Evaporation:

Engineering Hydrology
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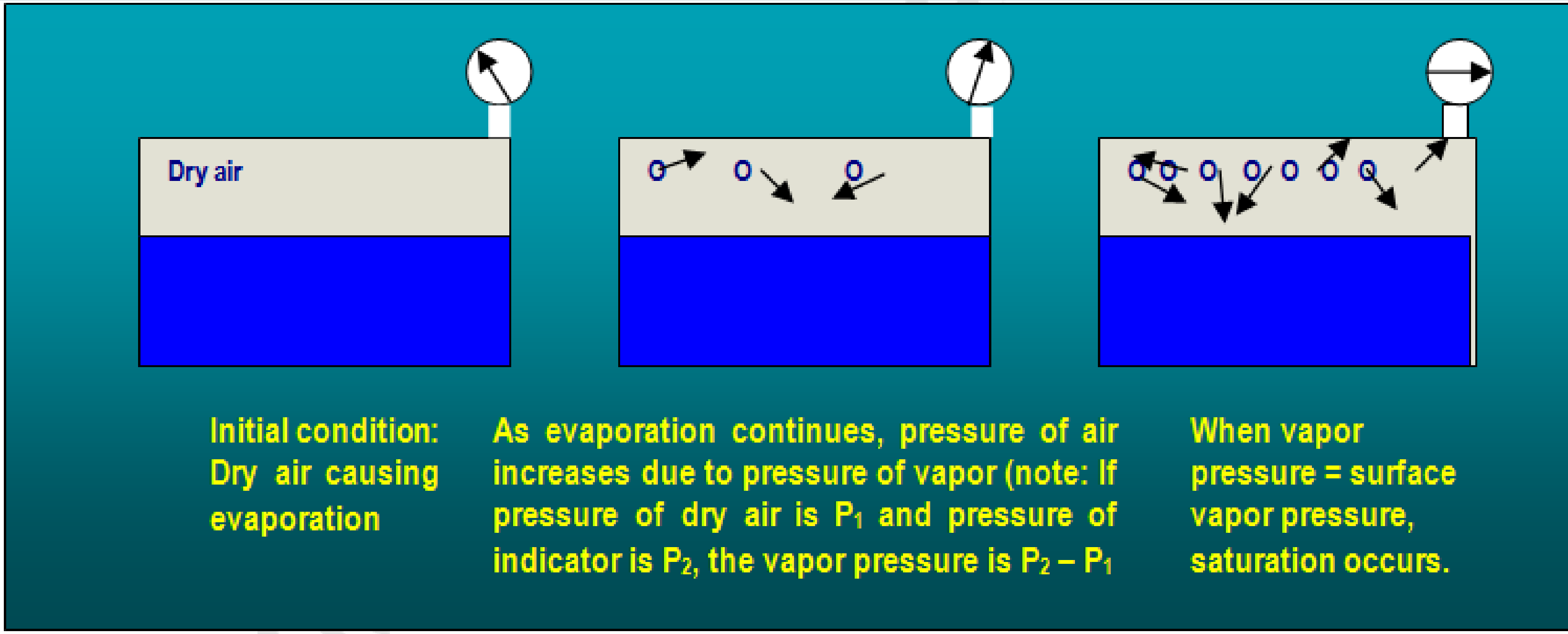
- **Evaporation is the process by which water is transferred from liquid state to gaseous state through transfer of energy. When a sufficient kinetic energy exists on the surface, water molecules can escape to the atmosphere by turbulent air.**

Factors Affecting Evaporation:

- **Temperature**: It is a measure of combined potential and kinetic energy of the body's atom.
- **Humidity and Vapor Pressure**: Water vapor in the air plays an important part in controlling weather patterns and evaporation processes. When the air is dry, evaporation takes place, causing an increase in the quantity of vapor in the air and an increase in vapor pressure. This process will continue until vapor pressure in the air is equal to vapor pressure at the surface. At this point, saturation will occur and further evaporation ceases.



