strength and timing of returning waves shows,
    - How much precip. there is (bigger or more raindrops send stronger signals)
    - Where the rain is falling
    - How fast rain is moving, toward or away from radar
- *See* NOAA (2009): https://youtu.be/KdKouCnhvPs

Also: https://www.canada.ca/en/environment-climate-change/services/weather-general-tools-resources/radar-overview/modernizing-network.html, and https://www.ncdc.noaa.gov/data-access/radar-data/nexrad

Bedient et al. (2013)



Sample NEXRAD rainfall data, Louisiana

Bedient et al. (2019)

Satellite-based measurement

- Satellites use special sensors to detect different types of energy emitted by the atmosphere and ground. They look at,
  - **Clouds**: Satellites use **visible and infrared light** to see clouds, their thickness and height. Tall, thick clouds often mean heavy rain or snow
  - **Microwaves for details**: Some satellites use **microwaves** to detect raindrops, snowflakes, or ice particles. This helps to measure how much precipitation is falling
  - **Ground temperature:** Satellites can also measure the **temperature of the ground or ocean.** Warm surfaces with no clouds usually mean no rain, while cooler surfaces under clouds often indicate rain

See NASA (2020), https://www.youtube.com/watch?v=wp46FvgYQeM (time: 3:50-7:17)

3. STORM ANALYSIS

- Important to differentiate between **actual** and **design** storms
  - **Actual rainfall:** real rainfall that occurs naturally and is measured with rain gauges or other methods
    - Useful for analyzing and understanding past events
  - **Design rainfall** (or **design storms**)**:** hypothetical or representative rainfall event based on statistical analysis of historical rainfall (point) data
    - Especially useful for low-frequency scenarios where data are unavailable or rare (50-year or 100-year storms)
    - Often represented through tools such as "IDF curves" and "design hyetographs"

- I.e. We can apply *statistical methods* to long series of rainfall data to develop "design storms" that help in design of
  - Hydraulic structures
  - Infrastructure design
  - Flood planning

X Project, Emergency spills
https://youtu.be/o3E4s59OSLQ

http://www.mrcsi.com/content/solutions/water-resources.html

Storm analysis

- Two primary parameters used to specify a storm are,
  - **Intensity** (mm/hr or in/hr)
  - **Duration** (minutes, hours)

- For design purposes, typically also want to estimate the **frequency** of occurrence of storm of given intensity and duration

- Results of analysis are location-specific – Intensity, duration, frequency relationships for "point rainfall" at a single "station" or gauge

Storm analysis → Storm models

- Several different methods are available to **design for storms,** based on gauge data
  1. Models of storm *depth* and *duration*
  2. Models of storm *intensity* and *duration*
  3. *Intensity-Duration-Frequency* (IDF) curves
  4. Design precipitation *hyetographs*

Key Concepts

- Intensity, duration and return period:
  - Can use rainfalls of various lengths (5 min to 24 h) to develop estimates of **intensity** (mm/hr) and **duration** (hr) of 2-yr, 5-yr, 10-yr, 25-yr, 50-yr, 100-yr … events
    - These n-yr terms represent the **return period** of the rainfall event → i.e. average length of time between two rainfall events that are at least as large as (*i.e.* ≥) a given depth and duration
    - *Obviously, larger rainfalls occur less frequently than smaller*
    - *Intensity tends to decrease with increasing duration*

http://www.geograph.org.uk/photo/231372

http://soundofheart.org/galacticfreepress/content/tropical-storm-isaac-continues-dump-rain-louisiana

Ponce (1989)

Key Concepts

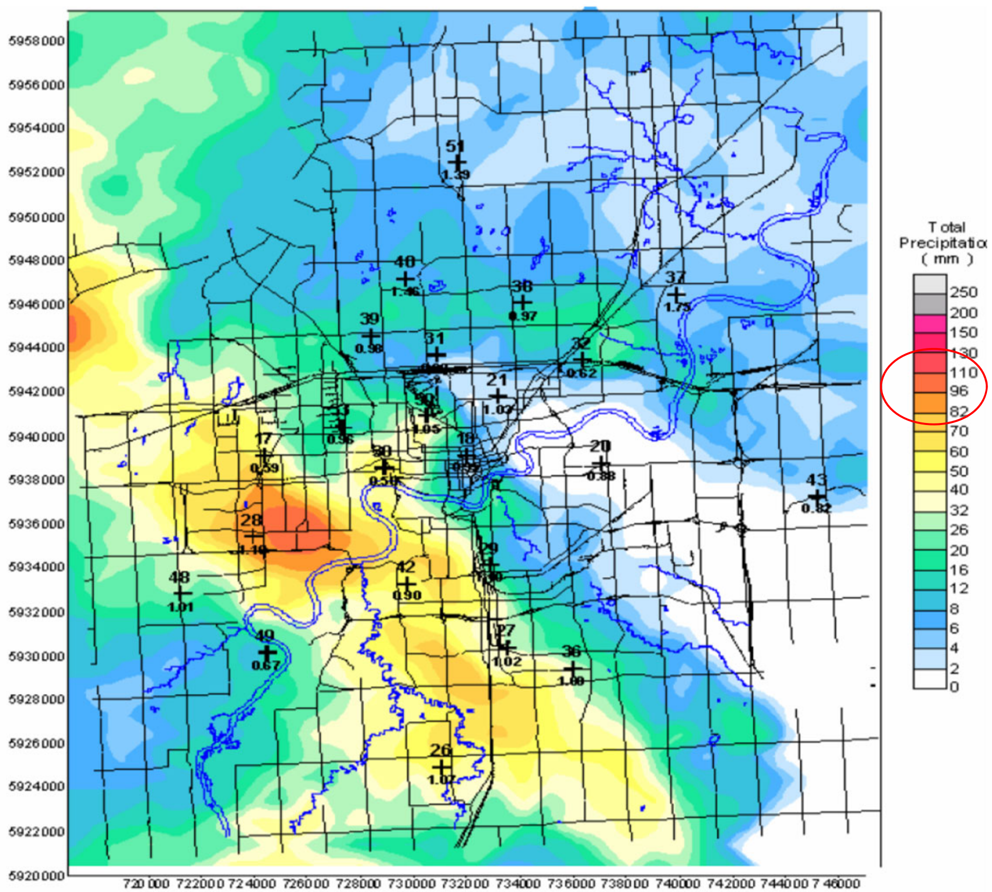
- Closely related to return period is **rainfall frequency** → the chance that a rainfall event of a given depth and duration will occur or be exceeded (*i.e.* ≥) during a chosen time period, usually one year
  - **Rainfall frequency** is a probability or "chance"

