

Water Evaporation in Areas of High Aridity

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ABSTRACT

This study was conducted to estimate the evaporation rate in an arid region; namely the Dead Sea. Estimation of evaporation helps in planning, operation and management of water resources. Direct measurement of evaporation rates on daily basis extended for one year. Daily energy-budget and Penman's evaporation rates were determined from available data to quantify evaporation rates and to assess the assumptions associated with Penman's method for use in an area characterized as arid. An attempt was made to correlate the evaporation rate with the meteorological data affecting it. A procedure was developed and found suitable for calculating the evaporation rate from the sea site and other similar regions of high aridity.

KEYWORDS: Water evaporation, Highly arid regions, Dead Sea.

INTRODUCTION

The determination of evaporation helps in planning, operation and management of water resources. Penman presented a theory for the estimation of evaporation using climatological data. The coefficients in Penman's theory were determined for a humid area; thus the formula applies best for areas under similar conditions.

In this study, an attempt is made to improve the accuracy of the evaporation equation, using coefficients to suit an area of high aridity. The Dead Sea area was chosen as a study area. Evaporation from class-A pans was recorded over a study period of one year.

Evaporation rates using Penman's equation were calculated, in addition to the rates using the new coefficients.

As compared with the actual measured data from class-A pans, the results of the improved equation proved to be good, and the coefficients included may be used for the determination of evaporation rates from

areas of high aridity.

The important role played by evaporation in the hydrological cycle means that attempts are continuously being made to improve the accuracy of its estimation and measurement.

Many of the formulae developed for estimating evaporation are based on Dalton's fundamental law. It states that if the actual vapor pressure of air above a water surface is less than the actual vapor pressure at the water surface, evaporation will take place.

Some of the methods used for evaporation determination are:

Water Balance Method

The input and output streams of the area account for the accumulation term in the water mass balance equation. This accumulation term may be considered zero or negligible over short or very long periods of time. Consequently, evaporation is calculated from the residual term in the water mass balance equation.

The water balance equation is generally written as:

$$E = P + I \pm U - O \pm S \quad \dots(1)$$

where:

E = Evaporation and transpiration (Evapotranspiration).

P = Total precipitation.

I = Surface inflow.

U = Underground outflow.

O = Surface outflow.

S = Change in storage contents.

The instruments and computational methods are described in detail in a report by the World Meteorological Organization.

Energy Balance Method

The evaporation rate is calculated from the energy utilized for evaporation and the latent heat of vaporization.

The energy conservation formulation around a solar evaporation system is given by:

$$Q_e + Q_w + Q_c = Q_s (1-r_s) - Q_f - Q_b + Q_g + Q_v \quad \dots (2)$$

where:

Q_e = Heat lost by evaporation.

Q_w = Heat advected by the mass of evaporated water.

Q_c = Heat lost by conduction.

Q_s = Heat of insulation

r_s = Reflected fraction of insulation.

Q_f = Change in heat storage of the water body.

Q_b = Effective bank radiation.

Q_g = Heat conducted from the bed.

Q_v = Heat advected in by streams, springs and underground seepage.

A complete description of each term is given by Anderson, as cited by Ferguson and Znamensky.

The energy balance method is usually denoted by a special approach since it can't be used without many special data concerning the water basin.

Penman's Theory

Penman presented a theory for the estimation of evaporation using climatological data. The theory is based on two requirements that must be met if continuous evaporation is to take place.

The first requirement is that there must be a supply

of energy to provide the latent heat of vaporization. The second requirement is that there must be a mechanism to remove the water vapor once produced.

The principal limitation of Penman's approach is the lack of sufficient weather measurements in most locations. In addition, the coefficients in Penman's theory were determined for a humid area; thus his formula applies better under similar conditions than in arid regions with low humidity.