Denoting e as the vapor pressure and e_s as the saturated vapor pressure, the relative humidity is defined as,

$$R = e / e_s$$

Vapor pressure is commonly expressed in bars, where,

1 bar = 10^5 Newtons / square meters (${10}^6$ dynes / cm^2)
1 mb = 1000 dynes / cm^2 = 0.03 Hg

Radiation:

It is the process by which electromagnetic radiation is propagated through free space. The propagation takes place at the speed of light (3.00 x 10^8 m s^{-1} in vacuum) by way of joint (orthogonal) oscillations in the electric and magnetic fields. This process is to be distinguished from other forms of energy transfer such as ;

1. conduction and convection. 2. Propagation of energy by any physical quantity governed by a wave equation.

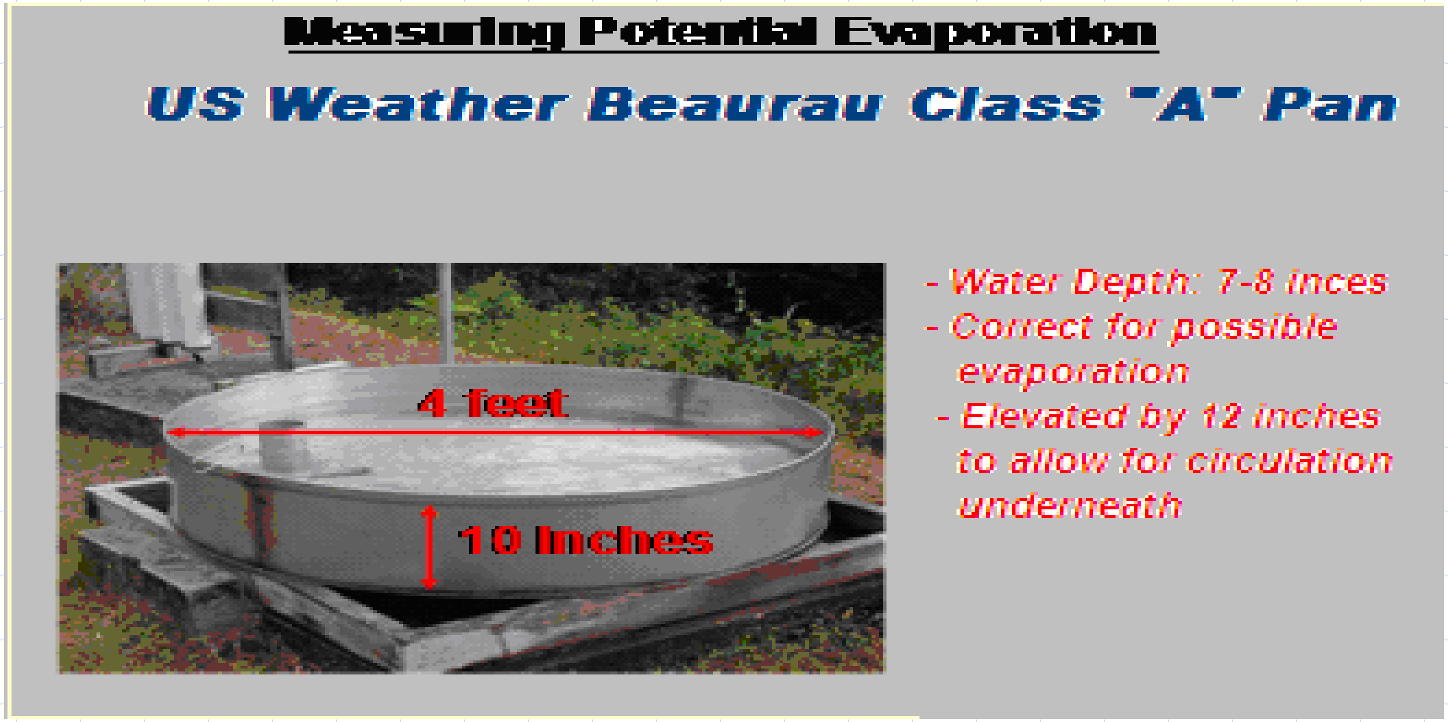
Wind Speed: Wind speed varies with the height above water surface. It can be calculated using the empirical formula,

$$V/V_o = (Z/Z_o)^{0.15}$$

Where V is the wind speed in mi/hr at Z height, V_o is the wind speed at height Z_o measured in ft of the anemometer (instruments designed to measure total wind speed)