*ChatGPT explains: "**Rainfall frequency** tells us the chance of a storm happening in a year, while **return period** tells us the average time we would expect to wait between storms of that size."*

- Example: if a 100-mm rainfall event lasting 6 hours occurs every 50 years on average in a particular location, then,
  - *Return period = 50 yrs, rainfall frequency = 1/50 yrs = 0.02*

Ponce (1989)

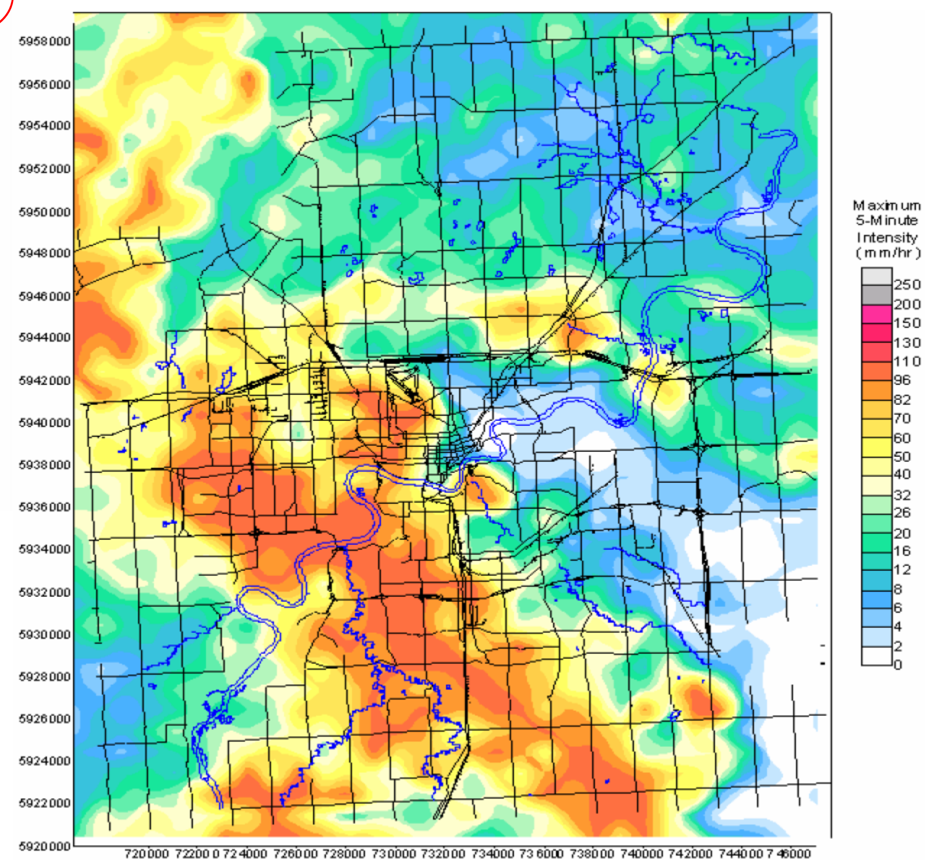
Depth and intensity graphs



Total Precipitation Depth (mm)

July 11, 2004

Note: Average annual precipitation for Edmonton is ≈ 500 mm



Max 5-Minute Intensity (mm/hr)

3.1 IDF CURVES

*For engineering design, we typically need to know the **intensity** and **duration** of precipitation events, as well as their **frequency** of occurrence!*

- These three storm characteristics can be related to one another in **equation** and/or **graphical** form
  1. *Equation* form can be tabulated for easier use…
  2. We can *graph* several intensity-duration curves, each for different frequencies/return periods, on the same chart!