Empirical Formulae

It was found that evaporation estimation derived from theoretical basis is complex. The parameters required are not directly measured. Therefore, several empirical formulae were developed. The statistically evaluated coefficients yield good results when applied to specific conditions. In case of application to areas with different boundary conditions, the use of these equations is questionable. Empirical formulae were given by Priestley Taylor, Kimberly Penman, Penman Montieth and Hargreaves, as cited by Weib and Menzel (2008), and others.

Direct Measurements

Standard measuring pans have been developed for direct measurement of evaporation. These pans measure evaporation under the same prevailing conditions of the evaporating water body. The rate of evaporation measured using these pans is not equal to the rate of evaporation from large free surfaces; thus correction factors are usually presented to estimate the correct rate of evaporation.

Study Area

The Dead Sea is part of the geomorphologic depression extending from east Africa through the Red Sea to the Turkish borders. It is situated in the deepest part of the Jordan Rift Valley between 31°4' to 31°46' N and 35°22' to 35°53' E. The water surface is about 400m below mean sea level. The Dead Sea surface area is about 800km². It reaches a maximum depth of about 330m.

The Dead Sea is a huge mineral lake due to the extremely high salinity of its water. It is used for the production of potash and other mineral salts.

The Dead Sea area is highly arid with temperatures rising in August to reach a daily average of 40°C and dropping to a minimum of 10°C in winter.

The average rainfall is 65mm/year and the relative humidity ranges between 57% in January and 27% in July.

The surrounding area is mountainous with shallow or lacking soil cover. There is no vegetation.

Experimental Set-up

For direct measurement of evaporation rates, Arab Potash Company site was selected. Evaporation pans were situated at 31° 10' N and 35° 32' E. The experimental site is flat. The Arab Potash Company uses this site as an experimental station.

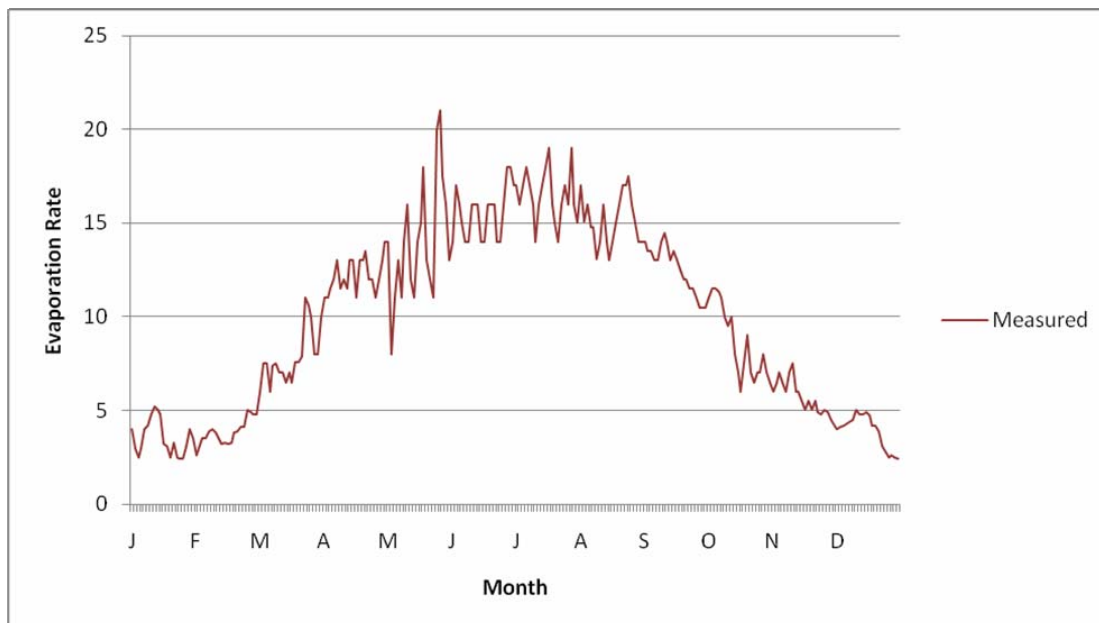


Figure 1: Measured evaporation rate during a year

USA standard A-pans were used to measure the evaporation rate. The pans are 1.22 m-diameter circular pans having a depth of 254mm. They are made of stainless steel and painted with black color to make them similar to the water body in absorption of temperature and radiation as well as to prevent erosion.

