Florida Department of Environmental Protection

Hydrology – 3a:
Hydrologic Abstractions

Mariano Guardo PhD, PE, D.WRE

September 30, 2014





Definition of Hydrologic Abstractions

- ***Hydrologic Abstractions*** are a series of hydrologic processes that catch part of the total rainfall prior to the start of surface runoff
- Many hydrologic designs require modeling of rainfall/runoff events. Runoff, in this case, is determined as the residual of the gross rainfall (after subtracting the hydrologic abstractions) over a specific site
- Estimates of those fractions (abstractions) from the total rainfall are, in this case, of crucial importance because they represent "losses" to the runoff process
- In conclusion, considering the concept of hydrologic or water budget, hydrologic abstractions are equal to precipitation minus surface runoff

- ❑ Infiltration
- ❑ Evaporation
- ❑ Transpiration
- ❑ Interception
- ❑ Depression Storage
- ❑ Detention Storage

Classification of Hydrologic Abstractions

- Infiltration is a hydrologic process in which part of the precipitation is absorbed into the ground
- It is important to realize there are other sources of water available for infiltration such as snowmelt and irrigation
- Generally infiltration constitutes the greatest portion of the hydrologic abstractions; therefore, it has a major effect not only on the magnitude of surface runoff generation but also its timing and distribution
- Additionally, infiltration plays a key role in groundwater recharge, evapotranspiration, soil erosion and transport of chemicals in surface and subsurface waters

Infiltration

- Subsequent to the infiltration, the water movement through a soil controls the supply of water for plant uptake and for evaporation at the soil surface
- Evaluation of the rate of infiltration through soils during a precipitation event is subject to limitations. It is influenced by natural conditions such as the type and extent of vegetation cover, characteristics of the ground surface and its topography, physical properties of the soil, rainfall intensity and water quality
- Researches cannot identify the exact relationship that exists to quantify infiltration because the infinite combinations of soils and other factors existing in nature

Infiltration

Infiltration: Measurements

- Measuring infiltration is performed by using infiltrometers
  - Sprinkler Infiltrometers emulate rainfall under controlled conditions (depth and duration); they duplicate a wide spectrum of rainfall intensities
  - Tension (Disk) Inflitrometer has a supply membrane at the base of the water reservoir. Tension pores can be eliminated from the soil infiltration flow

- Ring or Cylinder Infiltrometers are metal rings driven into the ground about 6-inch, water is applied inside the ring and intake measurement can be recorded. The double-ring infiltrometer is commonly used, the outer ring has the purpose of minimizing the lateral movement of the water through the soil profile generating as much as possible a prevalent vertical displacement by effects of solely gravity

Infiltration: Measurements

- Infiltration Equations for Large Watersheds
  - ***Horton*** Equation
  - ***Philip*** Equation
  - ***Green and Ampt*** Equation

- The ***Horton*** (R. E. Horton, 1930) infiltration equation has been widely used in hydrologic modeling. It is a three-parameter empirical equation, as follows:

$$f(t) = f_c + (f_o - f_c) \times e^{-kt} \quad ...[3.1]$$

Infiltration: Equations

where $f(t)$ is the infiltration rate (L/T) at time t, f_o is the initial (maximum) infiltration rate (L/T) at the beginning of the storm, f_c is the final (or steady-state) infiltration rate (L/T) that is achieved as the soil becomes saturated, and k is a constant ($1/T$) that controls the rate of decrease in f