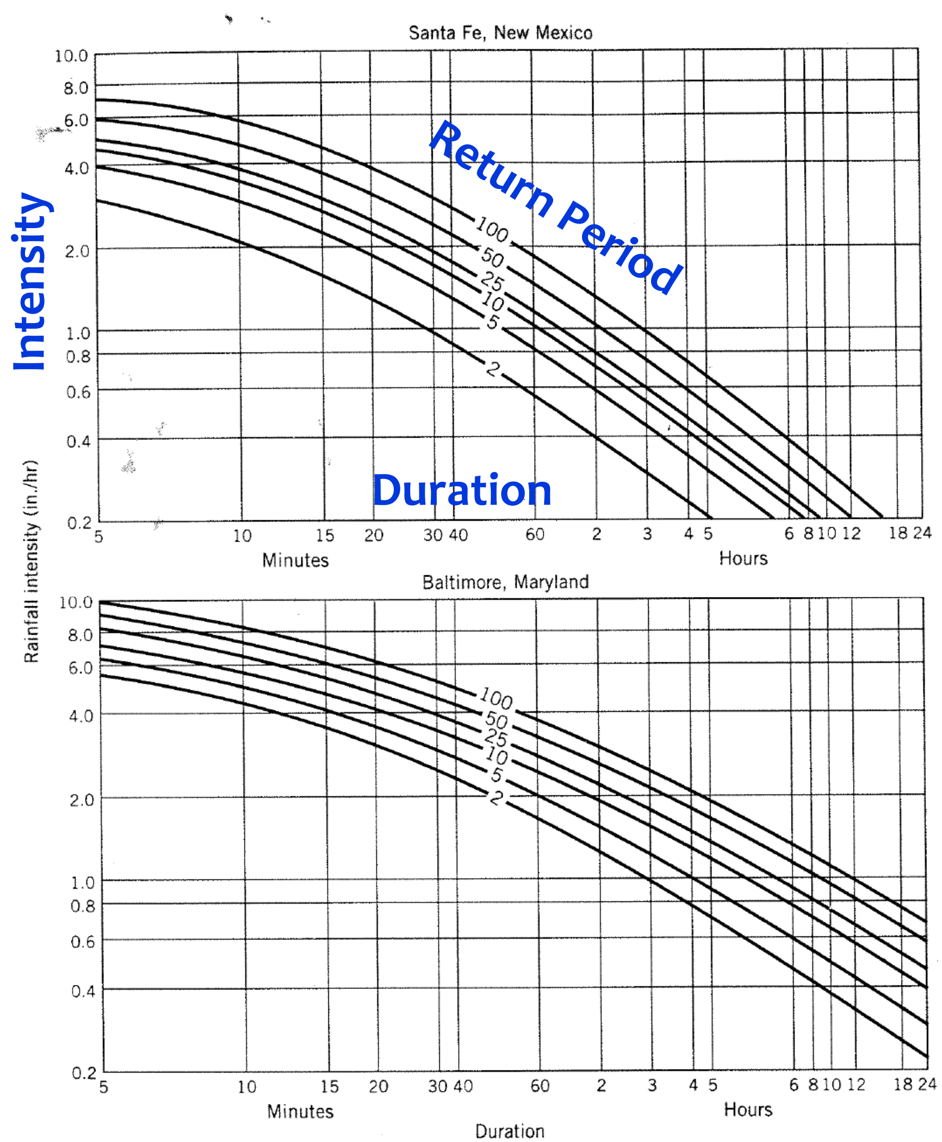


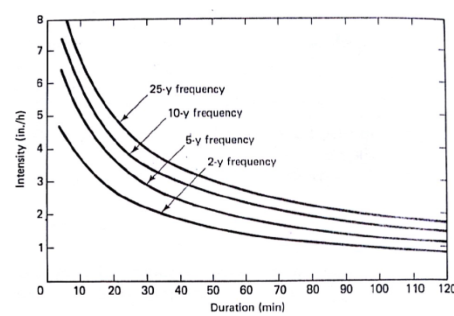
FIGURE 3.12 Intensity-duration frequency curves.

Combine in **one graph** information on ***intensity***, ***duration***, and ***frequency***:

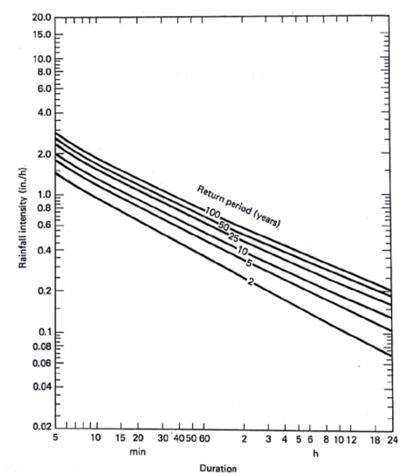
…and get *the **I-D-F** curve!*

Note that different scales possible:

Ponce (1989)



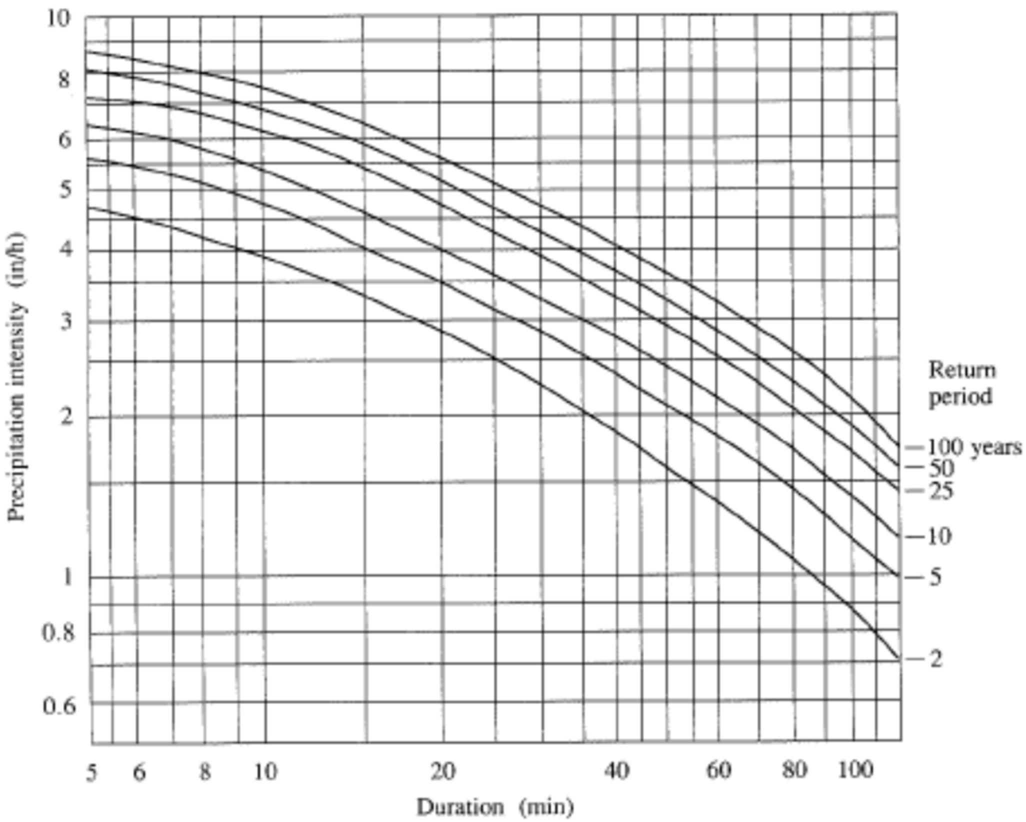
Intensity-duration-frequency curve with **arithmetic scale**



Intensity-duration-frequency curve with **logarithmic scale**

Ex 3: IDF curve use

Determine *i* (intensity) and *P* (depth) for a **20-min duration** storm with **5-yr return period** in Chicago



Intensity-duration-frequency curves of maximum rainfall in Chicago, U. S. A.