Other instruments were used such as thermometers, hydrometers, anemometer and radiometers. The sunshine hours were also measured.

Meteorological observations on daily basis at the experimental site extended for one year. The observations included temperature, relative humidity, sunshine hours and incoming short-wave radiation in

addition to evaporation from A-pans.

RESULTS AND DISCUSSION

Evaporation rate tends to fluctuate around a relatively high value during summer, and then decreases reaching a minimum value in January.

This trend is coincident with the average daily temperature and other weather conditions, especially wind velocity and relative humidity.

Actual evaporation rate fluctuation is shown in Fig. (1).

A comparison between Penman's method and pan

observations (after considering a pan coefficient of 0.75) showed that there is a big difference between the calculated and observed values in the dry season, while the difference diminishes in the wet season.

This difference is due to the high aridity of the Dead Sea area. An important climatological characteristic of the area is the absence of dependable rainfall. The mean annual rainfall in the area is 72mm, maximum and

minimum values are 152mm and 18mm, respectively. The relative humidity is 57% in January and 27% in June and July. The soil coverage is very shallow and there is no vegetation. Penman's approach for the determination of evapotranspiration was derived for humid well vegetated regions; thus it applies best for areas of similar conditions.

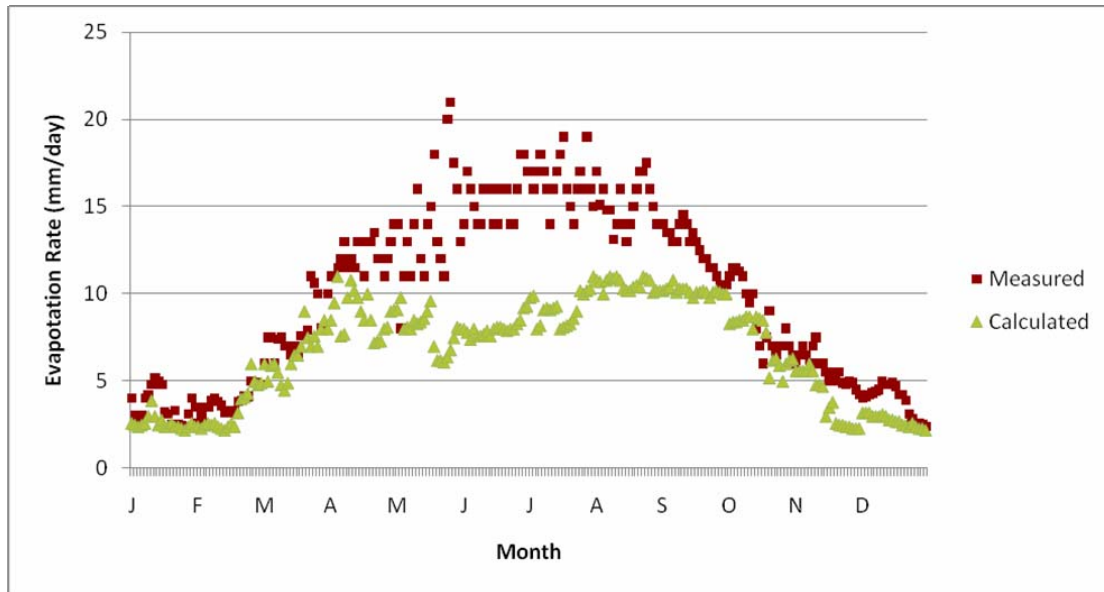


Figure 2: Measured and calculated evaporation rates according to Penman

To predict the evaporation rate equation following Penman's approach for the Dead Sea area and other similar arid regions, the following procedure was adopted:

- 1- The values of R_C/R_A are calculated as a function of the sunshine hours ratio (n/d). The following regression is obtained:

$$R_C = R_A (0.371 + 0.624 n/d) \quad \dots (3)$$

where

R_C = Sun and sky radiation actually received at earth's surface on a clear day.