Measurement of Evaporation:

a) **Evaporation Pans:** The most popular method of estimating evaporation. The best known is the US Weather Bureau **Class A Pan**



Class A Pan; a cylindrical container fabricated of galvanized iron or other rust-resistant metal with a depth of 25.4 cm (10 in.) and a diameter of 121.9 cm (48 in.). The pan is accurately leveled at a site that is nearly flat, well sodded, and free from obstructions. The water level is maintained at between 5 and 7.5 cm (2 and 3 in.) below the top of the rim, and periodic measurements are made of the changes of the water level with the aid of a hook gauge set in the still well. When the water level drops to 17.8 cm (7 in.), the pan is refilled. Its average pan coefficient is about 0.7.

b) Empirical Formulas:

Using mass transfer, evaporation takes the following general form:

$$E = K\, f(u)(e_s - e_a)$$

Where K is constant, f(u) is a function of wind speed at a given height, e is the actual vapor pressure at a given height, and e_s is the saturated vapor pressure at water surface,

The rate of evaporation from a lake can be calculated using empirical laws,

$$E = C\,(e_s - e)\,(1 + W/10)$$ .... Meyer (1944)

Where, E: Lake evaporation (inches / day)

$e_s - e$: Water vapor deficit (difference between saturated vapor pressur and actual vapor pressure of atmosphere in-Hg)

C: Constant (0.36 for open water, 0.5 for wet soil)

W: Wind Speed 25 ft above water level (mph)

$$E = (0.013 + 0.00016\, u_2)\, e\, [(100 - R_h) / 100]$$ .... Dunne ((1978)

Where, R_h: The relative humidity in %

e: Vapor pressure of air (mill bars)

u_2: Wind speed 2 m above water in km/day

TABLE A.2 Properties of Water

Traditional U.S. Units

Temperature (°F)	Specific gravity	Unit weight (lb/ft^3)	Heat of vaporization (Btu/lb)	Kinematic viscosity (ft^2/sec)	Vapor pressure mb	Vapor pressure psi	Vapor pressure in. Hg
32	0.99987	62.416	1073	1.93×10^{-5}	6.11	0.09	0.18
40	0.99999	62.423	1066	1.67×10^{-5}	8.36	0.12	0.25
50	0.99975	62.408	1059	1.41×10^{-5}	12.19	0.18	0.36
60	0.99907	62.366	1054	1.21×10^{-5}	17.51	0.26	0.52
70	0.99802	62.300	1049	1.06×10^{-5}	24.79	0.36	0.74
80	0.99669	62.217	1044	0.929×10^{-5}	34.61	0.51	1.03
90	0.99510	62.118	1039	0.828×10^{-5}	47.68	0.70	1.42
100	0.99318	61.998	1033	0.741×10^{-5}	64.88	0.95	1.94

SI Units

Temperature (°C)	Specific gravity	Density (g/cm^3)	Heat of vaporization (cal/g)	Kinematic viscosity (cs)	Vapor pressure (mm Hg)	Vapor pressure (mb)	Vapor pressure (g/cm^2)
0	0.99987	0.99984	597.3	1.790	4.58	6.11	6.23
5	0.99999	0.99996	594.5	1.520	6.54	8.72	8.89
10	0.99973	0.99970	591.7	1.310	9.20	12.27	12.51
15	0.99913	0.99910	588.9	1.140	12.78	17.04	17.38
20	0.99824	0.99821	586.0	1.000	17.53	23.37	23.83
25	0.99708	0.99705	583.2	0.893	23.76	31.67	32.30
30	0.99568	0.99565	580.4	0.801	31.83	42.43	43.27
35	0.99407	0.99404	577.6	0.723	42.18	56.24	57.34
40	0.99225	0.99222	574.7	0.658	55.34	73.78	75.23
50	0.98807	0.98804	569.0	0.554	92.56	123.40	125.83
60	0.98323	0.98320	563.2	0.474	149.46	199.26	203.19
70	0.97780	0.97777	557.4	0.413	233.79	311.69	317.84
80	0.97182	0.97179	551.4	0.365	355.28	473.67	483.01
90	0.96534	0.96531	545.3	0.326	525.89	701.13	714.95
100	0.95839	0.95836	539.1	0.294	760.00	1013.25	1033.23