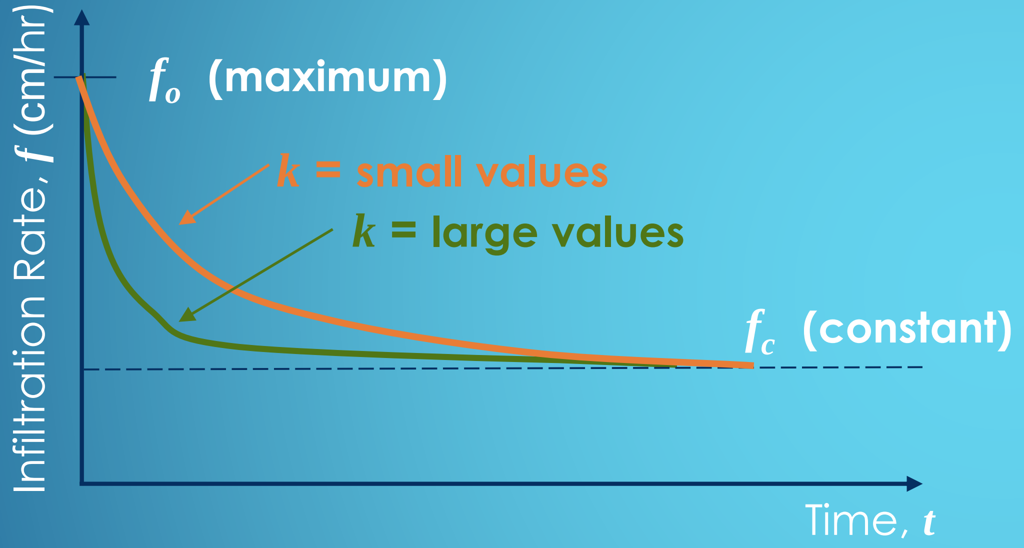


Table 3.1 Typical Parameters for the Horton Equation

Soil and cover conditions	f_o (cm/hr)	f_c (cm/hr)	k (1/hr)
Standard agricultural (bare)	28	0.6 – 22	1.6
Standard agricultural (turfed)	90	2 – 29	0.8
Peat	32	0.2 – 3	1.8
Fine sandy clay (bare)	21	0.2 – 2.5	2.0
Fine sandy clay (turfed)	26	1 – 3	1.4

Infiltration: Equations

- The ***Philip*** (J.R. Philip 1957) equation is based on the physical theory of infiltration, and has two parameters related to the initial soil moisture content and to the hydraulic conductivity of the soil, as follows:

$$f(t) = \frac{S}{2\sqrt{t}} + A \ldots [3.2]$$

where ***f(t)*** is the infiltration rate (*L/T*) at time ***t***, ***S*** is the sorptivity ($L/T^{1/2}$), and ***A*** is equivalent to the steady-state infiltration rate (*L/T*). ***S*** is a function of the soil suction potential and as ***A*** can be found from experiments

Infiltration: Equations

- The ***Green-Ampt*** (W.H. Green and G.A. Ampt, 1911) equation is based on an approximation of the Darcy Law of flow through a porous medium. Ponding water infiltrates into soil at two zones. The upper zone is the wetted zone (i.e., soil is saturated) and below it the unsaturated zone. The interface between the zones is the wetting front which moves in response to the capillary forces between the saturated and dry soil. As the soil pores are filled with water, the head losses created by the water flow through the porous medium is governed by Darcy Law. Neglecting the depth of ponding at the surface, and considering homogeneous soil with an initial and constant water content, the equation is:

Infiltration: Equations

$$f = K_h\left(\frac{L+S_f}{L}\right) \ldots [3.3]$$

where f is the infiltration rate (L/T), K_h is the hydraulic conductivity (L/T) of the saturated soil, L is the depth of the saturated soil, and S_f is the capillary suction at the wetting front (L). R.G. Mein and C.L. Larson (1973) have expressed this equation in a more convenient form:

$$f = K_h\left(1+\frac{S_f \times (\phi-\theta_i)}{F}\right) \ldots [3.4]$$

where the following new parameters: ϕ is the soil porosity (L^3/L^3), θ_i is the initial soil moisture content (L^3/L^3), and F is the accumulated infiltration (L)

Infiltration: Equations

- The following example illustrates how to estimate the parameters of the ***Horton*** infiltration equation from an infiltration test conducted using a ring infiltrometer with a 12-inch diameter. The table below presents data collected from the field test. The infiltration volumes are accumulated

Data Obtained from the Ring Infiltrometer Field Test (D=12 inch)

