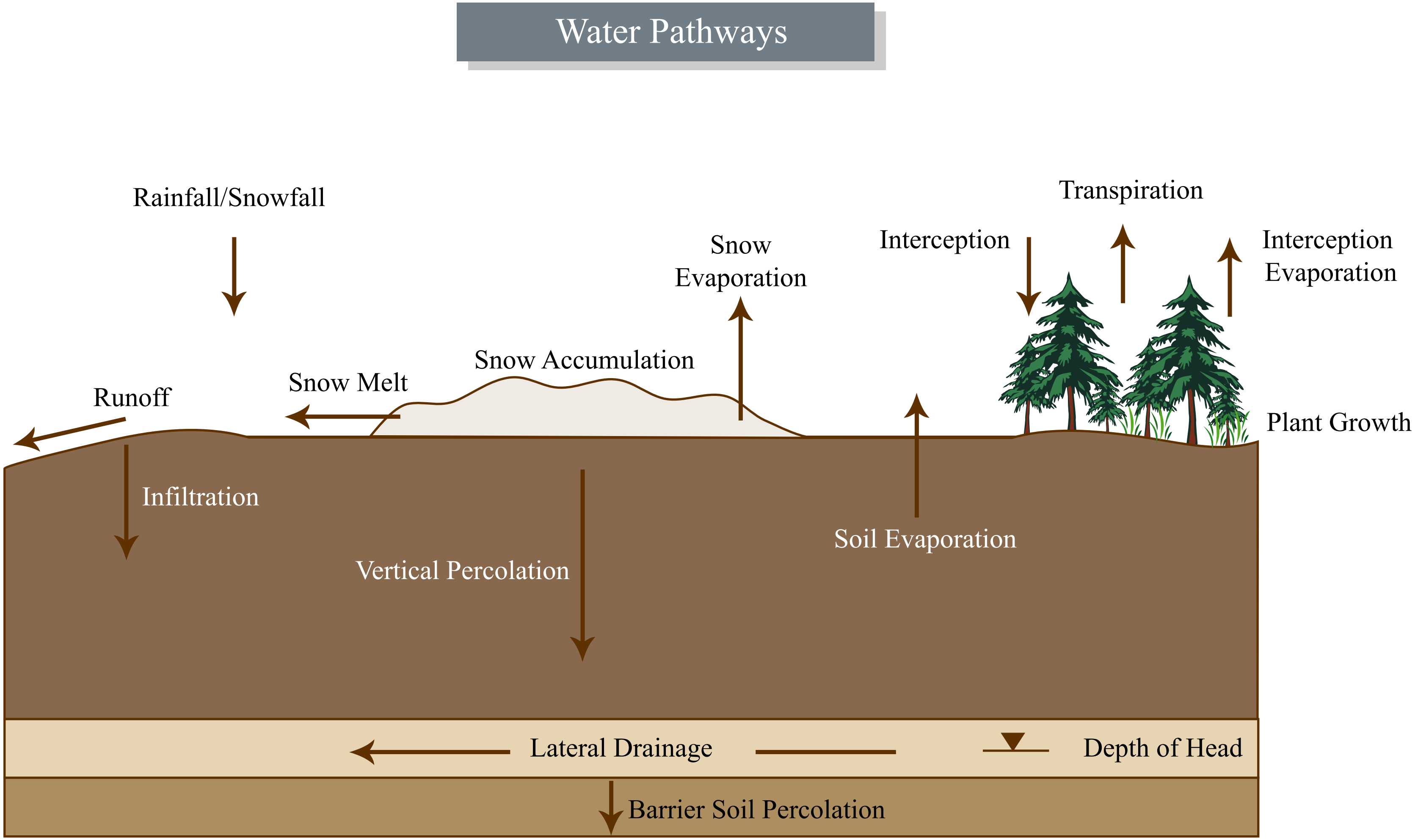
# Lecture 19

# Landfill hydrology

# Landfill hydrology




Adapted from: Peyton, R. L. and P. R. Schroeder. "Water Balance for Landfills." *Geotechnical Practice for Waste Disposal*. Edited by D. E. Daniel. New York: Chapman & Hall, 1993.

# Water balance during active filling

$L = P + S - E - WA$

L = leachate

P = precipitation

S = liquid squeezed from solid waste

E = evaporation

WA = water adsorbed into solid waste

# Water balance after closure

$$L = P + SM - RO - ET - DS - Q - WA + ME$$

P = precipitation

SM = snowmelt infiltration

RO = runoff

ET = evapotranspiration

DS = soil moisture storage

Q = lateral drainage in cap drainage layer

WA = water adsorbed into solid waste

ME = moisture extraction from waste

# ME term - Moisture extraction

Moisture extraction occurs via landfill gas collection system

Enhanced by heat in landfill

27 to 52ºC; 80 to 125ºF

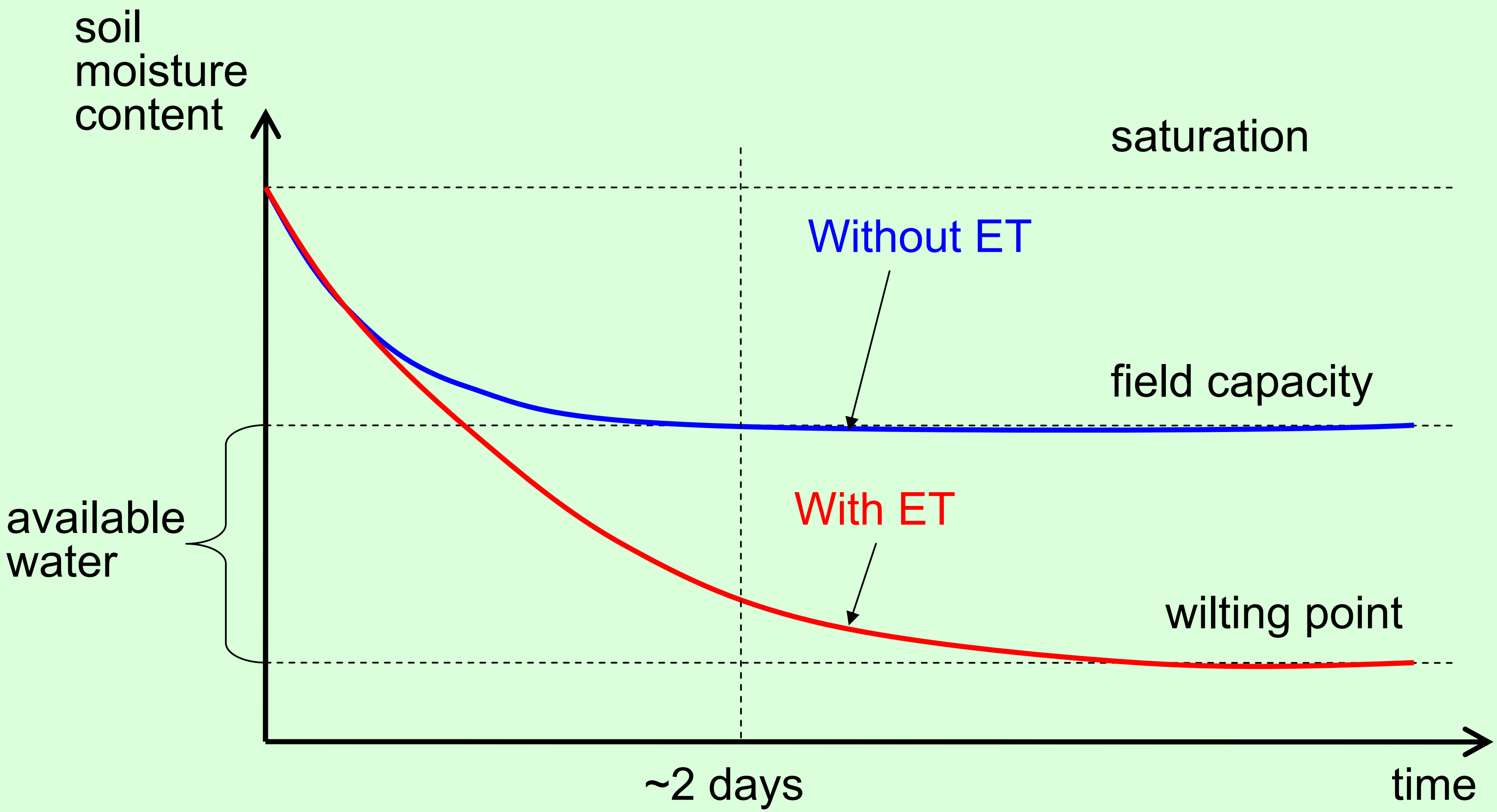
Every million $m^3$ of gas extracted includes 6.7 to 81 $m^3$ of condensate

