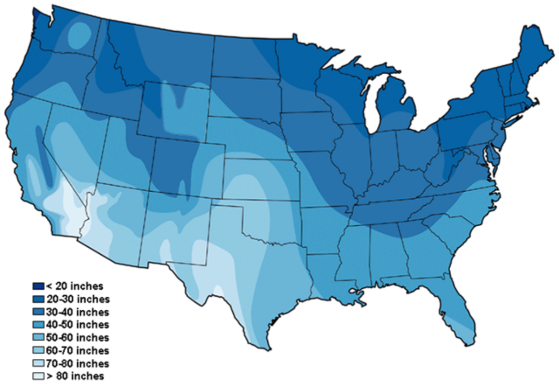
Salt evaporation ponds http://www.123rf.com/photo_5277564_salt-evaporation-ponds.html; See National Geog. (2017), https://youtu.be/0vVyw2rVA4Q

Civ E 321: Principles of Environmental Modelling and Risk

WEEK 3: EVAPORATION AND ET

Most information in Week 3 is from pages 56-57 and 111-122 *of **Bedient et al. (2019)***



http://nac.unl.edu/atlas/Map_Html/Climate/National/Mean_Annual_Lake_Evaporation/ET.htm

http://www.sciencedaily.com/releases/2013/04/130411194647.htm

http://www.crh.noaa.gov/lbf/?n=evap_pan

Section overview

- Introduction
- Measuring evaporation rates
- Estimating evaporation rates
- Estimating ET rates

1. EVAPORATION

"Evaporation is the process by which water in its liquid or solid state is transformed into water vapour, which mixes with the atmosphere" (Bedient et al. 2019: 56)

"Evapotranspiration (ET) is considered separately as the combined loss of water vapour from the surface of plants and the evaporation of moisture from soil" (Bedient et al 2019: 56)

- Evaporation is important in the **long-term water balance**
- Usually important for large-scale water resources project planning and water supply studies (especially in dry areas)
  - Knowledge of evaporation processes is important in predicting water losses to evaporation from a **lake** or **reservoir**
- *For a good conceptual review, see* https://youtu.be/Z4qgBT48NaU (Nash, 2019)

Bedient et al. (2019)

Evaporation time-scale

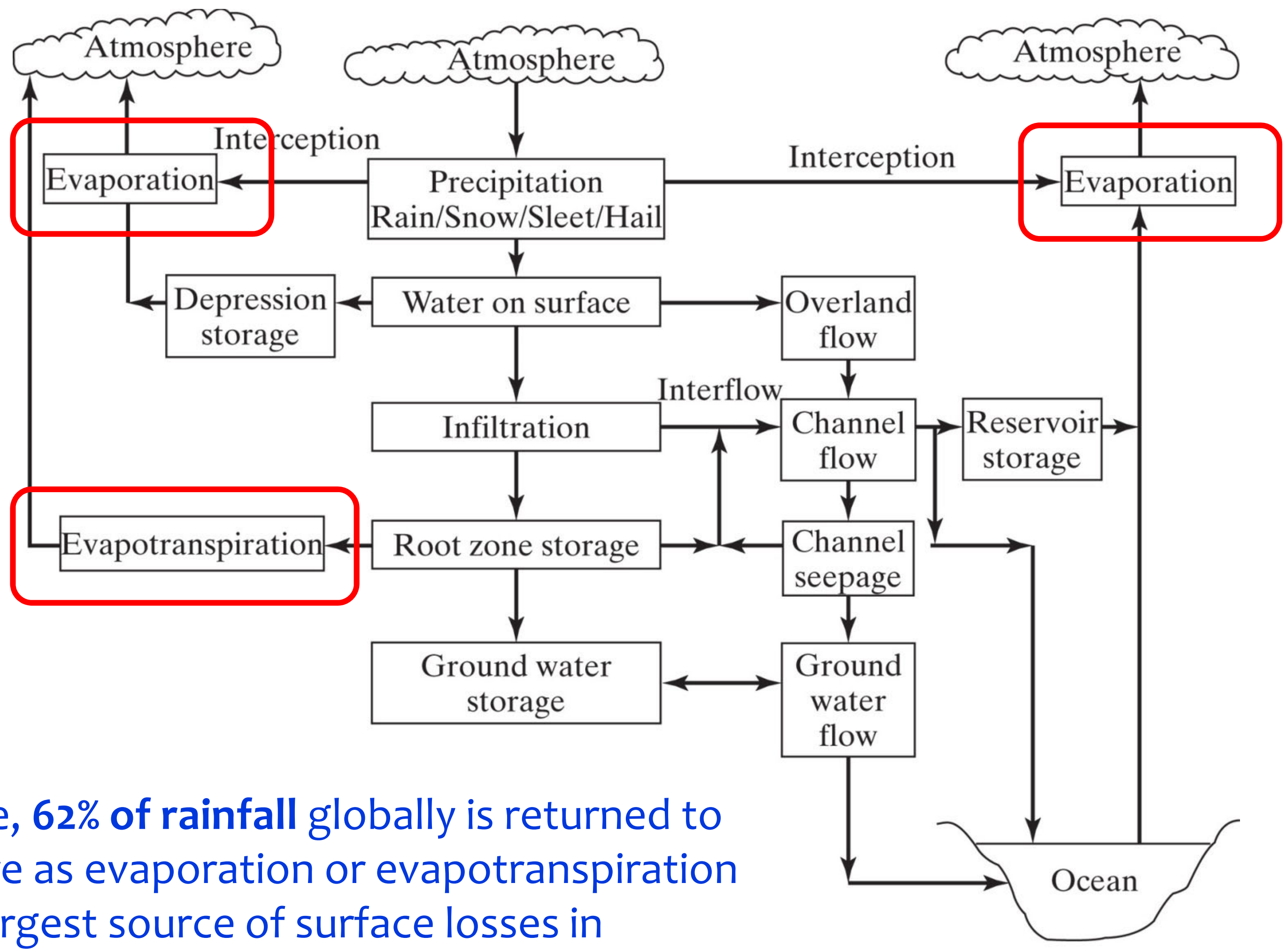
- **Short term:** Typical storms have 10 mm/h intensity
- However, evaporation is on order of 0.25 mm/hr
  - Normally, **evaporation neglected** for flood flow studies and urban drainage applications