Time (min)	0	2	5	10	20	30	60	90	150	240
Infiltration Volume (cm^3)	0	512	1261	2350	4240	5839	9650	13053	19585	29326

Infiltration: Test & Horton's Parameters

Infiltration Rates Calculations from a Ring Infiltrometer Test

t (min)	Infiltration Vol (cm^3)	t (hours)	Δt (hours)	ΣF (cm)	ΔF (cm)	f (cm/hour)
0	0	0.0	-	-	-	-
2	512	0.033	0.033	0.70	0.70	21.05
5	1261	0.083	0.050	1.73	1.03	20.53
10	2350	0.167	0.083	3.22	1.49	17.91
20	4240	0.333	0.167	5.81	2.59	15.54
30	5839	0.50	0.167	8.00	2.19	13.15
69	9650	1.00	0.50	13.23	5.22	10.45
90	13053	1.50	0.50	17.89	4.66	9.33
150	19585	2.50	1.00	26.84	8.95	8.95
240	29326	4.00	1.50	40.19	13.35	8.90
			4.00		40.19	

Columns 1 & 2: Data from Infiltration Test
Column 4: Time intervals from the test
Column 5: Accumulated Infiltration (L). From the IV (Test) divided by $A_{infiltrometer}$
Column 6: Discrete Infiltration (i.e., value for any time interval)
Column 7: Infiltration Rate, $f = \Delta F/\Delta t$

Ring Infiltrometer

D = 12 inch = 30.48 cm
A = 729.66 cm^3

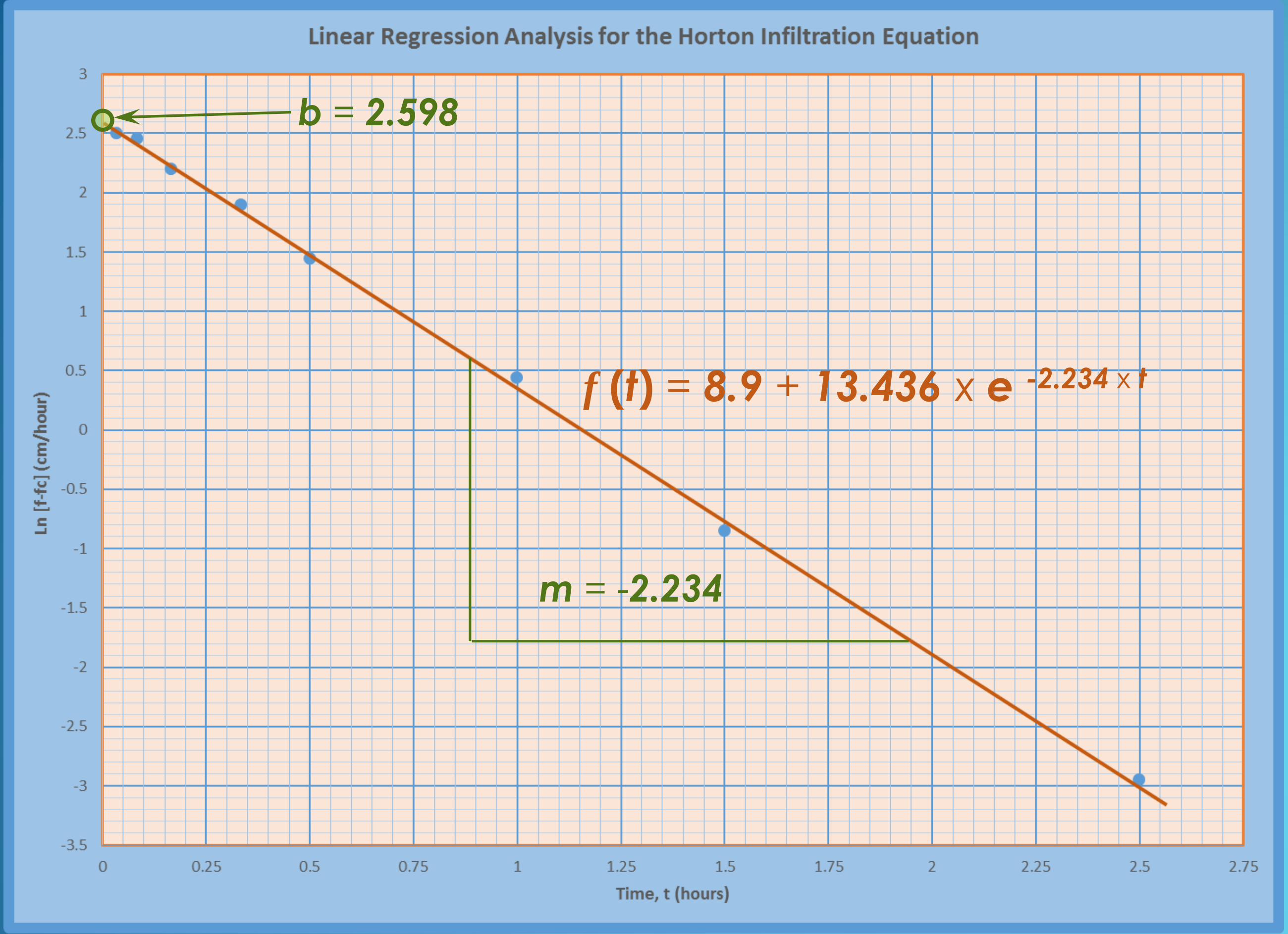
Infiltration: Test & Horton's Parameters