# Soil moisture

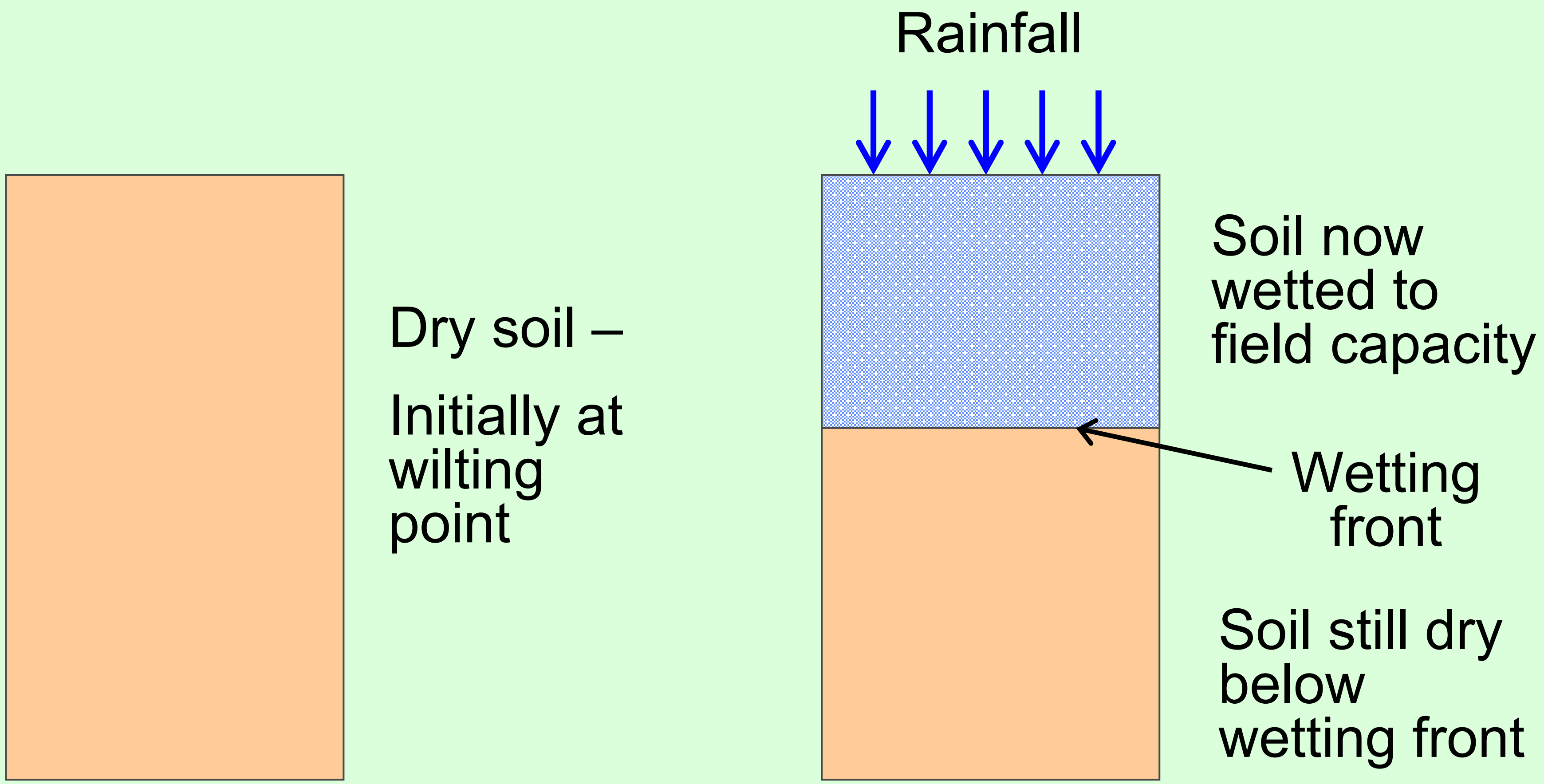
Soil moisture varies between:

- Saturation – 100% of pore space filled by water
- If allowed to drain by gravity → field capacity
  - Typically reached in about 2 days
- Evapotranspiration can remove additional water → wilting point
  - Duplicated in lab with suction of 25 atmospheres
- Difference between field capacity and wilting point is available water

# Soil moisture vs. time



# Soil moisture replenishment



# Soil moisture replenishment

Depth of soil determines how much rainfall is needed to bring soil to field capacity throughout soil column

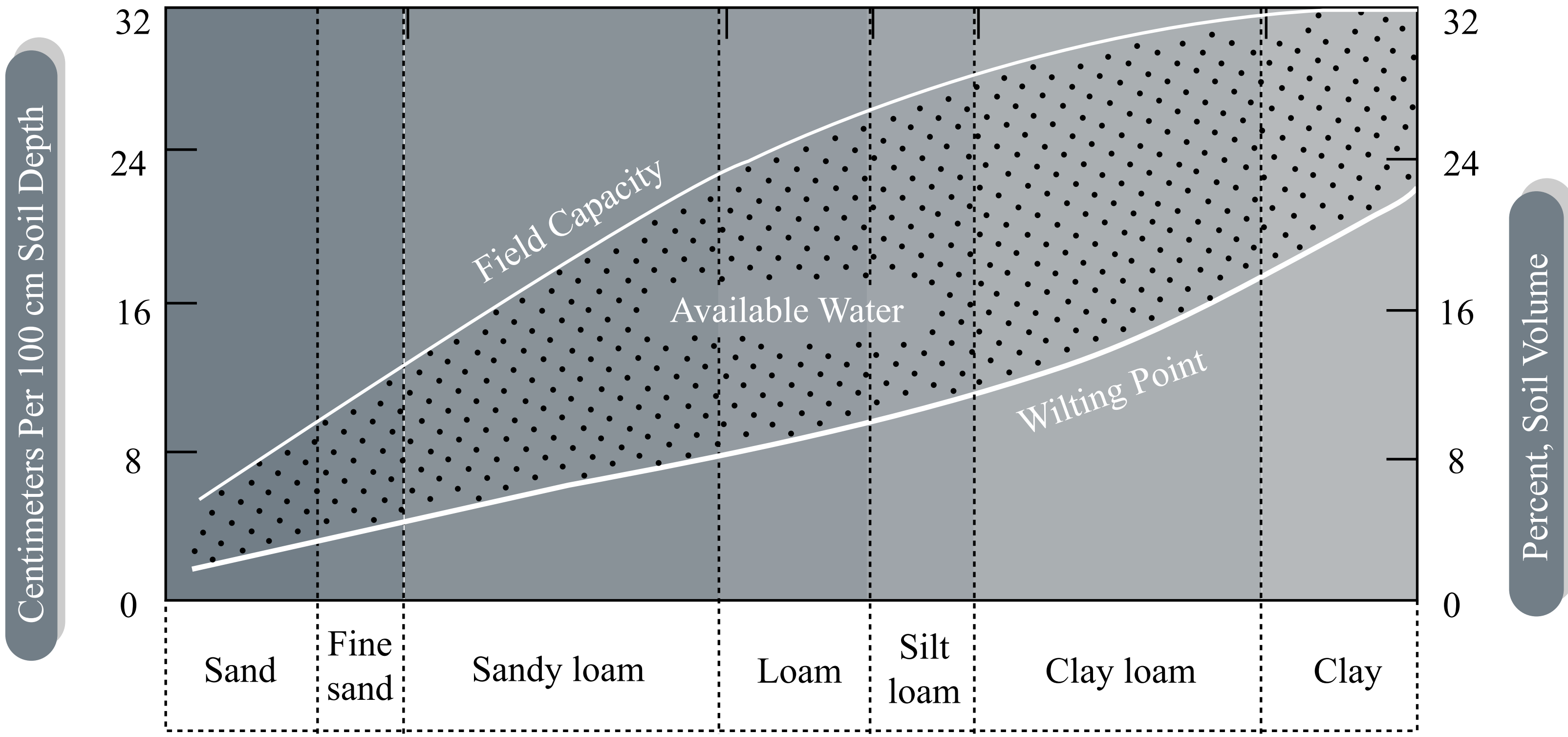
In dry climates, there is never enough rainfall to wet entire soil column and there is never ground-water recharge

# Typical soil properties

| Soil | Saturation (porosity) | Field capacity | Wilting point |
|---|---|---|---|
| Sand | 0.39 | 0.09 | 0.05 |
| Sandy loam | 0.40 | 0.18 | 0.06 |
| Loam | 0.43 | 0.24 | 0.12 |
| Clay | 0.42 | 0.40 | 0.20 |
| MSW | 0.67 | 0.29 | 0.08 |

All properties are expressed as fractions of bulk volume.

# Typical soil properties




Adapted from: Foth, H. D. *Fundamentals of Soil Science.* 8th ed. New York: John Wiley & Sons, 1990.