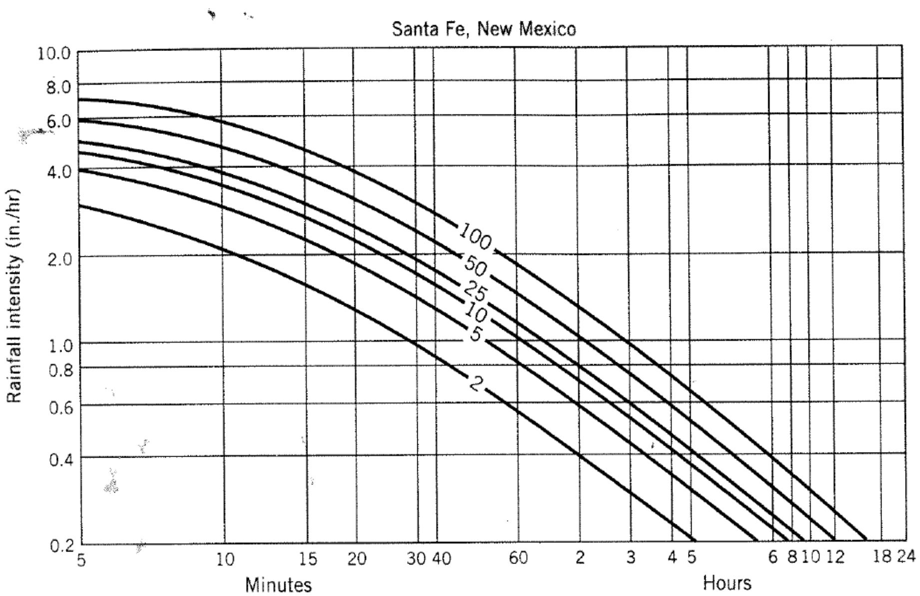
From the IDF curve for Chicago,

Maidment (2010), *course notes*

http://www.ce.utexas.edu/prof/maidment/GradHydro2010/Visual/DesignStorms.ppt

Ex 4: IDF curve application

Using the IDF curves for Santa Fe, NM, answer the following questions:

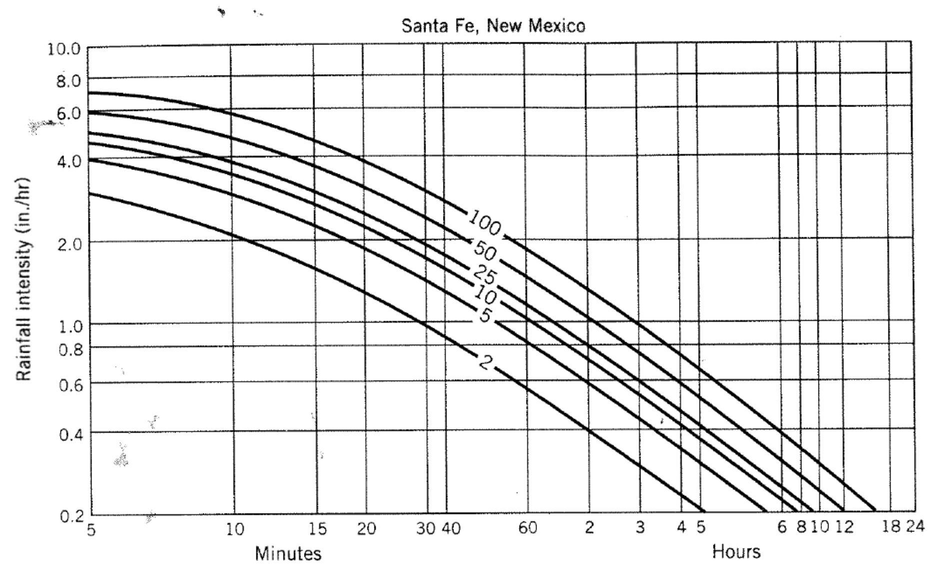


1. What is the rainfall intensity for a 50-yr storm event with a duration of 60 min?

2. If the duration were 5 hr for the 50-yr storm event, what would be the rainfall intensity and the total rainfall?

3. If the time of concentration of a watershed is 30-minutes, what would be the maximum rainfall intensity *(i* in in/hr) you would use to design a storm of 50-yr return period?

If the return period is only 2-yr, what would be the *i* you would use for this watershed?



Time of concentration is the time needed for water to flow from the remotest part of a watershed to the outlet – see internet sources incl. *Wikipedia* ("time of concentration").

4. What is the peak discharge (Q_{peak}) at the above watershed outlet if a 50-yr storm occurs over the watershed that is impervious and of rectangular shape with width 2 km and length 3 km? (Hint: use the watershed water balance equation). Express Q_{peak} in m^3/sec.

5. For the storm of part 4, estimate the *rainfall excess* in m^3 (1 inch = 0.0254m).

Rainfall excess is the rainfall that is neither retained on the land surface nor retained in the soil – in other words, it is the amount that runs off the watershed surface to become streamflow.

Design storms

- *How can we plan for extreme events?*
- Use IDF curves to derive **design rainfall** events!
  - Also called "**design rainstorm**" or "**design storms**"
  - *Characteristic components*: depth, P (mm); duration, D (min, hr); average intensity, $I = P/D$ (mm/min, mm/hr); *and for more complex design storms*: time-distribution of rainfall intensity, $i(t)$
  - *Examples*: 10-yr, 2-hour storm (50 mm/hr); 10-yr, 24-hour storm (7.6 mm/hr, or 183 mm total)
- Resulting **design storms** often used as input to hydrological models for drainage design or flood analysis

Musy et al. (2005), Module 1B, Engineering Hydrology
http://echo2.epfl.ch/VICAIRE/mod_1b/chapt_2/main.htm