- Regression Analysis to Determine f_o and k in the ***Horton*** Equation with f_c = 8.9 cm/hr

Transformation for Exponential Equation (Ln scale on y-axis)

t (hours)	f (cm/hour)	$f - f_c$ (cm/hour)	Ln $(f - f_c)$
0.0	-	-	-
0.033	21.05	12.15	2.497
0.083	20.53	11.63	2.454
0.167	17.91	9.01	2.198
0.333	15.54	6.64	1.893
0.50	13.15	4.25	1.447
1.00	10.45	1.55	0.436
1.50	9.33	0.43	-0.849
2.50	8.95	0.05	-2.954

Infiltration: Test & Horton's Parameters



Regression Equation

$y = \mathbf{m}\,x + \mathbf{b}$

m = *slope (from Ln graph)* = ***-2.234***

b = *y-intercept (from Ln graph that corresponds to t = 0 hours)* = ***2.598***

Horton Equation

$f_o - f_c = \mathbf{EXP\,(2.598)} = \mathbf{e^{2.598}} = \mathbf{13.436}$ cm/hour

$f_o = \mathbf{13.436}$ cm/hour + $\mathbf{8.9}$ cm/hour =

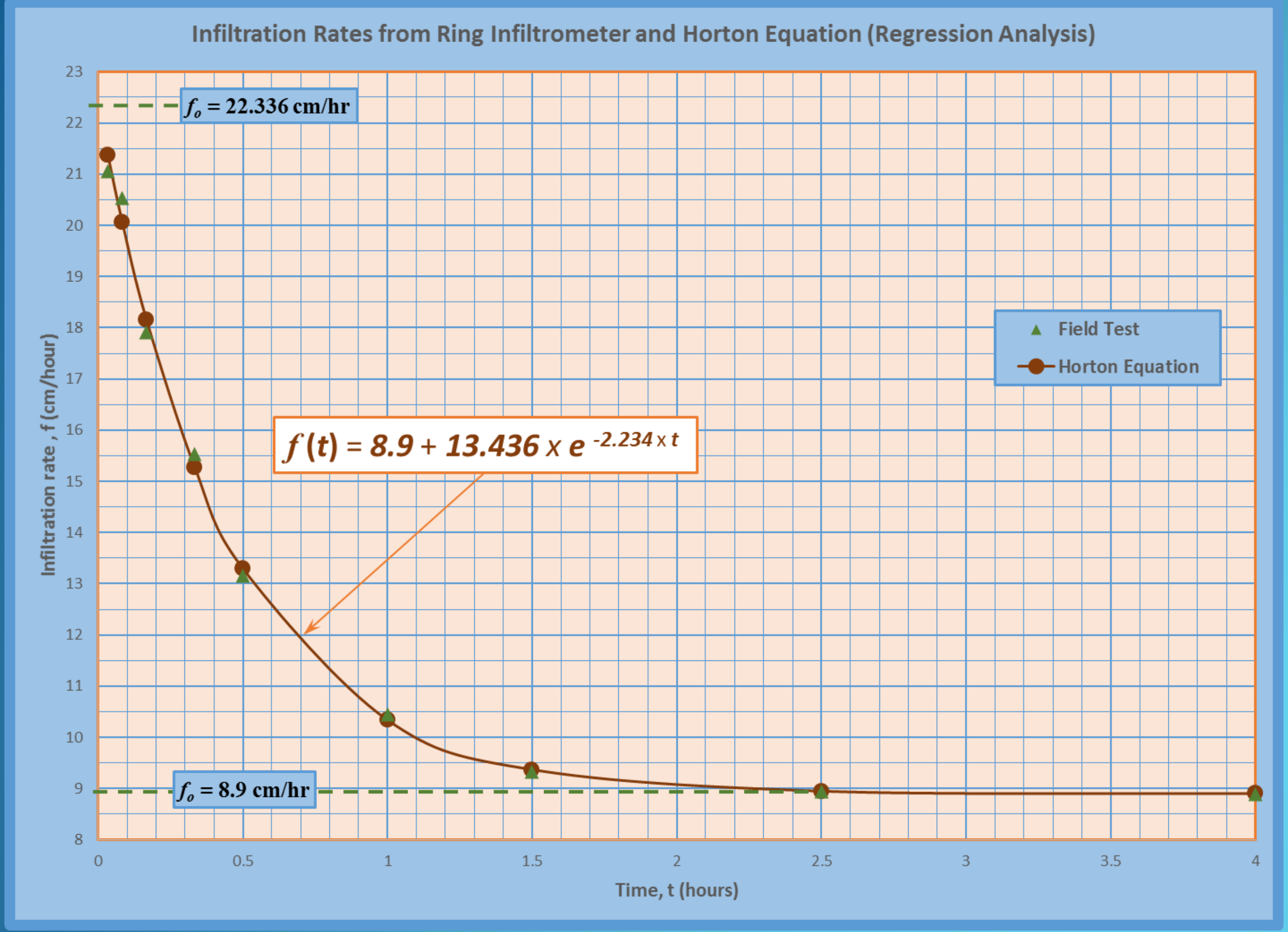
$f_o = \mathbf{22.336}$ cm/hour

k = **-m** = **2.234** 1/hour

r = *correlation coefficient* = ***-0.999***

f (cm/hour) = $\mathbf{8.9} + \mathbf{13.436} \times \mathbf{e}^{-2.234 \times t}$

Infiltration: Test & Horton's Parameters



Infiltration: Test & Horton's Parameters

- Evaporation is the change in the state of water from liquid to vapor as a result of heat addition, and it occurs everywhere in the hydrologic cycle
- Most evaporation loss comes from the oceans. It also derives from streams, lakes and even from rain drops. Evaporation occurs only if the surrounding air is not completely saturated (i.e., relative humidity is less than 100%)
- Solar energy must be available to cause water evaporation. This is possible due to the latent heat of vaporization in the water, which indicates that evaporation is a cooling process

Evaporation

- It is a function of solar radiation; difference in vapor pressure between the water and overlying air; humidity; temperature; wind and atmospheric pressure
- Evaporation can be measured either as the rate of loss of water (liquid) or as the rate of gain of water vapor by the atmosphere. Its amount can be estimated from:
  - ***Direct Measurements*** from Class A evaporation pan (or tank) or other evaporation devices
  - ***Water Budget*** technique
  - ***Mass Transfer*** (theoretical and empirical) and ***Energy Balance*** methods