Loam is a term from soil science to describe soils that contain a mix of clay, silt, and sand

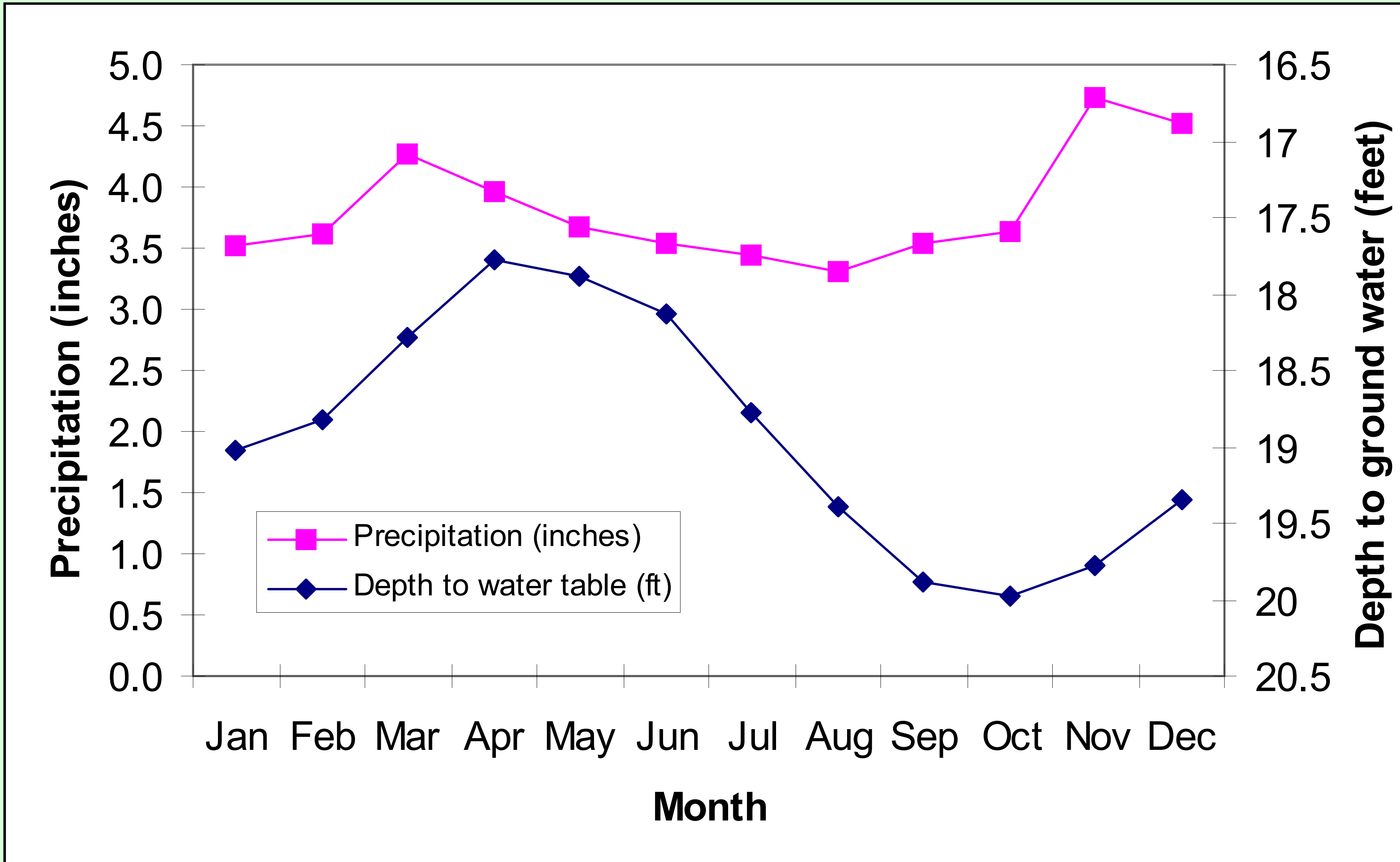
# Soil moisture vs. time

Soil moisture content constantly fluctuates:

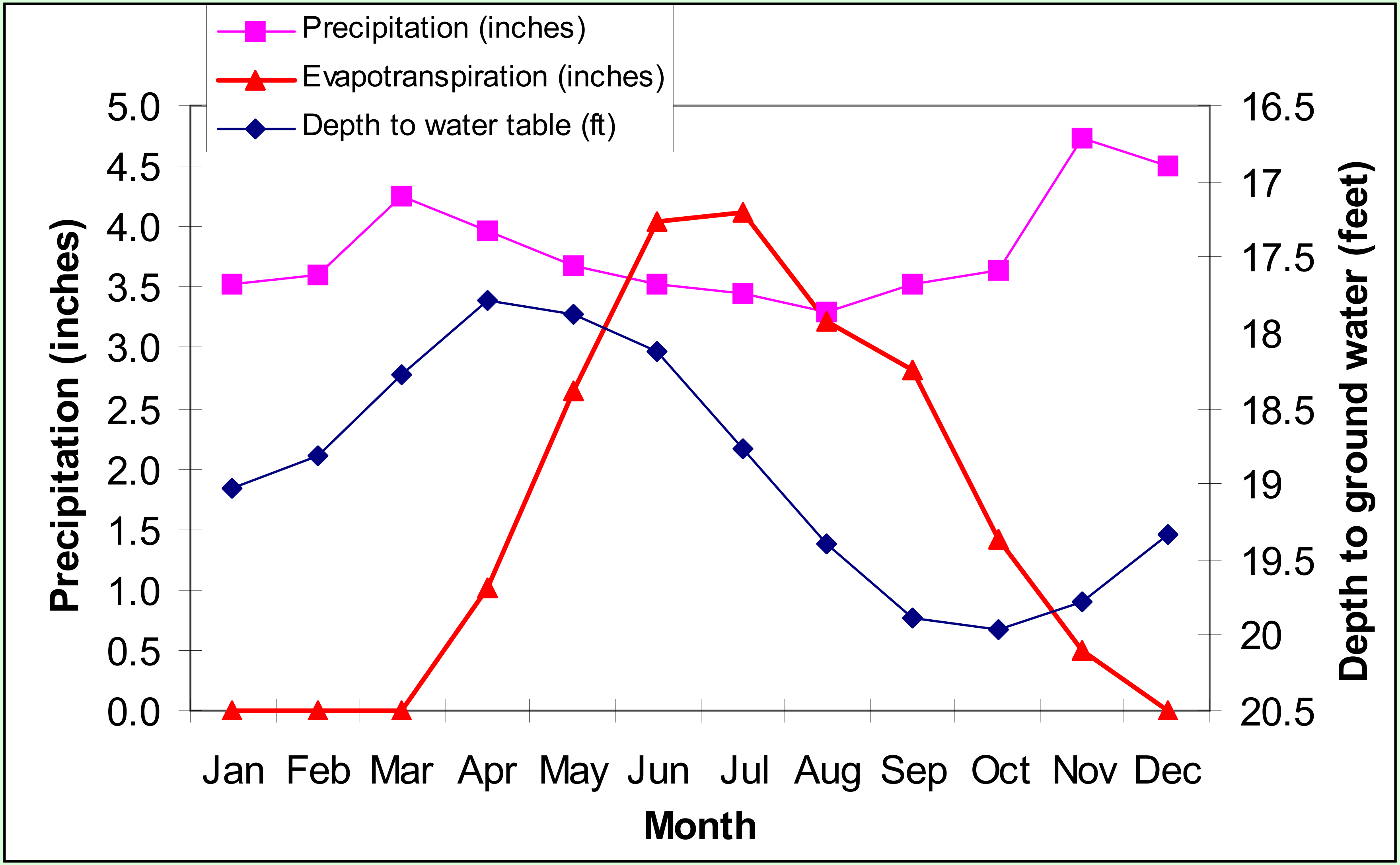
- Increased by rainfall
- Decreased by ET

Soil moisture has great influence on ground-water recharge

# Annual water-table cycle



# Annual water-table cycle



# Water-balance methods

Thornthwaite water balance – completed manually
(also called the Water Balance Method)

HELP model – computer program

# Thornthwaite water balance

Tabular procedure to determine water balance

Originally developed for natural soils, subsequently adapted to landfill analysis

Performs month-to-month bookkeeping of precipitation, ET, and soil moisture

# Thornthwaite water balance

C.W. Thornthwaite, 1948. An approach toward a rational classification of climate. *Geographical Review*, Vol. 38, No. 1, Pp. 55-94.

C.W. Thornthwaite and J.R. Mather, 1955. The water balance. Publications in Climatology, Vol. 8, No. 1, pp. 5-86. Laboratory of Climatology, Drexel Institute of Technology, Centerton, New Jersey.

C.W. Thornthwaite and J.R. Mather, 1957. Instructions and tables for computing potential evapotranspiration and the water balance. Publications in Climatology, Vol. 10, No. 3, pp.185-311. Laboratory of Climatology, Drexel Institute of Technology, Centerton, New Jersey. (downloadable from course web site)