Illustrative Example:

Use Meyer formula and Dunn formula to find the lake evaporation for a lake with mean value of air temperature is 87 F, and for water temperature is 63 F, average wind speed is 10 mph and relative humidity is 20%.

Solution:

-Using Meyer formula: From table, the saturated vapor pressure, e_s (@63°F= air temp) = 0.58 in. Hg
e_s (@87°F = water temp) = 1.29 in. Hg

$$E = C\,(e_s - e)\,(1 + W/10)$$

e = 1.29 x 0.20 = 0.26 in Hg / (0.03 Hg/mb) = 8.7 mb

For open water, C = 0.36 then E = 0.36 (0.58 – 0.26) [1+10/10 = 0.23 in/day

-Using Dunne's formula:

$$E = (0.013 + 0.00016\,u_2)\,e\,[(100 - R_h)\,/\,100]$$

Converting wind speed to km/day = (10 mph) (24hr/d) (1.6 km/mi) = 384 km/d

E = [0.013 + (0.00016 x 384)] (8.7) [(100-20)/100]

= 0.518 cm/day or = 0.204 in/day which is comparable to the previous value.

Author	Equation	Explanation
Dalton	E (i/mo) = $C(e_0-e_a)$	C=15 for small, shallow water and 11 for large deep water
Meyer	E (i/mo) = $11\ (1+0.1\ u_g)\ (e_0-e_a)$	e_a measured 30 above ground surface
Horton	E (i/mo) = $0.4\ [2 - \exp(-2u)])\ (e_0-e_a)$	u = speed of wind
Penman	E (i/day) = $0.35\ (1+0.24\ u_2)\ (e_0-e_a)$	u_2 = wind speed 2 meters above surface
Harbeck	E(i/day)=$0.001813\ u\ (e_0-e_a)[1-0.03(T_a-T_w)]$	T_a = Average Temp ^{0}C + 1.9^{0}C T_W = Average water surface temperature

Coaxial Chart: Penman (1948)

Penman developed an equation based on aerodynamic and energy balance equations for daily evaporation E and later Kohler (1955) developed an expression for lake evaporation in inches per day that is based on Penman's theory, If E_L designates average daily lake evaporation (in/day), then,