http://blogs.agu.org/landslideblog/2011/07/06/serious-landslide-impacts-in-china/

http://totallycoolpix.com/2011/01/the-australian-floods/

Bedient et al. (2019)

Hydrological cycle



On average, **62% of rainfall** globally is returned to atmosphere as evaporation or evapotranspiration
→ single largest source of surface losses in hydrological cycle (Dingman 2002)

Bedient et al. (2019)

Evaporation

- **Climatic factors** have significant effect
- Evaporation rates are,
  - High in arid/semi-arid regions (~2200 mm in US Southwest)
    - E.g. ~2.28 m/y at Lake Mead, largest reservoir by volume in US
  - Low in humid regions (~500 mm in US Northeast and Northwest)
    - Alberta: ~902 mm/y (PET) and ~364 mm/y (AET) (AAF, Morton method)

http://www.wildlifesafari.info/arid_zone_habitat.htm

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

Ponce (1989)

Evaporation example: Lakes

- A lake has an open surface, exposed to sunlight, wind, air temperature, etc. → *water evaporates*
- *So, is it easy to figure out these evaporative losses?*

*"The estimation of evaporation from lakes and reservoirs is **not a simple matter** as there are a **number of factors** that can affect the evaporation rates, notably the climate and physiography of the water body and its surroundings. In addition, the water has the potential to transport stored heat within the water body itself and into and out of it"*

(Finch and Calver, 2008, *Methods for quantification of evaporation from lakes*)

Bedient et al. (2019)

Evaporation

- Evaporation from a lake is function of,
  1. Solar radiation
  2. Water temperature
  3. Air temperature
  4. Vapour pressure diff. between water and overlying air
  5. Wind speed across lake

http://themoderatevoice.com/20800/into-the-wild/

http://www.travelimg.org/lake-wind-round-the-fountain-western-finland-finland.html

Bedient et al. (2019)

2. Determining Evaporation Rates

"Direct measurement of evapotranspiration is much more difficult and expensive than for precipitation and streamflow, and is usually impractical.

*Thus… hydrologists have **developed an array of methods** that provide estimates of evapotranspiration based on measurements of more readily measured quantities"* Dingman (2002: 272)

- So, next investigate several ways to determine evaporation rates:
    i. Evaporation pans
    ii. Water budget methods
    iii. Mass transfer methods
    iv. Energy budget methods
    v. Combination methods

i. Evaporation pans

- *Direct approach to measuring free-water evaporation is exposure of cylindrical pan of liquid water to atmosphere*
- Different pan configurations used in different countries (UK, US, Canada, Russia, etc.)
  - Canada and the US use "Class-A" pans. They are the recommended standard of the World Meteorological Org. (WMO)

http://hydrologycambodia.wordpress.com/

http://won.sdsu.edu/protected121/engineering_hydrology_101101_chapter_031.html

http://www.hydrokit.co.uk/product_details.php?pid=46

Dingman (2002)

Evaporation pans

- Siting evaporation pans:
  - On land, pans placed in clearings suitable for rain gauges, and surrounded by fence to prevent animals from drinking
    - Pans may be sunken so water surface is even with ground, or raised to a standard height above ground
  - For lake evaporation studies, can be placed in centre of floating platform