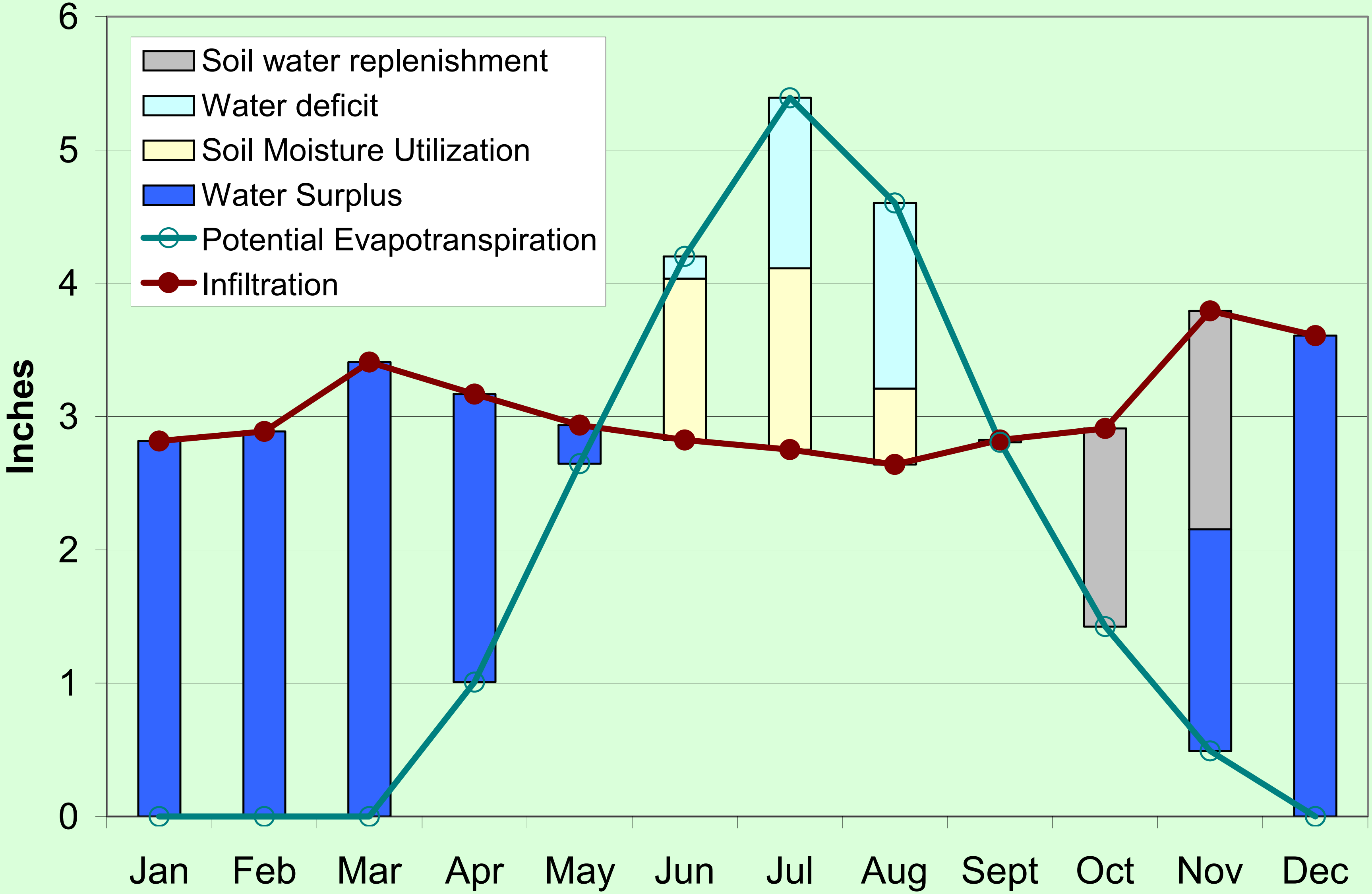
McBean, E.A., F.A. Rovers and G.J. Farquhar, 1995. *Solid Waste Landfill Engineering and Design*. Prentice Hall PTR, Englewood Cliffs, New Jersey.

# Thornthwaite balance for Massachusetts

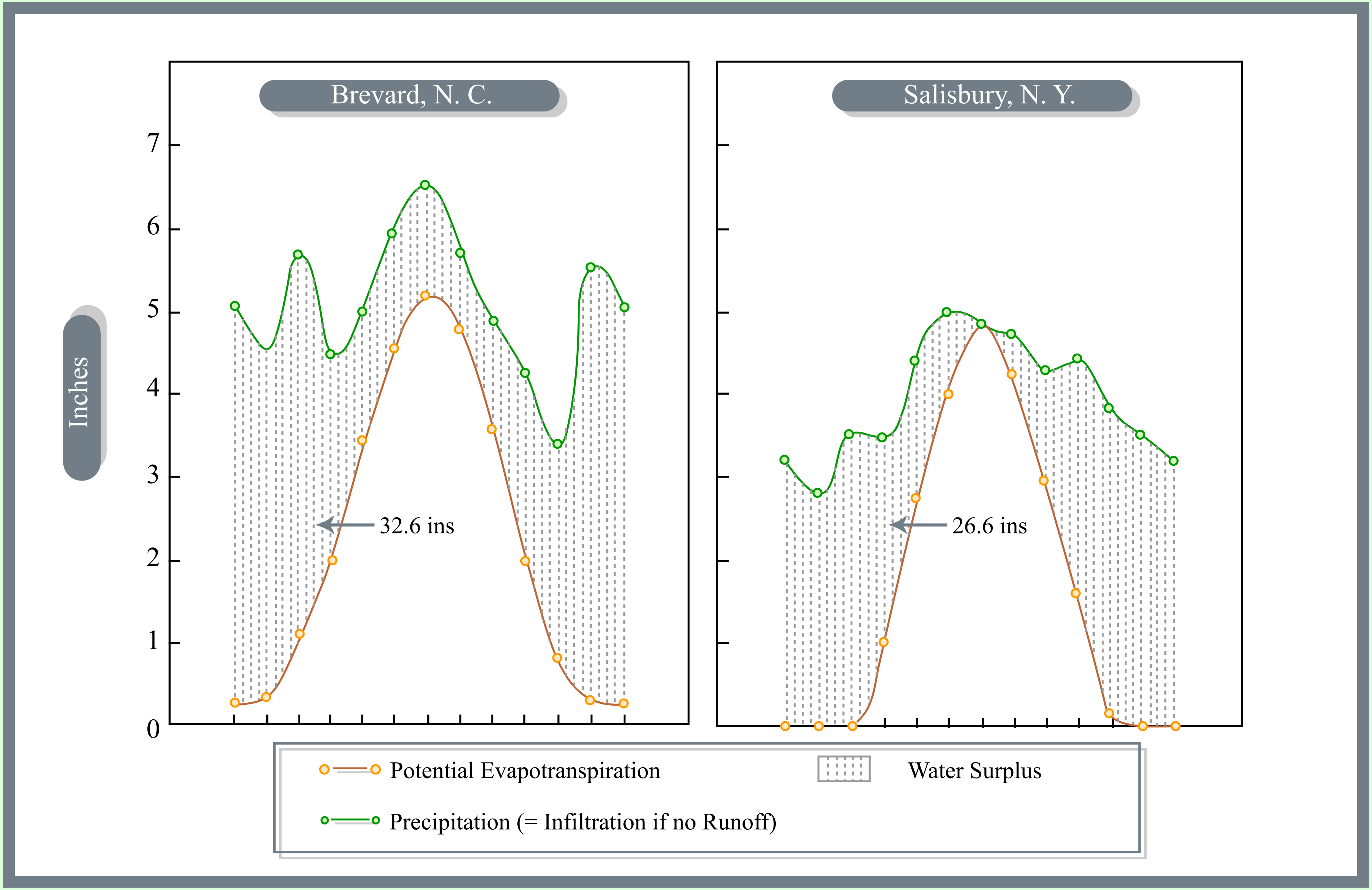
| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sept | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| T, Air temperature (F) | 24.3 | 25.9 | 34.4 | 46.3 | 57 | 66.9 | 72.1 | 70 | 62.4 | 51.9 | 40.6 | 28.7 | |
| T, Air temperature (C) | -4.3 | -3.4 | 1.3 | 7.9 | 13.9 | 19.4 | 22.3 | 21.1 | 16.9 | 11.1 | 4.8 | -1.8 | |
| i, Heat index | 0 | 0 | 0.13 | 2.02 | 4.69 | 7.78 | 9.6 | 8.85 | 6.31 | 3.33 | 0.93 | 0 | 43.64 |
| UPET, Unadjusted PE (inches) | 0 | 0 | 0 | 0.03 | 0.07 | 0.11 | 0.14 | 0.13 | 0.09 | 0.05 | 0.02 | 0 | |
| r, PE Adjustment factor | 24.5 | 24.6 | 30.8 | 33.6 | 37.8 | 38.2 | 38.5 | 35.4 | 31.2 | 28.5 | 24.6 | 23.4 | |
| PET, Potential Evapotranspiration (inches) | 0 | 0.0 | 0.0 | 1.0 | 2.6 | 4.2 | 5.4 | 4.6 | 2.8 | 1.4 | 0.5 | 0.0 | 22.6 |
| P, Precipitation (inches) | 3.5 | 3.6 | 4.3 | 4.0 | 3.7 | 3.5 | 3.4 | 3.3 | 3.5 | 3.6 | 4.7 | 4.5 | 45.7 |
| Cro, Runoff coefficient | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | |
| RO, Runoff (inches) | 0.7 | 0.7 | 0.9 | 0.8 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.9 | 0.9 | 9.1 |
| I, infiltration | 2.8 | 2.9 | 3.4 | 3.2 | 2.9 | 2.8 | 2.8 | 2.6 | 2.8 | 2.9 | 3.8 | 3.6 | 36.6 |
| I-PET (inches) | 2.8 | 2.9 | 3.4 | 2.2 | 0.3 | -1.4 | -2.6 | -2.0 | 0.0 | 1.5 | 3.3 | 3.6 | 14.0 |
| ACC WL, Accumulated Water Loss (inches) | | | | | | -1.4 | -4.0 | -6.0 | | | | | |
| Soil moisture capacity (inches)* | 4.0 | | | | | | | | | | | | |
| ST, Storage (inches) | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 2.8 | 1.4 | 0.9 | 0.9 | 2.4 | 4.0 | 4.0 | |
| ΔST, Change in Storage (inches) | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | -1.2 | -1.4 | -0.6 | 0.0 | 1.5 | 1.6 | 0.0 | |
| AET, Actual evapotranspiration (inches) | 0.0 | 0.0 | 0.0 | 1.0 | 2.6 | 4.0 | 4.1 | 3.2 | 2.8 | 1.4 | 0.5 | 0.0 | 19.7 |
| PERC, Percolation (inches) | 2.8 | 2.9 | 3.4 | 2.2 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.7 | 3.6 | 16.8 |
| Check: P = PERC+AET+ΔST+RO | 3.5 | 3.6 | 4.3 | 4.0 | 3.7 | 3.5 | 3.4 | 3.3 | 3.5 | 3.6 | 4.7 | 4.5 | |