Motivation: Extreme storms

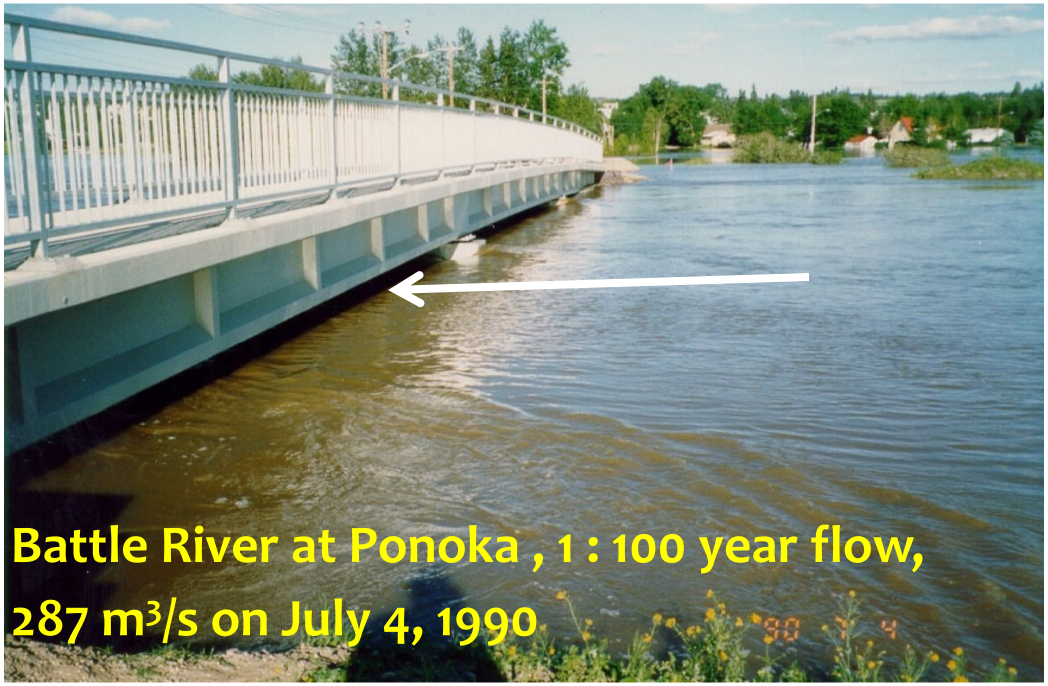
- **June 2005** storm in Calgary
  - $15 million damage, 1,500 persons evacuated, 730 cases of residential sewage back up, overflows at wastewater treatment plants
- **July 2, 6, 11, 2004** storms in Edmonton
  - 4000 basements flooded, roads (incl. Whitemud) flooded, ice!
- **July 12, 2012** storm in Edmonton
  - Over 1000 basements flooded
- **June 19-22, 2013** flood in Calgary and Southern Alberta
  - 75,000 people in Calgary and all 13,000 residents of High River ordered evacuated, possibly $5 billion of damage
- **August 25-28, 2017**: Hurricane Harvey, Houston TX
  - More than 40 in. (1000 mm+) of rain in some locations
  - At least 45 dead, more than 185 000 homes damaged
  - Insured flood damage estimates: $20-$35 billion (USD); uninsured ?
- **September 6-12, 2017**: Hurricane Irma, Caribbean and Florida
  - Estimate of 82 dead (43 in Caribbean and 39 in US)
  - 95% of buildings on St. Martin damaged, 60% uninhabitable
  - Insured damage estimates: $30-$40 billion in US (USD); uninsured ?

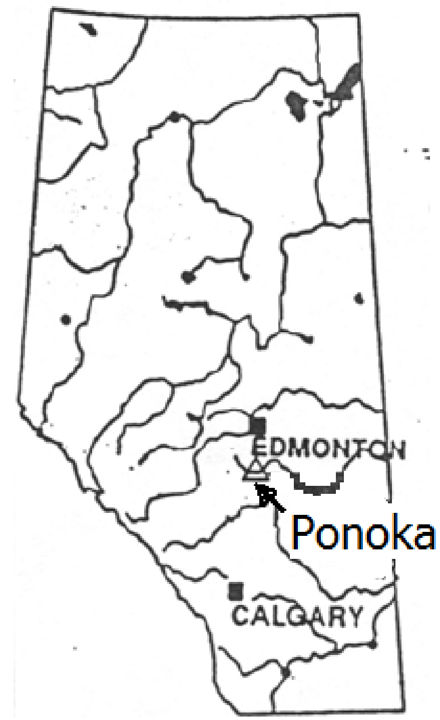
July 2, 6, 11, 2004 Storms

>185 mm of rain in parts of Edmonton

Outfall #15 washed out

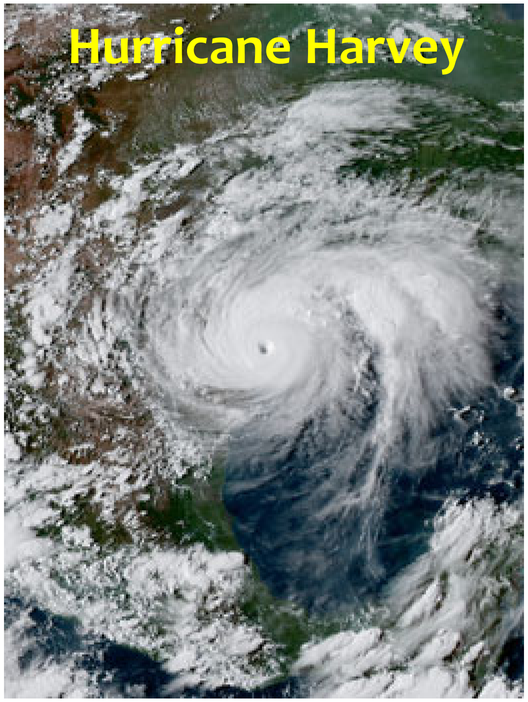
Figure 5. Washout at the Whitemud Trestle.