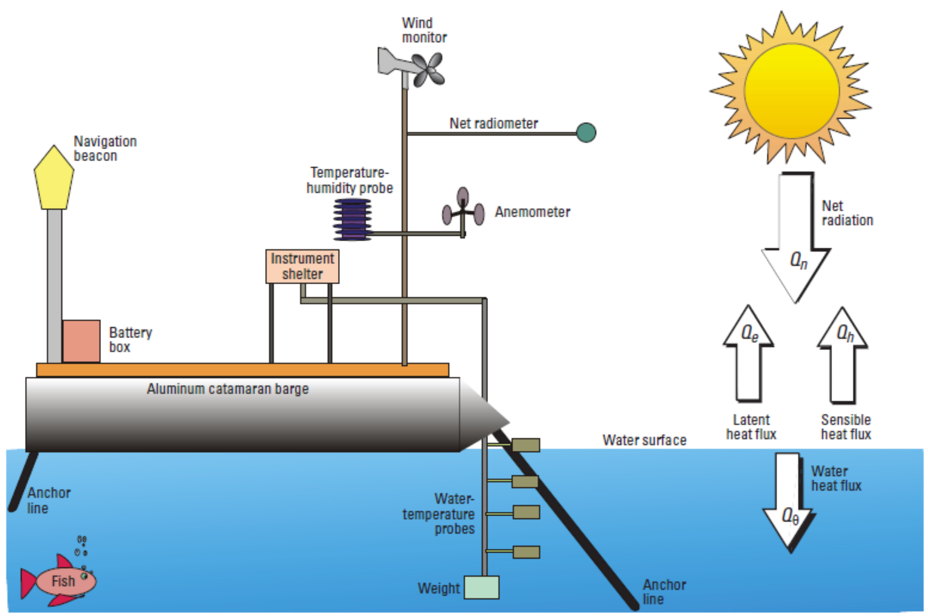


Figure 4. Instrument configuration on floating platforms on Lake Mead, Arizona and Nevada, and of energy fluxes at water surface.

Westenburg et al. (2006): USGS/USBR 2006-5252

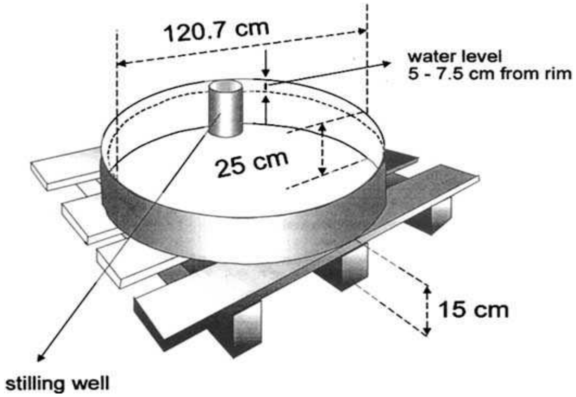
Dingman (2002)

Class-A pan

- Class-A pan appearance and use (Canada and the US)
  - Open, galvanized iron tank, 1.2 m (4 ft) in diameter, 25 cm (10 in) deep, and mounted 30.5 cm (12 in) above ground
  - Pan filled to depth of 20.3 cm (8 in) and must be refilled when depth falls to 17.8 cm (7 in)
  - Water surface level measured daily, and maintained a few cm below pan rim by adding small amounts of water as necessary
  - Evaporation computed as difference between observed levels, adjusted for any precipitation measured with standard rain gauge

http://www.isws.illinois.edu/atmos/statecli/Instruments/panevap.jpg

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



http://www.fao.org/docrep/x0490e/x0490e08.htm

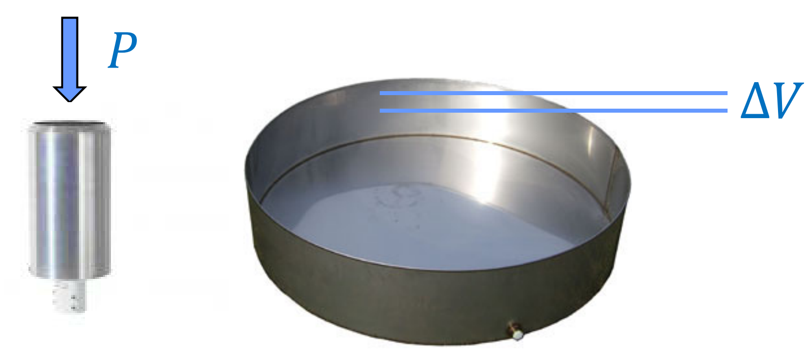
Bedient et al. (2019)

Evaporation pan calculations

- Calculating evaporative losses: a **simple water-balance equation** for a time-period (Δt) like 1 day is solved,

$$E = P - [V_2 - V_1] \qquad \Delta S = P - E$$

  - where P is the precipitation during Δt and V_1 and V_2 are water storages at beginning and end of Δt
  - Precipitation, P, is measured in adjacent, non-recording gauge
  - Storage volumes, V_1 and V_2, determined from water level in small "stilling well" in the pan, using high-precision micrometer called "hook gauge"



Dingman (2002)

Evaporation pan calculations

- *Complication: Evaporation pans are not the same as lakes…*
  - Pans have less heat-storage capacity → *warm quickly*
  - Pans lack surface and groundwater inputs and outputs
  - Pan sides (if pans are raised) exposed to sunlight and air
- These differences significantly affect the energy balance
  - Elevate the warm-season average temperature and vapour pressure and thus evaporation
  - Depress the fall-time pan evaporation

Dingman (2002)

Evaporation pan calculations

- The solution: “Pan coefficients”
  - Pan coefficients “scale” the evaporative losses from the pan to corresponding lake evaporation
  - Average value is 0.7 over the US, with seasonal variation

Table 2-8 Pan coefficient K_p for NWS Class A pan [16].