* Soil moisture capacity = 4 inches for grassed landfill cover

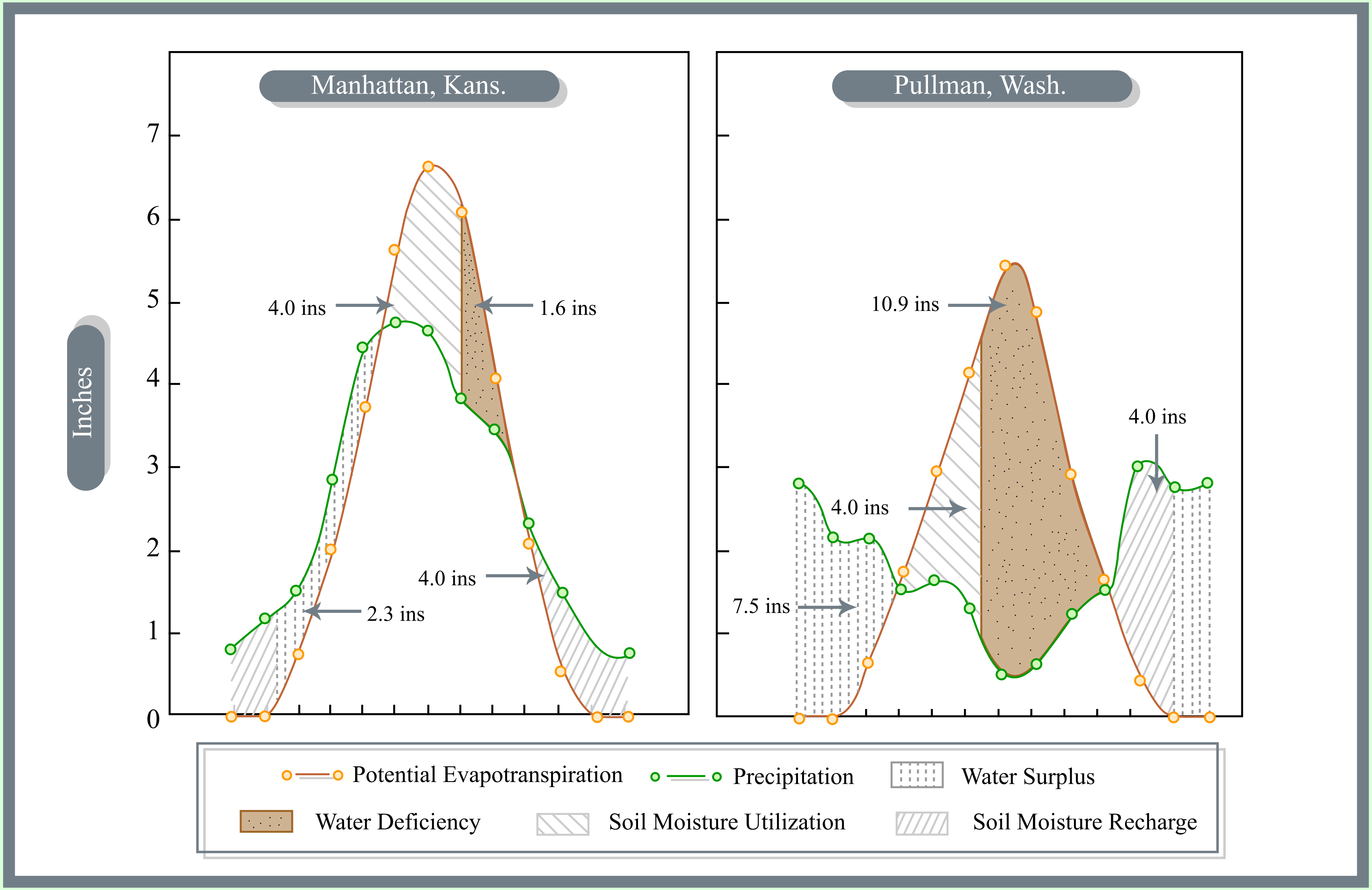
# Thornthwaite balance for Massachusetts



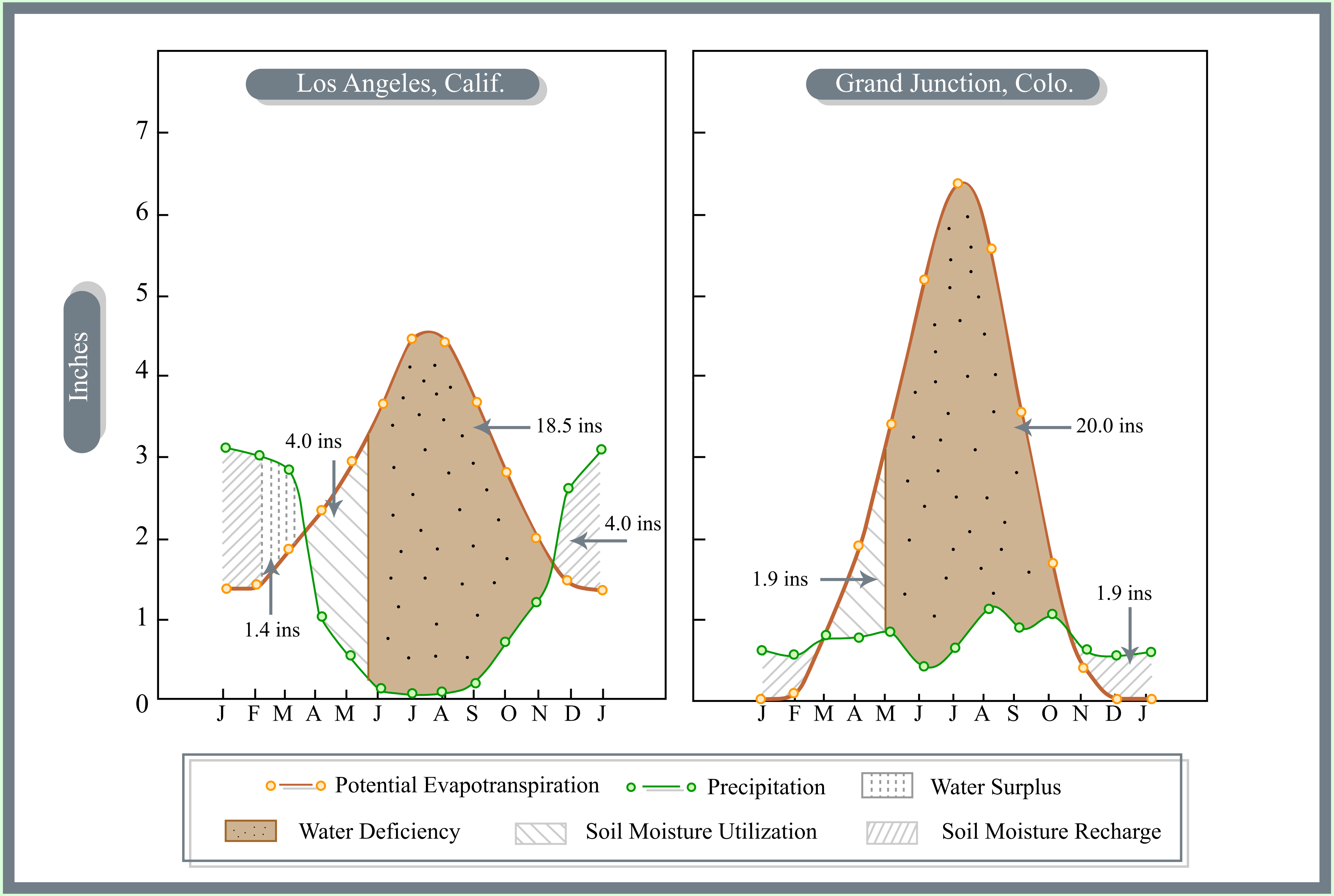
# Humid climates



# Subhumid and humid climates



# Dry climates



# Thornthwaite and Mather, 1957

"March of Precipitation and Potential Evapotranspiration at Selected Stations in the United States."
*Geogr Review* (January, 1948): Figure 4.