Evaporation: Measurements

Evaporation: Direct Measurements

- The ***Class A Evaporation Pan*** was standardized by NWS
- It is made of low carbon stainless steel or galvanized iron and normally installed on a wooden platform
- Its diameter is 47.5 inch (120.7 cm) and 10 inch (25.4 cm) deep. Therefore adding 7.7 gallons will raise the water level in the pan by one-inch
- Evaporation records can be measured by manual readings, analog output evaporation gauge and digital system (sensors)
- When evaporation data from a Class A Pan is applied to waterbodies (mainly lakes), it has to be multiplied for a pan coefficient (it ranges from 0.35 to 0.85 with a mean of 0.7, and depends on the specific location)

Experimental Average Values for Evaporation Pan Coefficients

Location	Class A	Sunken Tanks			
		BPI (1)	Colorado (2)	Young (3)	Symons (4)
Newel Reservoir, Canada		0.95			
Fort Collins, Colorado	0.70		0.79		
Denver, Colorado	0.67	0.94			
Fullerton, California	0.77	0.94	0.89	0.98	
Lake Elsinore, California	0.77			0.98	
Fort McIntosh, Texas	0.72			0.89	
Red Bluff Reservoir, Texas	0.68				
Lake Okeechobee, Florida	0.81		0.98		
Lake Hefner, Oklahoma	0.69	0.91	0.83	0.91	
South Africa					0.91

1) *Bureau of Plant Industry (BPI), USDA*
6-ft diameter and 2-ft deep
2) *Colorado Evaporation Pan*
3-ft x 3-ft square and 18-inch deep
3) *Arthur A. Young (1936), Division of Irrigation, USDA. Screened*
2-ft diameter
4) *Symons, South Africa*
6-ft x 6-ft square

$$Ev = C_p \times E_p \ldots \text{[3.5]}$$

Evaporation: Direct Measurements

Suggested Values for Evaporation Pan Coefficients for E_{rc}

Wind	Upwind Fetch (m)	Case A, Relative Humidity (%)			Upwind Fetch (m)	Case B, Relative Humidity (%)		
		<40	40-70	>70		<40	40-70	>70
Light (< 2 m/sec)	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 (2-5 m/sec)	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 (5-8 m/sec)	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 (> 8 m/sec)	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	0.45	0.45	0.50
	1000	0.55	0.60	0.65	1000	0.35	0.40	0.45

Case A: *Pan A surrounded by cropped fields or wet soils within prescribed fetch*

Case B: *Pan A surrounded by dry soils, bare areas within prescribed fetch*

$$E_{rc} = C_p \times E_p \ldots \textbf{[3.6]}$$

E_{rc} = Reference Crop Evaporation

Evaporation: Direct Measurements

Evaporation: Water Budget

- Evaporation of surface water (waterbodies) can be estimated by water budget methodology which is based on the continuity equation,

$$I - O = \frac{\Delta S}{\Delta t} \quad ...[3.7]$$

where ***I*** is all the inflows (*L*^{3}/*T*), ***O*** is the outflows (*L*^{3}/*T*) and ***ΔS/Δt*** is the change in storage (*L*^{3}/*T*). Including all the components of the Hydrologic Cycle,

$$P + Q_{in} + Seep_{in} - Q_{out} - R_{aq} - T - E_s = \frac{\Delta S}{\Delta t} \quad ...[3.8]$$

where ***P*** is precipitation, $\boldsymbol{Q_{in}}$ is the inflow or runoff $\boldsymbol{Q_{out}}$ is the outflow or discharge for a specific structure, $Seep_{in}$ seepage into the waterbody, R_{aq} is the aquifer recharge, T is the transpiration and E_s is the evaporation

- Eq. 3.8 can be algebraically manipulated to estimate E_s

$$E_s = P + Q_{in} - Q_{out} + G_{net} - \frac{\Delta S}{\Delta t} \quad ...[3.9]$$

where G_{net} is the net transfer of seepage through the ground equivalent to $Seep_{in} - R_{aq}$ and the transpiration T can be neglected for practical purposes. All the terms in Eqs. 3.8 and 3.9 are in volume units for a time period of interest (L^3/T). Inflow or runoff Q_{in} into the waterbody can be estimated relatively easy by streamgauging as well as Q_{out} by calibrated equations