	Pan surrounded by short green crop				Pan surrounded by dry fallow land [1]			
Relative humidity (%)		Low 40	Medium 40-70	High 70		Low 40	Medium 40-70	High 70
Wind speed (km/d)	Upwind distance of green crop (m)				Upwind distance of dry fallow (m)			
Light (less than 175)	0	0.55	0.65	0.75	0	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 (175-425)	0	0.50	0.60	0.65	0	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 (425-700)	0	0.45	0.50	0.60	0	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 (greater than 700)	0	0.40	0.45	0.50	0	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

[1] For extensive areas of bare fallow soil and no agricultural development, pan coefficients are reduced by: (1) 20% under hot windy condition; and (2) 5-10% for moderate wind, temperature, and humidity conditions.

Dingman (2002)

Ponce (2014)

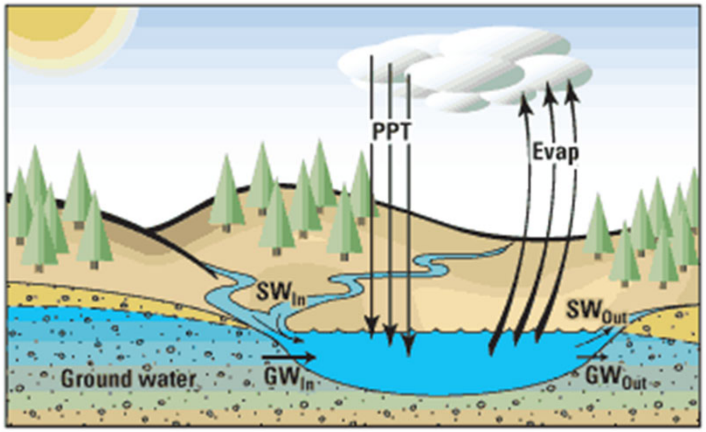
ii. WATER BUDGET METHOD

- **Estimating evaporation based on mass measurement:** Water budget method for lake evaporation based on *continuity equation:*

$$E = -\Delta S + I + P - O - GW$$

where ΔS is the change in storage, I and O are the surface inflow and outflow, P is the precipitation, and GW is subsurface seepage to groundwater

- The method is simple in theory, because all the terms are measurable
  - *However, measuring seepage can be difficult!*
  - *Further, all inflows/outflows gauged → not simple*
  - *Reservoir bathymetry must be known*
  - *Finally, measurement errors can affect results*



http://pubs.usgs.gov/sir/2005/5071/

Bedient et al. (2019)

Water budget method

- Method applied in 1950s at Lake Hefner, near Oklahoma City
  - Error was between 5% and 10%
  - Lake Hefner selected from more than 100 lakes and reservoirs as one of 3-4 that best met water budget requirements and had minimal seepage

Dizzy Drone Adventures (2019), https://youtu.be/L6M_phsBE8s

Bedient et al. (2019)

iii. Energy budget method

- **Estimating evaporation based on E measurement**
- *Most accurate and complex method*
- *In some situations*, energy balance approach can be easier than water budget
  - Can sometimes eliminate terms in energy balance
  - Can use regional climatic data
- Application requires measurement of
  - Incoming solar radiation
  - Outgoing longwave radiation
  - Conduction to ground
  - Water-advected energy
  - Change in stored energy

Bedient et al. (2019)

Energy budget method

- Overall energy budget of lake written in langleys per day, as,

$$Q_N - Q_h - Q_e = Q_\theta - Q_v$$

where Q_N = net radiation absorbed by water body

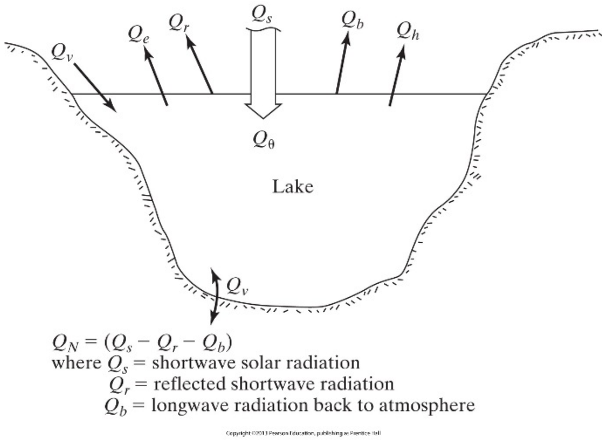
Q_h = sensible heat transfer (conduction, convection to atmosphere)

Q_e = energy used for evaporation

Q_θ = increase in energy stored in water body

Q_v = advected energy of inflow and outflow

Note: 1 langley (Ly) = 1 cal/cm2, and 1 cal = 4.18 J



Bedient et al. (2019), Fig. 2-13(a)

Bedient et al. (2019)

Energy budget equation

- Can revise previous equation to get E as,

$$E = \frac{Q_N + Q_v - Q_\theta}{\rho L_e (1 + R)}$$

  - Here, the sensible and latent energy terms replaced
    - Latent energy ($Q_e = \rho L_e E$) is evaporation component: L_e is latent heat of vaporization (cal/g), ρ is density (g/cm^3), and E is evaporation (cm/day)
    - Sensible heat, Q_h, replaced by Bowen ratio, R (next slide)
      - *Sensible heat transfer not readily computed*

Bedient et al. (2019)