# Steps 1 and 2 in Thornthwaite balance

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sept | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| T, Air temperature (F) | 24.3 | 25.9 | 34.4 | 46.3 | 57 | 66.9 | 72.1 | 70 | 62.4 | 51.9 | 40.6 | 28.7 | |
| T, Air temperature (C) | -4.3 | -3.4 | 1.3 | 7.9 | 13.9 | 19.4 | 22.3 | 21.1 | 16.9 | 11.1 | 4.8 | -1.8 | |
| i, Heat index | 0 | 0 | 0.13 | 2.02 | 4.69 | 7.78 | 9.6 | 8.85 | 6.31 | 3.33 | 0.93 | 0 | 43.64 |

T – Air temperature – find mean monthly air temperature for nearest weather station (http://www.ncdc.noaa.gov/, *Climates of the States*, *Climates of the World,* or *Weather of U.S. Cities*)

i – heat index – look up in T&M Table 1 or 2 as function of air temperature

# Steps 3 and 4 in Thornthwaite balance

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sept | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| T, Air temperature (F) | 24.3 | 25.9 | 34.4 | 46.3 | 57 | 66.9 | 72.1 | 70 | 62.4 | 51.9 | 40.6 | 28.7 | |
| T, Air temperature (C) | -4.3 | -3.4 | 1.3 | 7.9 | 13.9 | 19.4 | 22.3 | 21.1 | 16.9 | 11.1 | 4.8 | -1.8 | |
| i, Heat index | 0 | 0 | 0.13 | 2.02 | 4.69 | 7.78 | 9.6 | 8.85 | 6.31 | 3.33 | 0.93 | 0 | 43.64 |
| UPET, Unadjusted PE (inches) | 0 | 0 | 0 | 0.03 | 0.07 | 0.11 | 0.14 | 0.13 | 0.09 | 0.05 | 0.02 | 0 | |
| r, PE Adjustment factor | 24.5 | 24.6 | 30.8 | 33.6 | 37.8 | 38.2 | 38.5 | 35.4 | 31.2 | 28.5 | 24.6 | 23.4 | |

UPET – Unadjusted potential evapotranspiration – look up in T&M Table 3, 4, or 5 as function of temperature and heat index

r – PE adjustment factor for duration of sunlight – look up in Table 6 or 7 as function of latitude and month

# Steps 5 and 6 in Thornthwaite balance

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sept | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| T, Air temperature (F) | 24.3 | 25.9 | 34.4 | 46.3 | 57 | 66.9 | 72.1 | 70 | 62.4 | 51.9 | 40.6 | 28.7 | |
| T, Air temperature (C) | -4.3 | -3.4 | 1.3 | 7.9 | 13.9 | 19.4 | 22.3 | 21.1 | 16.9 | 11.1 | 4.8 | -1.8 | |
| i, Heat index | 0 | 0 | 0.13 | 2.02 | 4.69 | 7.78 | 9.6 | 8.85 | 6.31 | 3.33 | 0.93 | 0 | 43.64 |
| UPET, Unadjusted PE (inches) | 0 | 0 | 0 | 0.03 | 0.07 | 0.11 | 0.14 | 0.13 | 0.09 | 0.05 | 0.02 | 0 | |
| r, PE Adjustment factor | 24.5 | 24.6 | 30.8 | 33.6 | 37.8 | 38.2 | 38.5 | 35.4 | 31.2 | 28.5 | 24.6 | 23.4 | |
| PET, Potential Evapotranspiration (inches) | 0 | 0.0 | 0.0 | 1.0 | 2.6 | 4.2 | 5.4 | 4.6 | 2.8 | 1.4 | 0.5 | 0.0 | 22.6 |
| P, Precipitation (inches) | 3.5 | 3.6 | 4.3 | 4.0 | 3.7 | 3.5 | 3.4 | 3.3 | 3.5 | 3.6 | 4.7 | 4.5 | 45.7 |

PET = r × UPET – potential evapotranspiration – amount of ET that could occur if there was sufficient soil moisture

P – precipitation – find mean monthly precipitation for nearest weather station

# Step 7 in Thornthwaite balance

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sept | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| T, Air temperature (F) | 24.3 | 25.9 | 34.4 | 46.3 | 57 | 66.9 | 72.1 | 70 | 62.4 | 51.9 | 40.6 | 28.7 | |
| T, Air temperature (C) | -4.3 | -3.4 | 1.3 | 7.9 | 13.9 | 19.4 | 22.3 | 21.1 | 16.9 | 11.1 | 4.8 | -1.8 | |
| i, Heat index | 0 | 0 | 0.13 | 2.02 | 4.69 | 7.78 | 9.6 | 8.85 | 6.31 | 3.33 | 0.93 | 0 | 43.64 |
| UPET, Unadjusted PE (inches) | 0 | 0 | 0 | 0.03 | 0.07 | 0.11 | 0.14 | 0.13 | 0.09 | 0.05 | 0.02 | 0 | |
| r, PE Adjustment factor | 24.5 | 24.6 | 30.8 | 33.6 | 37.8 | 38.2 | 38.5 | 35.4 | 31.2 | 28.5 | 24.6 | 23.4 | |
| PET, Potential Evapotranspiration (inches) | 0 | 0.0 | 0.0 | 1.0 | 2.6 | 4.2 | 5.4 | 4.6 | 2.8 | 1.4 | 0.5 | 0.0 | 22.6 |
| P, Precipitation (inches) | 3.5 | 3.6 | 4.3 | 4.0 | 3.7 | 3.5 | 3.4 | 3.3 | 3.5 | 3.6 | 4.7 | 4.5 | 45.7 |
| Cro, Runoff coefficient | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | |
| RO, Runoff (inches) | 0.7 | 0.7 | 0.9 | 0.8 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.9 | 0.9 | 9.1 |

Cro – runoff coefficient – empirical coefficient representing fraction of rainfall that runs off (not included in Thornthwaite's original method)

RO – monthly runoff = P × Cro

# Runoff coefficients for landfill

| Runoff Coefficients | |
|---|---|
| Surface Conditions: Grass cover (slope) | Runoff Coefficient |
| Sandy soil, flat, 2% | 0.05 - 0.10 |
| Sandy soil, average, 2-7% | 0.10 - 0.15 |
| Sandy soil, steep, 7% | 0.15 - 0.20 |
| Heavy soil, flat, 2% | 0.13 - 0.17 |
| Heavy soil, average, 2-7% | 0.18 - 0.22 |
| Heavy soil, steep, 7% | 0.25 - 0.35 |

Adapted from: McBean, E. A., F. A. Rovers, and G. J. Farquhar. *Solid Waste Landfill Engineering and Design*. Englewood Cliffs, New Jersey: Prentice Hall PTR, 1995.

# Steps 8 and 9 in Thornthwaite balance

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sept | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| T, Air temperature (F) | 24.3 | 25.9 | 34.4 | 46.3 | 57 | 66.9 | 72.1 | 70 | 62.4 | 51.9 | 40.6 | 28.7 | |
| T, Air temperature (C) | -4.3 | -3.4 | 1.3 | 7.9 | 13.9 | 19.4 | 22.3 | 21.1 | 16.9 | 11.1 | 4.8 | -1.8 | |
| i, Heat index | 0 | 0 | 0.13 | 2.02 | 4.69 | 7.78 | 9.6 | 8.85 | 6.31 | 3.33 | 0.93 | 0 | 43.64 |
| UPET, Unadjusted PE (inches) | 0 | 0 | 0 | 0.03 | 0.07 | 0.11 | 0.14 | 0.13 | 0.09 | 0.05 | 0.02 | 0 | |
| r, PE Adjustment factor | 24.5 | 24.6 | 30.8 | 33.6 | 37.8 | 38.2 | 38.5 | 35.4 | 31.2 | 28.5 | 24.6 | 23.4 | |
| PET, Potential Evapotranspiration (inches) | 0 | 0.0 | 0.0 | 1.0 | 2.6 | 4.2 | 5.4 | 4.6 | 2.8 | 1.4 | 0.5 | 0.0 | 22.6 |
| P, Precipitation (inches) | 3.5 | 3.6 | 4.3 | 4.0 | 3.7 | 3.5 | 3.4 | 3.3 | 3.5 | 3.6 | 4.7 | 4.5 | 45.7 |
| Cro, Runoff coefficient | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | |
| RO, Runoff (inches) | 0.7 | 0.7 | 0.9 | 0.8 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.9 | 0.9 | 9.1 |
| I, infiltration | 2.8 | 2.9 | 3.4 | 3.2 | 2.9 | 2.8 | 2.8 | 2.6 | 2.8 | 2.9 | 3.8 | 3.6 | 36.6 |
| I-PET (inches) | 2.8 | 2.9 | 3.4 | 2.2 | 0.3 | -1.4 | -2.6 | -2.0 | 0.0 | 1.5 | 3.3 | 3.6 | 14.0 |
| ACC WL, Accumulated Water Loss (inches) | | | | | | -1.4 | -4.0 | -6.0 | | | | | |

I = P - RO = infiltration

I – PET = Infiltration less potential evapotranspiration = water available for storage

# Step 10 in Thornthwaite balance

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sept | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| T, Air temperature (F) | 24.3 | 25.9 | 34.4 | 46.3 | 57 | 66.9 | 72.1 | 70 | 62.4 | 51.9 | 40.6 | 28.7 | |
| T, Air temperature (C) | -4.3 | -3.4 | 1.3 | 7.9 | 13.9 | 19.4 | 22.3 | 21.1 | 16.9 | 11.1 | 4.8 | -1.8 | |
| i, Heat index | 0 | 0 | 0.13 | 2.02 | 4.69 | 7.78 | 9.6 | 8.85 | 6.31 | 3.33 | 0.93 | 0 | 43.64 |
| UPET, Unadjusted PE (inches) | 0 | 0 | 0 | 0.03 | 0.07 | 0.11 | 0.14 | 0.13 | 0.09 | 0.05 | 0.02 | 0 | |
| r, PE Adjustment factor | 24.5 | 24.6 | 30.8 | 33.6 | 37.8 | 38.2 | 38.5 | 35.4 | 31.2 | 28.5 | 24.6 | 23.4 | |
| PET, Potential Evapotranspiration (inches) | 0 | 0.0 | 0.0 | 1.0 | 2.6 | 4.2 | 5.4 | 4.6 | 2.8 | 1.4 | 0.5 | 0.0 | 22.6 |
| P, Precipitation (inches) | 3.5 | 3.6 | 4.3 | 4.0 | 3.7 | 3.5 | 3.4 | 3.3 | 3.5 | 3.6 | 4.7 | 4.5 | 45.7 |
| Cro, Runoff coefficient | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | |
| RO, Runoff (inches) | 0.7 | 0.7 | 0.9 | 0.8 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.9 | 0.9 | 9.1 |
| I, infiltration | 2.8 | 2.9 | 3.4 | 3.2 | 2.9 | 2.8 | 2.8 | 2.6 | 2.8 | 2.9 | 3.8 | 3.6 | 36.6 |
| I-PET (inches) | 2.8 | 2.9 | 3.4 | 2.2 | 0.3 | -1.4 | -2.6 | -2.0 | 0.0 | 1.5 | 3.3 | 3.6 | 14.0 |
| ACC WL, Accumulated Water Loss (inches) | | | | | | -1.4 | -4.0 | -6.0 | | | | | |
| Soil moisture capacity (inches)* | 4.0 | | | | | | | | | | | | |
| ST, Storage (inches) | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 2.8 | 1.4 | 0.9 | 0.9 | 2.4 | 4.0 | 4.0 | |