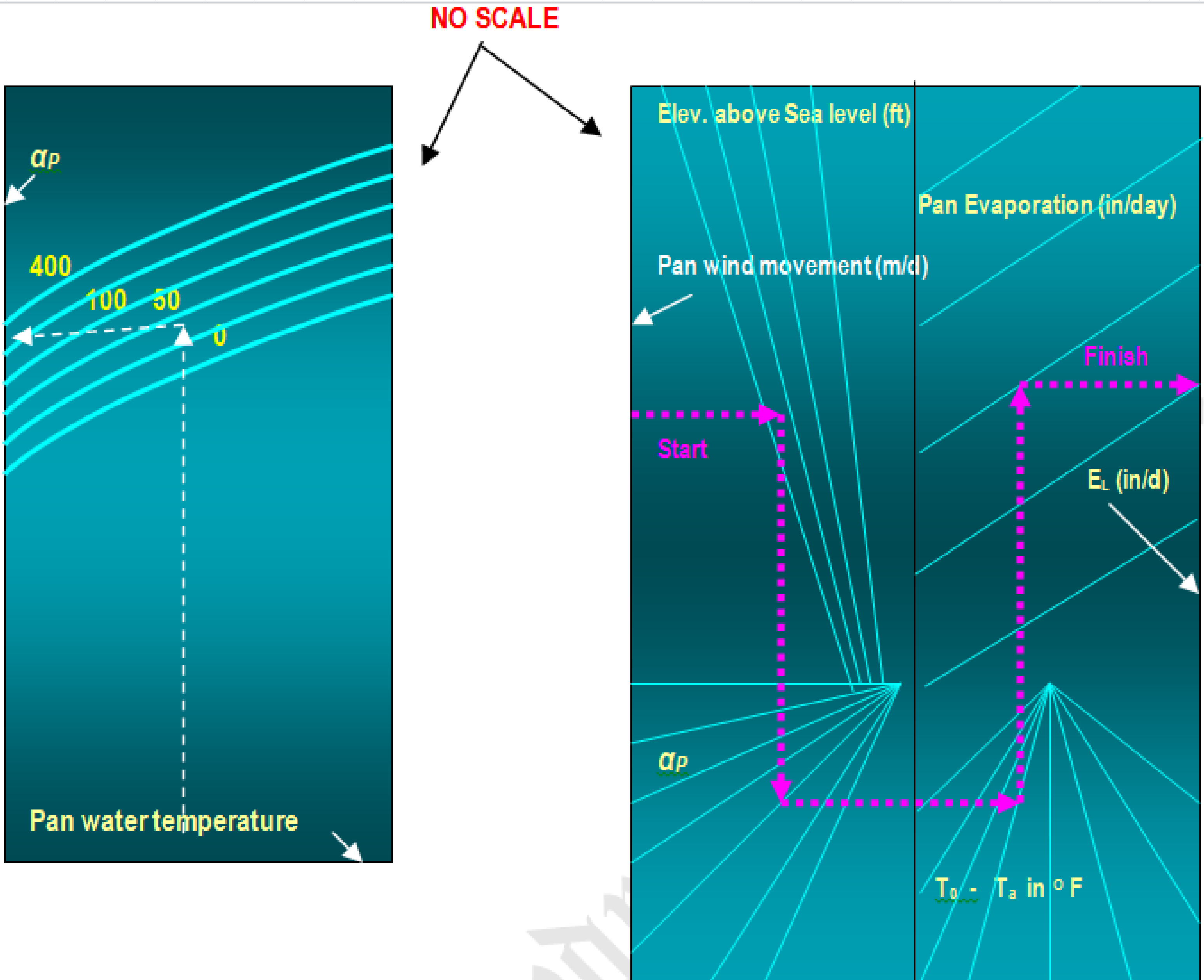
$$E_L = 0.7\,[E_P + 0.00051\,P\,\alpha_P\,(0.37 + 0.0041\,u_P)\,(T_0 - T_a)^{0.88}$$

- E_L → Lake Evap. in/day
- T_0 Outer face Temp of pan ^{o}F
- T_a Air Temp. in ^{o} F
- u_P → Windspeed in mi/day
- α_P → Advected Energy (For given Temp & wind speed ,use chart to obtain α_P)
- P → Atmospheric pressure in in-Hg

$$\alpha_P = 0.13 + 0.0065T_0 - (6.0 \times 10^{-8}\,T_0^3) + 0.016\,u_P^{0.36}$$ (Use Chart below to obtain α_P)

Steps of Using the Coaxial Chart:

- *From pan water temperature (measured in °F) and pan wind speed (measured mi/day), use chart A to obtain α_P.*
- *From wind speed u_P start at the upper left hand of the coaxial chart (chart B) to the elevation (in feet) above mean sea level.*
- *Turn right to the value of α_P in the lower left chart.*
- *Turn left to the value of $(T_0 - T_a)$ in the lower right chart.*
- *Turn left to pan evaporation in the upper right chart.*
- *Turn right to read lake evaporation.*


NO SCALE
αp
400
100
50
0
Pan water temperature
Elev. above Sea level (ft)
Pan Evaporation (in/day)
Pan wind movement (m/d)
Finish
Start
E_L (in/d)
αp
T_0 - T_a in °F