Bowen ratio calculation

- The **Bowen ratio,** R, is ratio of heat loss by conduction to heat loss by evaporation
- Bowen ratio used as measure of **sensible heat transfer**
  - Can be computed as,

$$R = 0.66\left(\frac{T_s - T_a}{e_s - e_a}\right)\left(\frac{P}{100}\right) = \gamma\frac{T_s - T_a}{e_s - e_a}$$

where P is atmospheric pressure (mb)

T_a and T_s are air and water temperatures (°C)

e_a is vapour pressure of air (mb)

e_s is saturation vapour pressure at surface water temperature (mb)

γ is the psychrometric constant 0.66P/1000 (mb/°C)

- *Note:* ***Psychrometric constant*** *relates partial pressure of water in air to the air temperature:* $e_a = e_s - \gamma(T_{dry} - T_{wet})$*, where* T_{dry} *is the temperature reading from a dry thermometer in air, and* T_{wet} *is the reading from a wet thermometer bulb (from which water can evaporate to air)*

Bedient et al. (2019)

Read on own

Solar radiation measurement

- Measure incoming and reflected solar radiation (Q_s and Q_r) with "pyranometer"
  - Routinely done at only a few scattered locations
  - *Learn more about pyranometers*: https://youtu.be/g4zd9gFMaS0 (Hukseflux, 2019)
- **Empirical alternative** is given by,

$$K = K_{in}(1 - a)$$

  - where K is the net incoming solar radiation, K_{in} is the total incoming solar radiation, and a is the albedo
  - Albedo is "reflectivity" (snow a = 0.8-0.9; water a = 0.1)

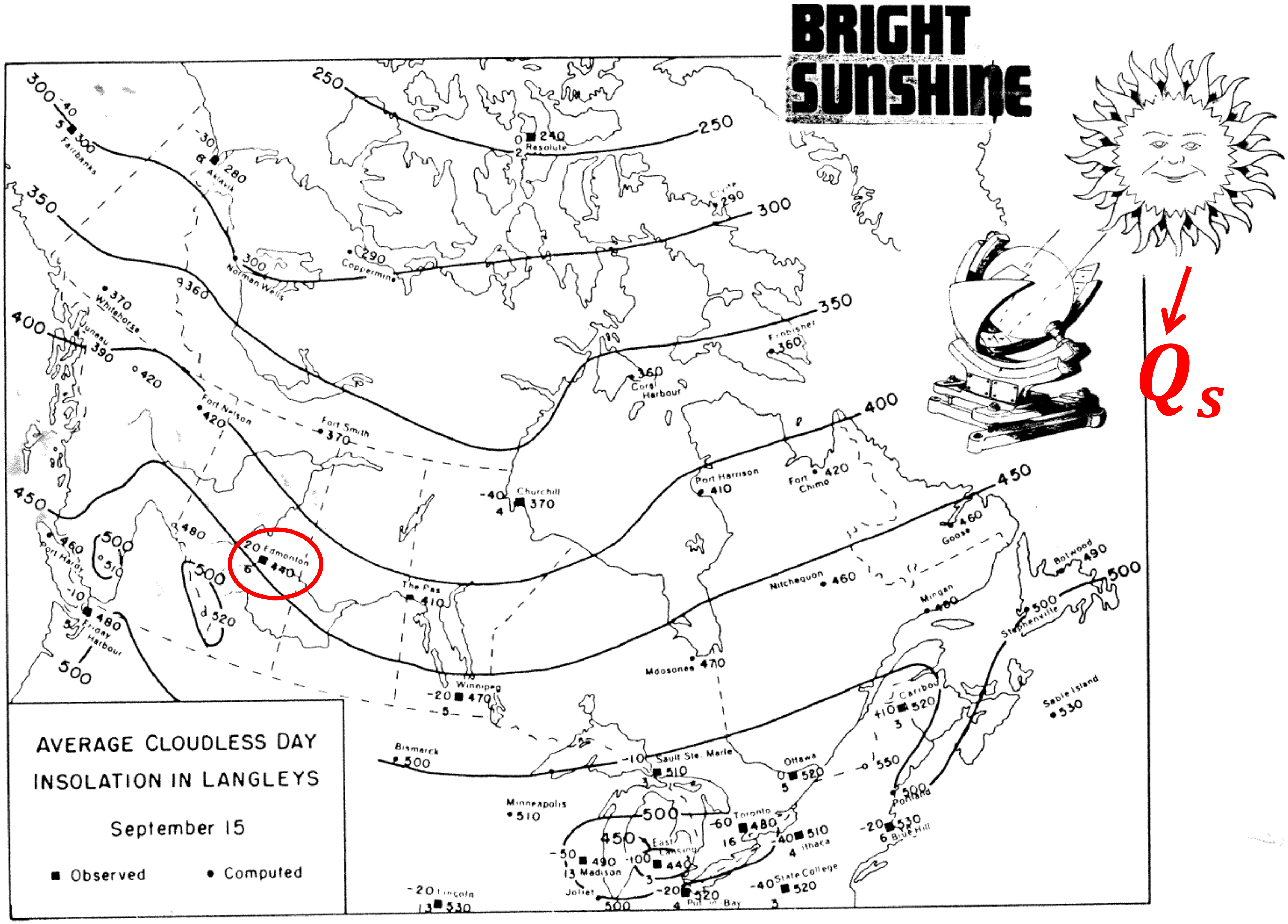
$$K_{in} = [0.355 + 0.68(1 - C)]K_{cs}$$