ACC WL – accumulated water loss = running total of negative I – PET values

Moisture capacity = function of soil depth and type

# Moisture capacity

Moisture capacity =
field capacity ×
depth of root zone

T&M Table 10 also gives
moisture capacities

Provisional Water Holding Capacities for Different Combinations of Soil and Vegetation

| Soil type | Available water | | Root zone | | Applicable soil moisture retention table | |
|---|---|---|---|---|---|---|
| | mm/m | in./ft | m | ft | mm | in. |
| **Shallow-Rooted Crops (spinach, peas, beans, beets, carrots, etc.)** | | | | | | |
| Fine sand | 100 | 1.2 | .50 | 1.67 | 50 | 2.0 |
| Fine sandy loam | 150 | 1.8 | .50 | 1.67 | 75 | 3.0 |
| Silt loam | 200 | 2.4 | .62 | 2.08 | 125 | 5.0 |
| Clay loam | 250 | 3.0 | .40 | 1.33 | 100 | 4.0 |
| Clay | 300 | 3.6 | .25 | .83 | 75 | 3.0 |
| **Moderately Deep-Rooted Crops (corn, cotton, tobacco, cereal grains)** | | | | | | |
| Fine sand | 100 | 1.2 | .75 | 2.50 | 75 | 3.0 |
| Fine sandy loam | 150 | 1.8 | 1.00 | 3.33 | 150 | 6.0 |
| Silt loam | 200 | 2.4 | 1.00 | 3.33 | 200 | 8.0 |
| Clay loam | 250 | 3.0 | .80 | 2.67 | 200 | 8.0 |
| Clay | 300 | 3.6 | .50 | 1.67 | 50 | 6.0 |
| **Deep-Rooted Crops (alfalfa, pastures, shrubs)** | | | | | | |
| Fine sand | 100 | 1.2 | 1.00 | 3.33 | 100 | 4.0 |
| Fine sandy loam | 150 | 1.8 | 1.00 | 3.33 | 150 | 6.0 |
| Silt loam | 200 | 2.4 | 1.25 | 4.17 | 250 | 10.0 |
| Clay loam | 250 | 3.0 | 1.00 | 3.33 | 250 | 10.0 |
| Clay | 300 | 3.6 | .67 | 2.22 | 200 | 8.0 |
| **Orchards** | | | | | | |
| Fine sand | 100 | 1.2 | 1.50 | 5.00 | 150 | 6.0 |
| Fine sandy loam | 150 | 1.8 | 1.67 | 5.55 | 250 | 10.0 |
| Silt loam | 200 | 2.4 | 1.50 | 5.00 | 300 | 12.0 |

Adapted from: McBean, E. A., F. A. Rovers and G. J. Farquhar. *Solid Waste Landfill Engineering and Design*. Englewood Cliffs, New Jersey: Prentice Hall PTR, 1995.

# Step 11 in Thornthwaite balance

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sept | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| T, Air temperature (F) | 24.3 | 25.9 | 34.4 | 46.3 | 57 | 66.9 | 72.1 | 70 | 62.4 | 51.9 | 40.6 | 28.7 | |
| T, Air temperature (C) | -4.3 | -3.4 | 1.3 | 7.9 | 13.9 | 19.4 | 22.3 | 21.1 | 16.9 | 11.1 | 4.8 | -1.8 | |
| i, Heat index | 0 | 0 | 0.13 | 2.02 | 4.69 | 7.78 | 9.6 | 8.85 | 6.31 | 3.33 | 0.93 | 0 | 43.64 |
| UPET, Unadjusted PE (inches) | 0 | 0 | 0 | 0.03 | 0.07 | 0.11 | 0.14 | 0.13 | 0.09 | 0.05 | 0.02 | 0 | |
| r, PE Adjustment factor | 24.5 | 24.6 | 30.8 | 33.6 | 37.8 | 38.2 | 38.5 | 35.4 | 31.2 | 28.5 | 24.6 | 23.4 | |
| PET, Potential Evapotranspiration (inches) | 0 | 0.0 | 0.0 | 1.0 | 2.6 | 4.2 | 5.4 | 4.6 | 2.8 | 1.4 | 0.5 | 0.0 | 22.6 |
| P, Precipitation (inches) | 3.5 | 3.6 | 4.3 | 4.0 | 3.7 | 3.5 | 3.4 | 3.3 | 3.5 | 3.6 | 4.7 | 4.5 | 45.7 |
| Cro, Runoff coefficient | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | |
| RO, Runoff (inches) | 0.7 | 0.7 | 0.9 | 0.8 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.9 | 0.9 | 9.1 |
| I, infiltration | 2.8 | 2.9 | 3.4 | 3.2 | 2.9 | 2.8 | 2.8 | 2.6 | 2.8 | 2.9 | 3.8 | 3.6 | 36.6 |
| I-PET (inches) | 2.8 | 2.9 | 3.4 | 2.2 | 0.3 | -1.4 | -2.6 | -2.0 | 0.0 | 1.5 | 3.3 | 3.6 | 14.0 |
| ACC WL, Accumulated Water Loss (inches) | | | | | | -1.4 | -4.0 | -6.0 | | | | | |
| Soil moisture capacity (inches)* | 4.0 | | | | | | | | | | | | |
| ST, Storage (inches) | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 2.8 | 1.4 | 0.9 | 0.9 | 2.4 | 4.0 | 4.0 | |
| ΔST, Change in Storage (inches) | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | -1.2 | -1.4 | -0.6 | 0.0 | 1.5 | 1.6 | 0.0 | |

ST – soil moisture storage

= soil moisture capacity at start of dry season (red box)

= look up in T&M Tables 11-33 for months with negative I-PET (yellow box) as a function of accumulated water loss

= last month's ST plus I-PET up to field capacity

# Steps 12 and 13 in Thornthwaite balance

△ ST – change in soil moisture from last month

AET – actual ET

= PET for wet months, I ≥ PET

= I – △ST for dry months, I < PET)

(i.e., in wet months you can only evapotranspirate the infiltration plus water that can be extracted from soil)

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PET, Potential Evapotranspiration (inches) | 0 | 0.0 | 0.0 | 1.0 | 2.6 | 4.2 | 5.4 | 4.6 | 2.8 | 1.4 | 0.5 | 0.0 | 22.6 |
| P, Precipitation (inches) | 3.5 | 3.6 | 4.3 | 4.0 | 3.7 | 3.5 | 3.4 | 3.3 | 3.5 | 3.6 | 4.7 | 4.5 | 45.7 |
| Cro, Runoff coefficient | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | |
| RO, Runoff (inches) | 0.7 | 0.7 | 0.9 | 0.8 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.9 | 0.9 | 9.1 |
| I, infiltration | 2.8 | 2.9 | 3.4 | 3.2 | 2.9 | 2.8 | 2.8 | 2.6 | 2.8 | 2.9 | 3.8 | 3.6 | 36.6 |
| I-PET (inches) | 2.8 | 2.9 | 3.4 | 2.2 | 0.3 | -1.4 | -2.6 | -2.0 | 0.0 | 1.5 | 3.3 | 3.6 | 14.0 |
| ACC WL, Accumulated Water Loss (inches) | | | | | | -1.4 | -4.0 | -6.0 | | | | | |
| Soil moisture capacity (inches)* | 4.0 | | | | | | | | | | | | |
| ST, Storage (inches) | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 2.8 | 1.4 | 0.9 | 0.9 | 2.4 | 4.0 | 4.0 | |
| ΔST, Change in Storage (inches) | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | -1.2 | -1.4 | -0.6 | 0.0 | 1.5 | 1.6 | 0.0 | |
| AET, Actual evapotranspiration (inches) | 0.0 | 0.0 | 0.0 | 1.0 | 2.6 | 4.0 | 4.1 | 3.2 | 2.8 | 1.4 | 0.5 | 0.0 | 19.7 |