Battle River at Ponoka , 1 : 100 year flow,
287 m³/s on July 4, 1990
'90 7 4

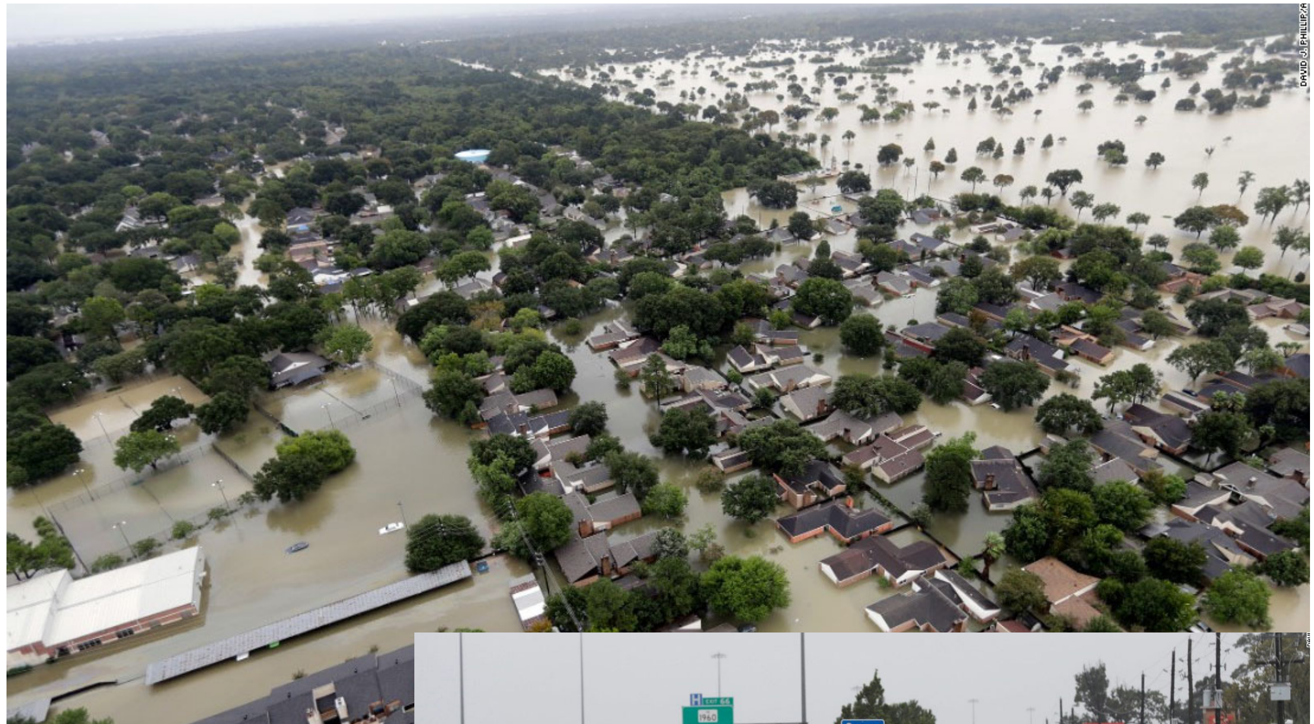

EDMONTON
Ponoka
CALGARY


1948 Flood
Flow of 232 m³/s


~ 4.5 m³/s (low) Oct. 29, 2000



Source: NOAA’s GOES-16 satellite



http://www.cnn.com/2017/08/26/us/gallery/hurricane-harvey/index.html

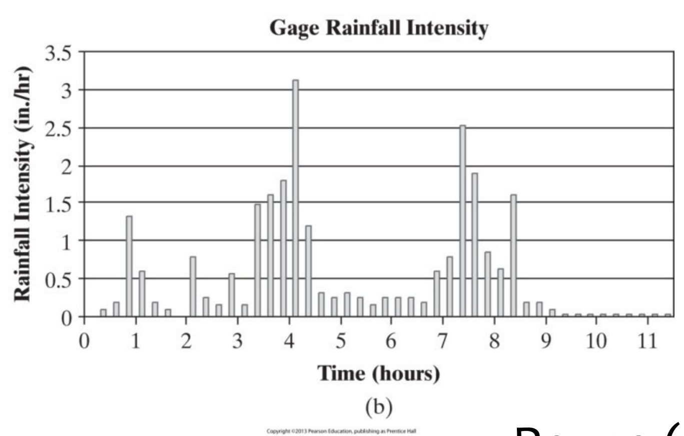
Hurricane Dorian, Bahamas, 2019

Hurricane Dorian leaves parts of the Bahamas in complete ruin
https://youtu.be/-zoQQnLvA_U, Sept. 3, 2019, CBC News

3.2 Design hyetograph

- IDF curves assume storm of constant intensity (I) for given duration (D)
  - However, I is not constant, especially for longer storms
  - *Result: underestimation of peak flows*

- Further, instantaneous values of rainfall intensity likely to be important in reality, especially for flood peaks during longer storms
  - *We have seen instantaneous graphs of rainfall before:* ***hyetographs***



Ponce (1989)

Design hyetograph

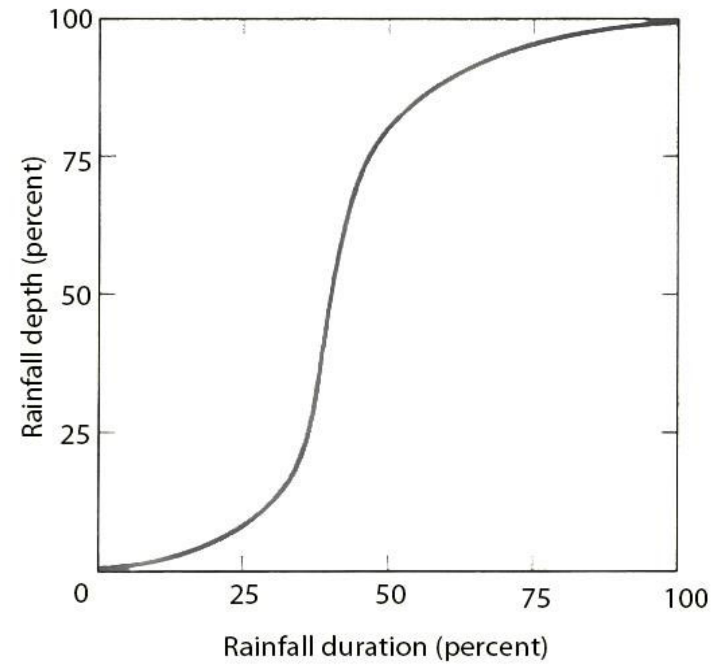
- ***Hyetographs*** are histograms of rainfall depth (or rainfall intensity) per unit time
  - *Time on* x *axis, and depth on* y *axis*
- An alternative form is the "***temporal rainfall distribution***", which shows both rainfall and duration as *percentages of the total*
  - These dimensionless graphs are used to convert a **given storm depth** into a hyetograph
  - *They produce a variation of rainfall over the storm*

- *Design hyetographs are often called "synthetic storm hyetographs"*

Ponce (1989)

Ex 5: Design hyetograph

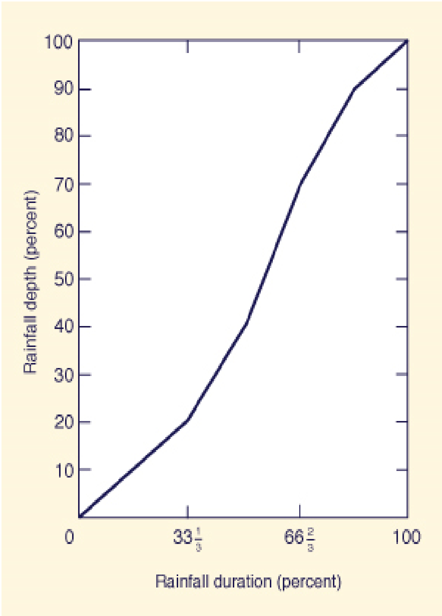
- Use the curve at right to calculate a hyetograph for a 15-cm, 6-hr storm
  - Solution approach:
    1) Use time increments of 1 hour (1/6) of storm.
    2) Look up rainfall depth percentages that match 17%, 33%, 50%, 66%... of the duration.
    3) multiply each rainfall depth percentage by 15cm, and graph the resulting depths, one value per hour interval