  - where K_{in} is estimated from the clear-sky solar radiation, K_{cs}, and the fraction of sky that is cloud-covered, C
  - K_{cs} is determined from latitude and time of year
  - Can also get K_{in} from gridded satellite data

Dingman (2002)

Read on own

Average Cloudless Day Insolation (Langleys)



Q_s

Longwave radiation

- Longwave radiation can be approximated with the **Blackbody radiation theory,**
- $Q_b = \varepsilon\sigma(T_a^4 - T_s^4)$

where Q_b = net longwave radiation

σ = 5.67 x 10^{-8} W m^{-2} K^{-4} is the Stefan Boltzmann constant

ε = atmospheric emissivity

T_a= air temperature in Kelvin

T_s= surface temperature in Kelvin

Dingman (2002)

Water-advected energy

- Calculation based on inflow and outflow volumes of water and their heat contents,

$$A_w = c_w \cdot \rho_w (P \cdot T_a + I \cdot T_{in} - O \cdot T_{out} + G_{in} \cdot T_{G\ in} - G_{out} \cdot T_{G\ out})$$

where c_w is specific heat of water

ρ_w is density of water

P is precipitation

I and O are inflow and outflow

G_{in} and G_{out} are groundwater flows

Ts are air and water temperatures

Dingman (2002)

iv. Mass transfer method

- Based on concept of turbulent transfer of water vapour from surface to atmosphere
- Many empirical formulas derived to express evaporation rate as *function of vapour-pressure differences and wind speed* above lake or reservoir
  - Such equations often based on **diffusive flux of vapour:**

$$E = (e_s - e_a)(a + bu)$$

where e_s is saturation vapour pressure at T_s of water surface

e_a is vapour pressure at a fixed level above water surface and is product of RH and e_s at T_a of air

u is wind speed

a, b are empirical constants that depend chiefly on height at which wind, air vapour pressure measured

Bedient et al. (2019)

Mass transfer method

- Obstacle to comparing different empirical equations is variability in measurement heights for u and e_a
  - Measure u and e_a at standard 2 m above ground
  - *See how wind speed and direction are measured*: https://youtu.be/SqbTrbxWT1o (UK Met Service, 2014)
- Also, take into account pan coefficients

- This formula also used at **Lake Hefner** and **Lake Mead**, with slight modification:

$$E = bu_2(e_s - e_2)$$

where E is in cm/day, b = 0.012 cm s d^{-1} m^{-1} mb^{-1} for Lake Hefner and 0.0118 for Lake Mead, e_s is vapour pressure at water surface in mb, e_2 is vapour pressure at 2 m above surface in mb, and u_2 is wind speed at 2 m above water surface in m/s

Bedient et al. (2019)

v. Combined Methods

"Penman (1948) first used best features of ***mass transfer*** *and* ***energy budget*** *methods to derive a* ***water surface evaporation*** *relation that is fairly easy to compute"*

- **Advantage:** water or soil temperature need not be known
  - Thus, very useful for evapotranspiration studies in which it is hard to determine temperature of vegetation

- *When surface temperature of body of water can be determined, better to use energy budget approach*

Bedient et al. (2019: 115)

Penman equation

- The **Penman equation** is,

Energy Equation
(think about the units…)

$$E_h = \underbrace{\frac{\Delta}{\Delta + \gamma} Q_N}_{\text{Net radiation component}} + \underbrace{\frac{\gamma}{\Delta + \gamma} E_a}_{\text{Mass transfer component}}$$

where E_h is flux of latent heat from evaporation ($E_h = \rho L_e E$)
Δ is slope of e_s vs. T curve (mb/°C)
Q_N is the net radiation absorbed (*units of energy/area-time*)
E_a is "drying power" of the air (*units of energy/area-time*)

Aside:

$E_h = \rho L_e E$ *Solve for this!*

Units: $\left[{}^{cal}/_{cm^2 \cdot day}\right] = \overset{\rho}{\left[{}^{g}/_{cm^3}\right]} \overset{L_e}{\left[{}^{cal}/_{g}\right]} \overset{E}{\left[{}^{cm}/_{day}\right]}$

Note: ${}^{cal}/_{cm^2 \cdot day} \rightarrow {}^{J}/_{m^2 \cdot day} \rightarrow {}^{W}/_{m^2} \quad (W = J/s)$
$= Ly/day$

Bedient et al. (2019)

Penman equation

- *Continuing from previous slide,*
  - The slope term, Δ, can be found from,

$$\Delta = \frac{de_s}{dT} = \frac{2.7489 \times 10^8 \times 4278.6}{(T + 242.79)^2} e^{\left(-\frac{4278.6}{T+242.79}\right)}$$

  - and the "drying power" of the air, E_a, is given by,

$$E_a = \rho L_e (a + bu)(e_{sa} - e_a)$$

where $a + bu$ is from mass-transfer method (wind speed and empirical coefficients)

e_{sa} is saturation vapour pressure at temperature of air

e_a is actual vapour pressure in air

Bedient et al. (2019)