# Step 14 in Thornthwaite balance !!!

PERC – percolation

= (I – PET – $\triangle$ST)  for wet months, I $\geq$ PET

= 0 for dry months, I < PET

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sept | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| T, Air temperature (F) | 24.3 | 25.9 | 34.4 | 46.3 | 57 | 66.9 | 72.1 | 70 | 62.4 | 51.9 | 40.6 | 28.7 | |
| T, Air temperature (C) | -4.3 | -3.4 | 1.3 | 7.9 | 13.9 | 19.4 | 22.3 | 21.1 | 16.9 | 11.1 | 4.8 | -1.8 | |
| i, Heat index | 0 | 0 | 0.13 | 2.02 | 4.69 | 7.78 | 9.6 | 8.85 | 6.31 | 3.33 | 0.93 | 0 | 43.64 |
| UPET, Unadjusted PE (inches) | 0 | 0 | 0 | 0.03 | 0.07 | 0.11 | 0.14 | 0.13 | 0.09 | 0.05 | 0.02 | 0 | |
| r, PE Adjustment factor | 24.5 | 24.6 | 30.8 | 33.6 | 37.8 | 38.2 | 38.5 | 35.4 | 31.2 | 28.5 | 24.6 | 23.4 | |
| PET, Potential Evapotranspiration (inches) | 0 | 0.0 | 0.0 | 1.0 | 2.6 | 4.2 | 5.4 | 4.6 | 2.8 | 1.4 | 0.5 | 0.0 | 22.6 |
| P, Precipitation (inches) | 3.5 | 3.6 | 4.3 | 4.0 | 3.7 | 3.5 | 3.4 | 3.3 | 3.5 | 3.6 | 4.7 | 4.5 | 45.7 |
| Cro, Runoff coefficient | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | |
| RO, Runoff (inches) | 0.7 | 0.7 | 0.9 | 0.8 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.9 | 0.9 | 9.1 |
| I, infiltration | 2.8 | 2.9 | 3.4 | 3.2 | 2.9 | 2.8 | 2.8 | 2.6 | 2.8 | 2.9 | 3.8 | 3.6 | 36.6 |
| I-PET (inches) | 2.8 | 2.9 | 3.4 | 2.2 | 0.3 | -1.4 | -2.6 | -2.0 | 0.0 | 1.5 | 3.3 | 3.6 | 14.0 |
| ACC WL, Accumulated Water Loss (inches) | | | | | | -1.4 | -4.0 | -6.0 | | | | | |
| Soil moisture capacity (inches)* | 4.0 | | | | | | | | | | | | |
| ST, Storage (inches) | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 2.8 | 1.4 | 0.9 | 0.9 | 2.4 | 4.0 | 4.0 | |
| $\Delta$ST, Change in Storage (inches) | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | -1.2 | -1.4 | -0.6 | 0.0 | 1.5 | 1.6 | 0.0 | |
| AET, Actual evapotranspiration (inches) | 0.0 | 0.0 | 0.0 | 1.0 | 2.6 | 4.0 | 4.1 | 3.2 | 2.8 | 1.4 | 0.5 | 0.0 | 19.7 |
| PERC, Percolation (inches) | 2.8 | 2.9 | 3.4 | 2.2 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.7 | 3.6 | 16.8 |
| Check:  P = PERC+AET+$\Delta$ST+RO | 3.5 | 3.6 | 4.3 | 4.0 | 3.7 | 3.5 | 3.4 | 3.3 | 3.5 | 3.6 | 4.7 | 4.5 | |

# What does Thornthwaite balance give us?

Estimate of percolation below the root zone
(This is the water that will get to the landfill cap)

Understanding of seasonal distribution of P, ET, and percolation

Estimate of recharge for ground-water models

# HELP

**HELP – Hydrologic Evaluation of Landfill Performance**

Developed by U.S. Army Corps of Engineers for EPA

Multiple versions over the years as model has been corrected and improved – current version is 3.07

# HELP model capabilities

Quasi-two-dimensional: includes some vertical infiltration layers and some lateral drainage layers

Capacity to consider up to 20 soil layers plus 5 barrier/liner systems

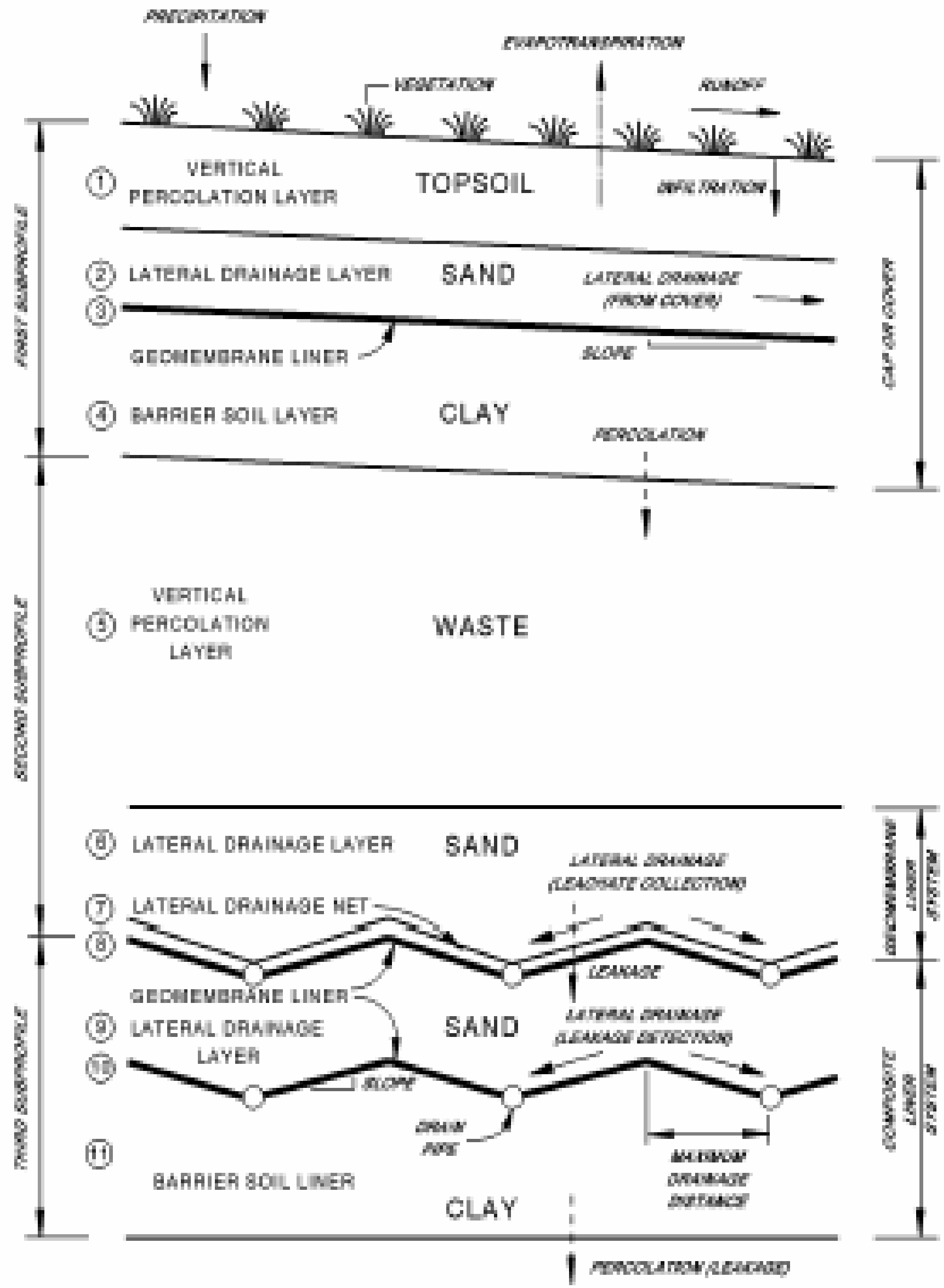
Simulates processes through time on daily time step

# HELP model capabilities

Program databases:

- Database of ~100 cities in the U.S. and Canada with meteorologic data and other default parameters
- 42 pre-defined “soil” types
- 23 soils
- 10 geomembranes and liners
- 3 drainage layers (2 geonets and gravel)
- 6 waste types

# HELP components




Source: Schroeder, P. R., Dozier, T.S., Zappi, P. A., McEnroe, B. M., Sjostrom, J. W., and Peyton, R. L. (1994). "The Hydrologic Evaluation of Landfill Performance (HELP) Model: Engineering Documentation for Version 3," EPA/600/R-94/168b, September 1994, U.S. Environmental Protection Agency Office of Research and Development, Washington, DC.

# HELP components

- Precipitation infiltration on leaf cover
- Surface processes:
  - Rainfall runoff using SCS method
  - Snow accumulation and snowmelt
- Topsoil layer processes:
  - Vertical drainage – independent of depth of water above
  - Similar to Thornthwaite analysis: water balance approach based on potential ET
  - Simulates seasonal effects:
    - Frozen soil in winter
    - Vegetative growth as function of temperature

# HELP Components

- Vertical soil flow
  - Computes unsaturated hydraulic conductivity as function of soil moisture using Brooks-Corey equation
  - Vertical drainage through soil
- Percolation through soil liner or leakage through geomembrane
- Lateral drainage to leachate collection system
  - Use Boussinesq approximation for lateral ground-water flow in drainage layers
  - Considers leachate recirculation

# HELP components

Barrier soil layers

- Vertical leakage that is a function of depth of water atop liner
- Considers multiple leakage modes through FML, composite liners, or clay liners

# Limitations of model

Liner performance does not vary with time: does not consider aging effects

Assumes static configuration of layers: does not consider different stages in landfill development such as waste filling, closure, etc.

Models flow quantity only: does not model leachate quality

Model results are only as good as inputs: considerable uncertainty in liner leakage, number of holes, depth of ponding, etc.

Other limitations govern sequence of layers

# Limitations with HELP model

Can under-predict runoff: short intense storms are averaged out over one-day time step

The configuration of a drainage net immediately above the top liner leads to inaccurate results

See this reference for additional information on model limitations: Berger, K., 2002. Potential and Limitations of Applying HELP Model for Surface Covers. *Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management, ASCE*. Vol. 6, No. 3, Pg. 192-203. July 2002.