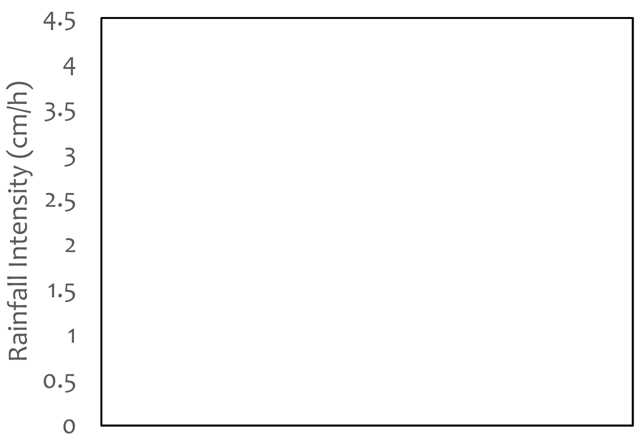
- *Note: Each location has different* temporal rainfall dist. curve

Ponce (1989)

Use the dimensionless temporal rainfall distribution shown below to derive a design hyetograph for a 15-cm, 6-h storm.



Segment	Duration (%)	Depth (%)	Time (h)	Depth (cm)	Intensity (cm/hr)
0	0				
1	17%				
2	33%				
3	50%				
4	67%				
5	84%				
6	100%				



Design hyetographs: SCS curves

- *Another application of design hyetograph concept:*

- In 1970s, US Dept. of Agriculture's *Soil Conservation Service* (SCS) developed set of four *dimensionless temporal rainfall distribution curves* for **24 hour rainfalls** and one for **6 hour rainfall** → **SCS curves**
  - Note: SCS now called **NRCS** (Natural Resources Conservation Service)
  - **Type I** and **Type IA** : Pacific maritime (wet winter, dry summer)
  - **Type III** curve: Gulf of Mexico and Atlantic (tropical storms)
  - **Type II** curve: Rest of the US

Mays (2011), Chapter 7

SCS Type I-III curves

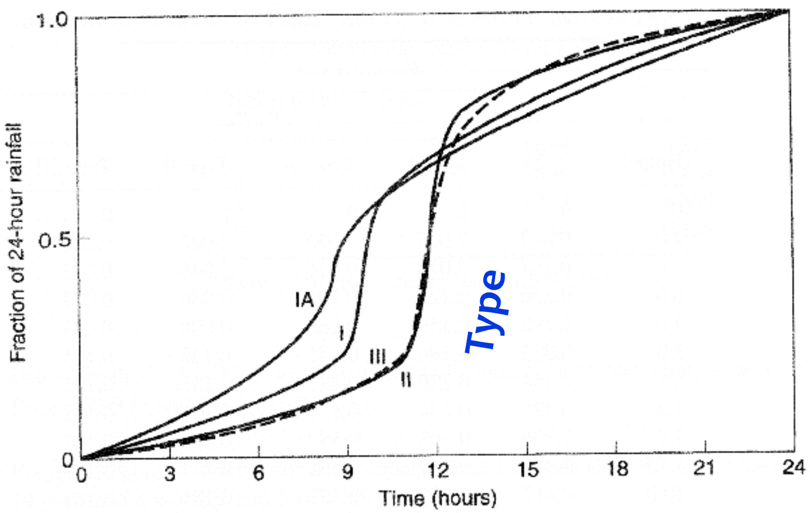
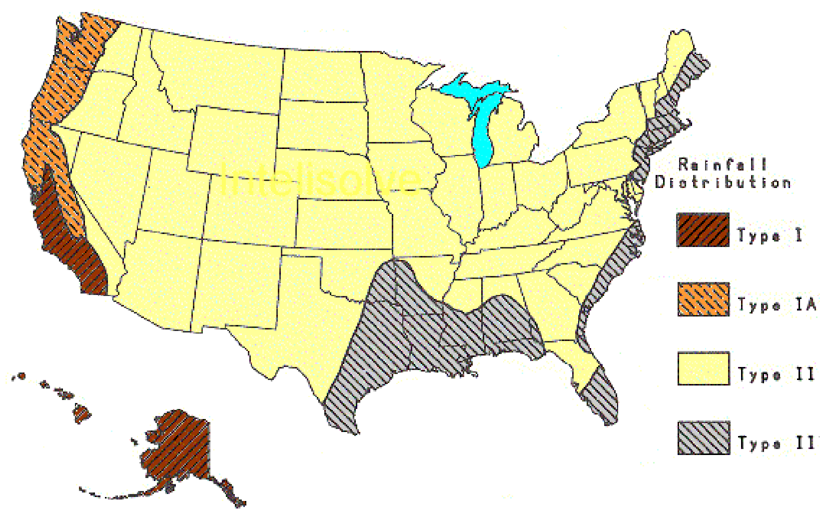


Figure 7.2.16 Soil Conservation Service 24-hour rainfall hyetographs (from U.S. Department of Agriculture Soil Conservation Service (1986)).

24-hour rainfall hyetographs

Where each curve applies…



Mays (2011), Chapter 7

SCS curve tables

- For calculation purposes, SCS curves are also tabulated:

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	4.50	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	1.00	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			

Can interpolate between these values (t = 1, t = 3, etc.)

P_{24} is intensity (mm/h) x duration (h), which gives total storm depth.

Example: for Type III, half the total 24-h rainfall (P_{24}) has fallen by t = 12 h, or halfway through the storm.