Evaporation: Water Budget

Evaporation: Mass Transfer Methods

- Mass transfer equations are based on the concept of mixing at the air-liquid interface which is controlled by the turbulent exchange of water vapor by eddy motion from an evaporating surface to the atmosphere
- Many equations, both empirical and theoretical, have been developed. Empirical equations are based on correlations with other climatic data such as humidity, wind, solar radiation and temperature

- The ***Dalton*** equation is a relationship between evaporation and vapor pressure

$$Ev = K \times (e_{ws} - e_a) \ldots [3.10]$$

where Ev is the direct evaporation, K is a coefficient dependent upon wind velocity and atmospheric pressure and e_{ws} and e_a are the saturation vapor at water surface temperature and vapor pressure of the air, respectively

- The ***Meyer*** equation was published in 1942,

$$E_d = c \times (e_{ws} - e_a) \times \left(1 + \frac{W}{10}\right) \ldots [3.11]$$

where $\boldsymbol{E_d}$ is the daily evaporation (*inch*), $\boldsymbol{c}$ is an empirical coefficient equal to ***0.36*** for waterbodies such as lakes and reservoirs and ***0.50*** for small ponds or puddles, $\boldsymbol{e_{ws}}$ and $\boldsymbol{e_a}$ are the saturation vapor pressure at water surface temperature and vapor pressure of the air (*inch of Hg*), respectively, and $\boldsymbol{W}$ is the wind speed *(mph)* measured at 25 ft above the surface

Evaporation: Mass Transfer Methods

- The Energy Balance method is also an application of continuity or the conservation of mass written in terms of energy. The transport of water pressure and heat occurs due to turbulent diffusion. The ***Bowen Ratio*** (***B***) relates the two physical parameters,

$$B = \frac{Q_h}{Q_e} = \gamma \frac{\Delta T}{\Delta e} \ldots[3.12]$$

where $\boldsymbol{Q_h}$ is the energy available in the water mass as sensible heat (*E/L²-day*), $\boldsymbol{Q_e}$ is the energy used in evaporation (*E/L²-day*), $\boldsymbol{\gamma}$ is the psychrometric constant (*P/°C*), and $\boldsymbol{\Delta T/\Delta e}$ represents the ratio of change in temperature and the saturation vapor pressure at the surface water and in the air (*°C/P*)

Evaporation: Energy Balance Methods

Evaporation: Energy Balance Methods

- The balance of all energy fluxes associated with solar radiation, heat and evaporation results in what is commonly known as the ***Bowen Ratio*** Equation

$$E_B = \frac{R_n - G}{1 + B} \quad \text{...[3.13]}$$

where $\boldsymbol{E_B}$ is the evaporation rate (*L/day*), $\boldsymbol{R_n}$ is the net radiation (*E/L*^{2}*-day*), $\boldsymbol{G}$ is the soil heat flux (*E/L*^{2}*-day*) and $\boldsymbol{B}$ is the Bowen ratio. In order to have consistent units in Eq. 3.12, the energy fluxes $\boldsymbol{R_n}$ and $\boldsymbol{G}$ have to be divided by the mass density of evaporated water, $\boldsymbol{\rho}$ (*M/L*^{3}) and the latent heat of vaporization L_h (*E/M*). Evaluating the psychrometric constant γ in Eq. 3.12 for specific units, B can be evaluated as follows,

$$B = 0.61 \times \frac{p}{1000} \times \frac{(T_{ws} - T_a)}{(e_{ws} - e_a)} \ldots[3.14]$$

where p is the atmospheric pressure (*mb*), T_{ws} and T_a are the water surface and air temperatures (°C), respectively and e_{ws} and e_a are the saturation vapor pressure at water surface temperature and vapor pressure of the air (*mb*), respectively

Evaporation: Energy Balance Methods

Florida Department of Environmental Protection

Questions?

Thank you!