Ex 1: Penman equation

Meyer (1944) gives an example of the mass transfer equation for Minnesota lakes,

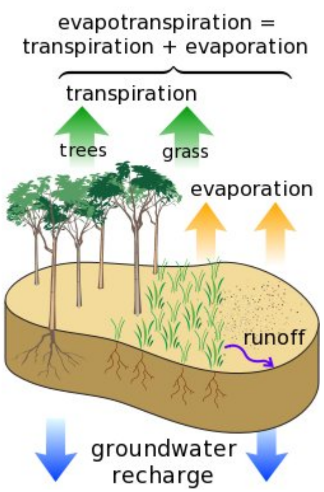
$$E = 0.0106(1 + 0.1u)(e_s - e_a)$$

with E in in/day, u in mph, and vapour pressures in mb. For an air temperature of 32.2 °C, wind speed of 20 mph, relative humidity of 30%, and net radiation flux of 400 Ly/day, estimate the evaporation rate using the Penman equation. Assume atmospheric pressure is 1000 mb, so the psychometric constant = 0.66 mb/°C

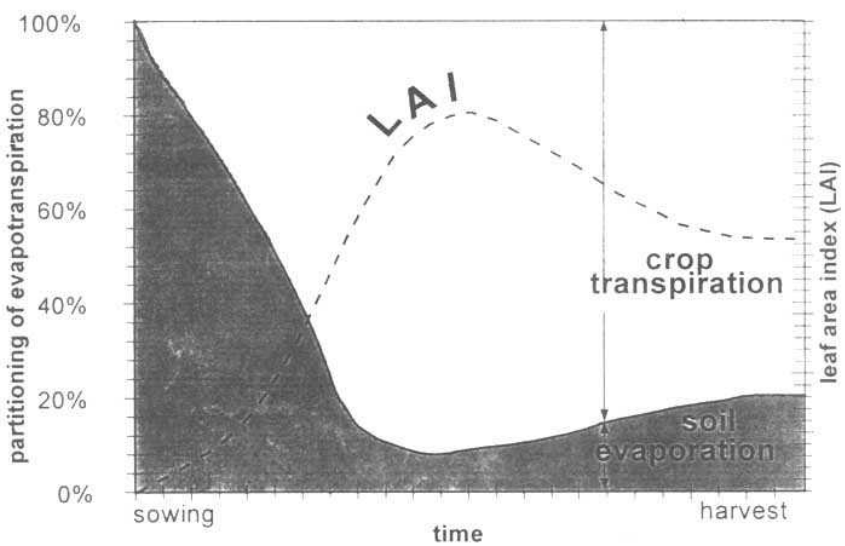
Example 2-9 in Bedient et al. (2019)

3. EVAPOTRANSPIRATION

- For water budget of whole watershed, usually concerned with total **evaporation** from all free-water surfaces and bare soil plus **transpiration** from plants
  - *Combined evaporation and transpiration losses called evapotranspiration (ET)*



http://people.ucsc.edu/~bkdaniel/



Partitioning between evaporation and transpiration for crops over growing season (Allen et al. 1998), FAO, Chapter 1

Bedient et al. (2019)

Evapotranspiration

- **Evapotranspiration** is a **maximum** if water supply to plant and soil surface is unlimited → this maximum ET is called "**potential evapotranspiration**" (PET), or "**reference ET**"
  - **Potential ET** (PET) is approx. equal to evaporation from a large, free-water surface
  - **Reference ET** is rate of ET from extended surface of grass of uniform height, actively growing, fully watered
  - **Actual ET** is almost always ≤ Potential ET
    - Actual ET can exceed Potential ET when leaf surface area is large and temperature is high
  - Actual ET typically limited by moisture supply to plants
    - Moisture supply depends on soil qualities and root depth

Bedient et al. (2019)

Reference ET, ET_o

- Most ET estimates based on modification of **Penman equation** for different assumptions about transfer coefficients (a and b terms in E_a equation) and vegetation surface (*Penman was developed for open-water surfaces*)
- There are four main types:
  1. Temperature models
  2. Radiation models
  3. Combination models
  4. Pan-evaporation models
- Commonly used equations include **Penman-Monteith** (recommended by FAO); Thornthwaite (1948); Blaney-Criddle (1950); Turc (1954); Priestly-Taylor (1972)

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

Thornthwaite equation

- A widely-used temperature model, based on annual "temperature efficiency index", J, defined as the sum of 12 monthly heat index, I, values:

$$PET(0) = 1.6\left(\frac{10T}{J}\right)^{c}$$

where $c = 0.000000675J^3 - 0.0000771J^2 + 0.01792J + 0.49239$ and

$$I = \left(\frac{T}{5}\right)^{1.514}$$

- The PET value that results is for 0° (equator), and is scaled to the correct latitude by, $PET = K \cdot PET(0)$

Ponce (1989)

Thornthwaite equation

TABLE A-4 CONSTANT *K* IN THORNTHWAITE METHOD[1]