Cumulative values (incremental additions to a final value of 1.000, or 100%)

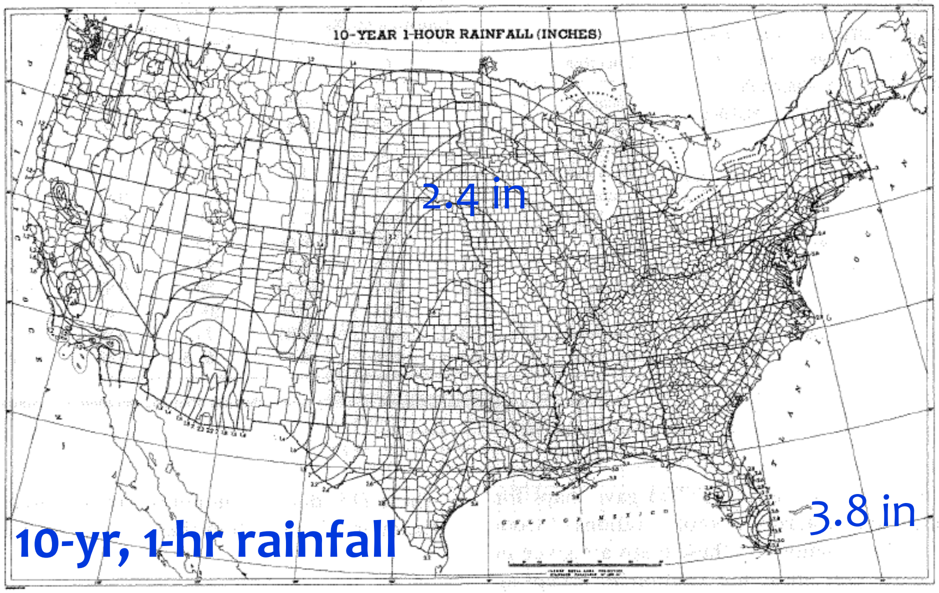
Source: US Dept of Agriculture's Soil Conservation Service (1973, 1986)

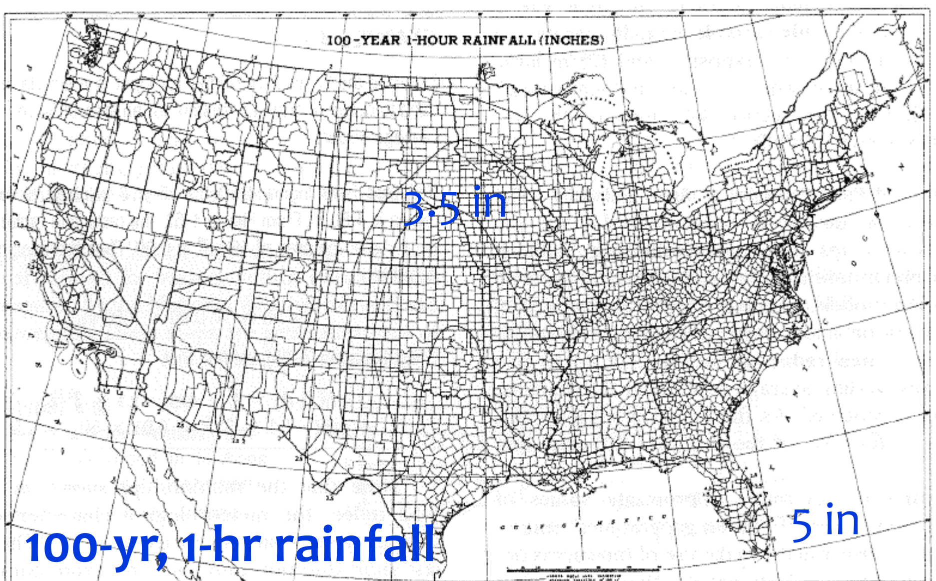
Mays (2011), Chapter 7

Isohyetals

- Based on storm analysis, can also graph rainfall **depth contours** for watersheds or larger regions
  - Based on series of “point measurements”: lots of individual rainfall gauge records
  - Show lines of equal rainfall depth on map
  - Applications:
    - Map rainfall contours for specific storm
    - Map depth contours for design storm with specified return period and duration

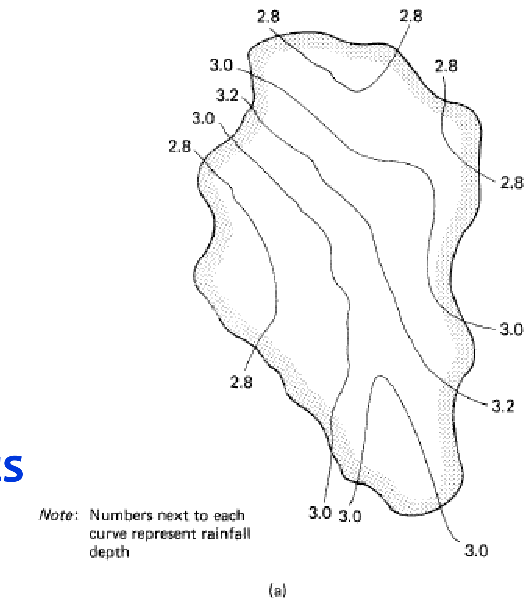
Isohyetals



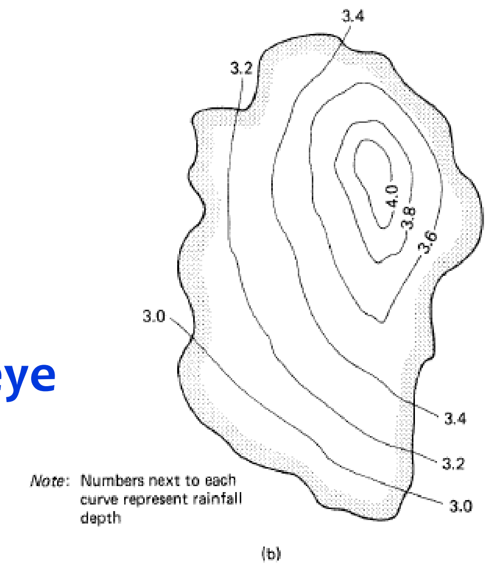


Dingman (2002), Fig. 4-51

Storm isohyets



Storm eye



Ponce (1989), Fig 2-4

Next topics: Losses/abstractions

- **Rainfall** is the key input to the surface component of hydrological cycle → *recall the* ***water budget***,

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

- Now begin to address **other components** of the water budget: the **losses** or "**abstractions**"
  - *Evaporation, transpiration and infiltration*
- *Next topic is first and second of these losses:* Evaporation+transpiration = **evapotranspiration**

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