Latitude	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
60°N	0.54	0.67	0.97	1.19	1.33	1.56	1.55	1.33	1.07	0.84	0.58	0.48
50°N	0.71	0.84	0.98	1.14	1.28	1.36	1.33	1.21	1.06	0.90	0.76	0.68
40°N	0.80	0.89	0.99	1.10	1.20	1.25	1.23	1.15	1.04	0.93	0.83	0.78
30°N	0.87	0.93	1.00	1.07	1.14	1.17	1.16	1.11	1.03	0.96	0.89	0.85
20°N	0.92	0.96	1.00	1.05	1.09	1.11	1.10	1.07	1.02	0.98	0.93	0.91
10°N	0.97	0.98	1.00	1.03	1.05	1.06	1.05	1.04	1.02	0.99	0.97	0.96
0°	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10°S	1.05	1.04	1.02	0.99	0.97	0.96	0.97	0.98	1.00	1.03	1.05	1.06
20°S	1.10	1.07	1.02	0.98	0.93	0.91	0.92	0.96	1.00	1.05	1.09	1.11
30°S	1.16	1.11	1.03	0.96	0.89	0.85	0.87	0.93	1.00	1.07	1.14	1.17
40°S	1.23	1.15	1.04	0.93	0.83	0.78	0.80	0.89	0.99	1.10	1.20	1.25
50°S	1.33	1.19	1.05	0.89	0.75	0.68	0.70	0.82	0.97	1.13	1.27	1.36

[1] *K* is a constant to correct PET for latitudes other than 0° (Eq. 2-47).

Ponce (1989)

Priestley-Taylor equation

- Priestley and Taylor proposed that potential ET be taken as radiation part of Penman equation (i.e. with $E_a = 0$), multiplied by an empirical constant,

$$E = a \frac{\Delta \cdot {Q_N}/{\rho L_e}}{\Delta + \gamma}$$

where $E = PET$ in cm/day, a is a constant (1.26 or 1.3), Q_N is net radiation in Langleys (note: sometimes given in W/m²), L_e is the latent heat of vaporization in cal/g, Δ is defined above, and is in units of mb/°C, and γ is the psychrometric constant, 0.66 mb /°C

Ponce (1989)

Penman-Monteith equation

- Equation selected by FAO for irrigated crops,

$$ET_0 = \frac{0.408\Delta(Q_N - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

where ET_0 is the reference ET (or ~PET) (mm/day)

Q_N is net radiation at crop surface (MJ/m²/day)

G is soil heat flux density (MJ/m²/day) (*small*)

T is air temperature at 2 m height (°C)

e_s and e_a are vapour pressures (kPa)

u_2 is wind speed at 2 m height (m/s)

Allen et al. (1998)

Ex 2: Thornthwaite equation

Use the Thornthwaite method to estimate the potential ET of Vancouver, at 49°11':

Mon	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T_i (°C)	2.5	4.6	5.8	8.8	12.2	15.1	17.3	17.1	14.2	10	5.9	3.9
I	0.35	0.88	1.25		3.86	5.33	6.55	6.43	4.86	2.86	1.29	
PET (0)	1.06	2.04	2.62		5.85	7.37	8.53	8.43	6.89	4.72	2.67	
K	0.71	0.84	0.98		1.28	1.36	1.33	1.21	1.06	0.90	0.76	
PET (cm/m)	0.75	1.72	2.57		7.49	10.0	11.35	10.2	7.31	4.25	2.03	

Total PET for Vancouver = mm/year

Index-of-dryness method

- The Budyko hypothesis (1974):
  - Over long timescales, the fraction of precipitation lost to ET (or ET/P) is primarily controlled by "climate aridity", defined as *the ratio of atmospheric evaporative demand to precipitation*
  - This "aridity measure" (often written as PET/P) is called the "**index of dryness**"
  - Budyko-type equations describe how ET/P varies between:
    - **Energy-limited** (humid) climates
    - **Water-limited** (arid) climates
    - Many empirical Budyko-type equations exist…

Index-of-dryness method

- A common Budyko-type equation (Fu-type form):
  - Dimensionless: $$\frac{AET}{P} = \left[1 + \left(\frac{P}{PET}\right)^{w}\right]^{\frac{-1}{w}}$$
  - Dimensional (equivalent): $$AET = \frac{P}{\left[1+\left(\frac{P}{PET}\right)^{w}\right]^{\frac{1}{w}}}$$
    - *AET* = Mean annual actual evapotranspiration (Actual ET)
    - *P* = Mean annual precipitation
    - *PET* = Mean annual potential evapotranspiration
    - *w* = empirical parameter representing watershed characteristics (vegetation, soils, seasonality, storage effects)
  - Interpretation:
    - $PET \ll P$ means $AET \approx PET$ (energy-limited)
    - $PET \gg P$ means $AET \approx P$ (water-limited)

Ex. 3: Index of dryness

In western Kansas, the mean annual potential evapotranspiration is 125 cm, and the mean annual precipitation is 80cm. Estimate the index of dryness and the actual evapotranspiration for grassed catchments.

Continuing with losses

- Recall that **rainfall** is the key input to the surface component of hydrological cycle: *the **water budget***,
$$P - R - G - E - T = \Delta S$$

- Continue to address **other components** of the water budget: the **losses** or "**abstractions**"
  - *Evaporation, transpiration and infiltration*
- *Next topic is third of these losses:* **infiltration**
$$P - R - G - E - T = \Delta S$$