R_A = Angot's value of solar radiation arriving at the atmosphere.

- 2- The value of R_1 , which is the net amount of radiation absorbed at surface after reflection, is considered as:

$$R_1 = R_C (1-r) \quad \dots (4)$$

where r is the reflection coefficient taken to be 0.06 in the present study, so:

$$R_1 = 0.94 R_C \quad \dots (5)$$

- 3- The value of R_B which is the long wave radiation from the earth surface is taken to be:

$$R_B = \sigma T_a^4 (0.47 - 0.077 e^{0.5}) (0.2 + 0.8n/d) \quad \dots (6)$$

where:

σ = Lummer and Pringsheim constant
 = 117.74×10^{-9} g. cal/cm²/day.

T_a = Absolute temperature.

e = Actual vapor pressure of air in mm Hg.

The net amount of energy finally remaining at the water free surface is given by H in the form:

$$H = R_I - R_B \quad \dots (7)$$

$$H = R_A (0.371 + 0.624n/d) (1 - 0.06) - (117.74 \times 10^{-9}) (T_a^4) (0.47 - 0.077e^{0.5}) (0.2 + 0.8n/d) \quad \dots (8)$$

The value of H is converted heat to evaporation rate in mm/day by dividing it by (a), where:

$$a = 60.65 - 0.0695t \quad \dots (9)$$

where t is the average daily temperature in °C.

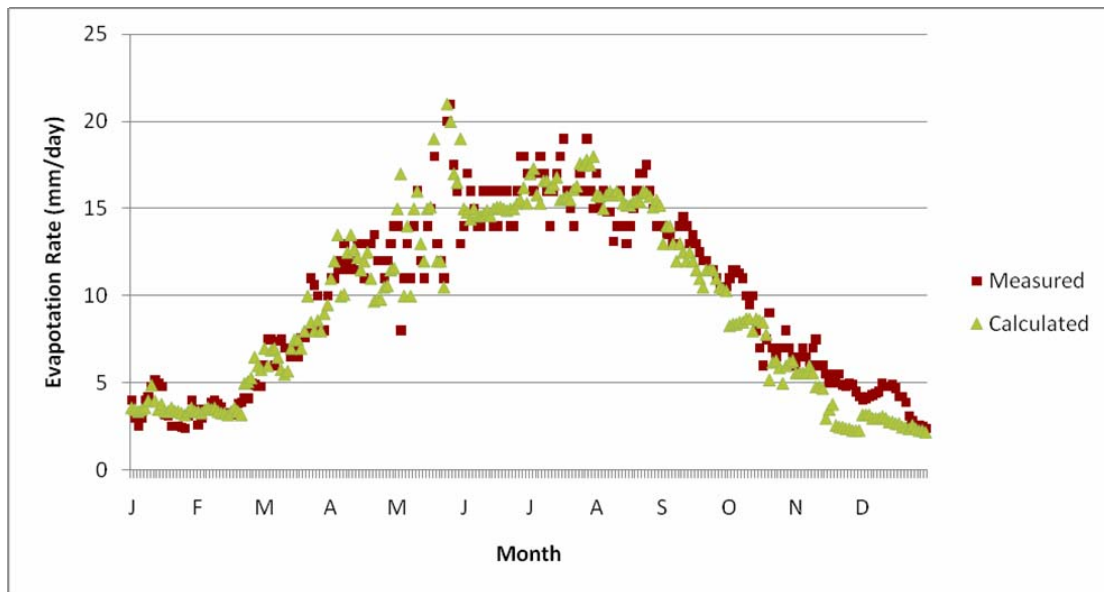


Figure 3: Measured and calculated evaporation rates

4- By simple regression, the equations for the hypothetical case of equal temperatures of air and water are obtained in the form:

$$E_a = 0.35 e_s (1 - h) (0.985 + 0.262 U_2) \quad \text{for } t \leq 20^\circ\text{C}. \quad \dots(10)$$

$$E_a = 0.35 e_s (1 - h) (1.790 + 0.417 U_2) \quad \text{for } t \leq 30^\circ\text{C}. \quad \dots (11)$$

$$E_a = 0.35 e_s (1 - h) (2.980 + 0.875 U_2) \quad \text{for } t > 30^\circ\text{C}. \quad \dots(12)$$

where:

E_a = Open water evaporation per unit volume for the same air and water temperature in mm / day.

e_s = Saturation vapor pressure of air at t °C.

U₂ = Wind speed at a standard height of 2 meters, in m/sec.

h = Relative humidity.

5- The net heat evaluated to remain at a free water surface is used up in four ways:

$$H = E_o + K + S + C \quad \dots (13)$$

where:

E_o = Heat available for evaporation from open water surface.

K = Convective heat transfer from the surface.

S = Increase in heat of the water mass.

C = Increase in heat of the environment.

The last two terms are considered negligible; thus the above equation reduces to:

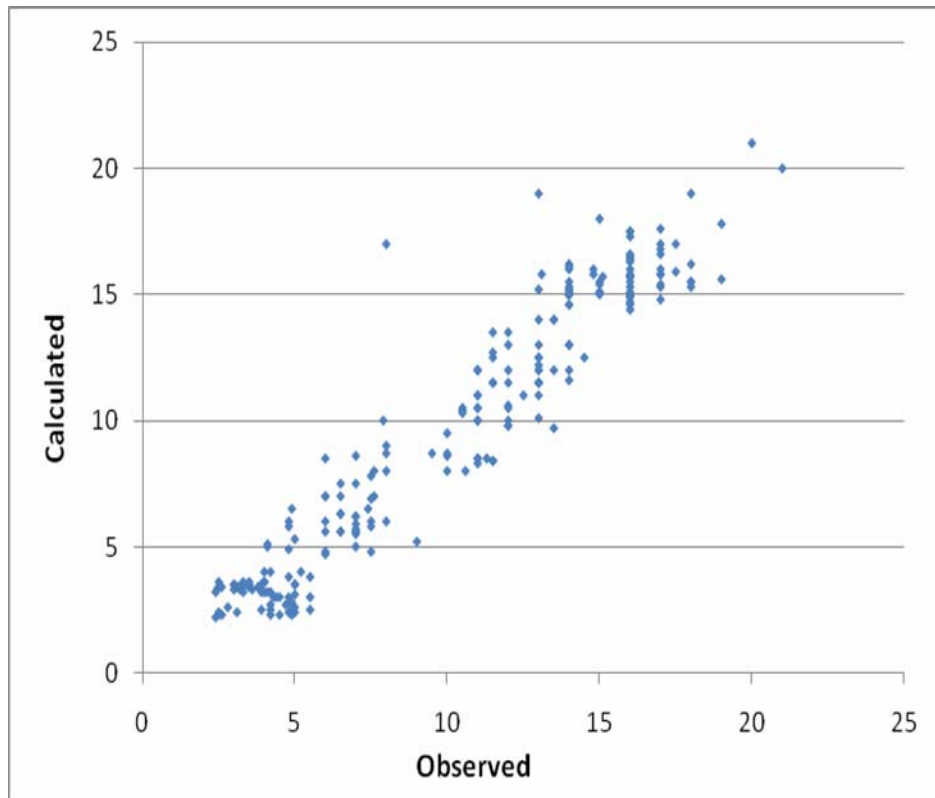


Figure 4: Measured versus calculated evaporation rates

Table 1. Comparison of average annual measured pan evaporation rates versus calculated potential evapotranspiration and percentage deviation of calculated value from measured value

Method	Annual Evaporation Rate	Percentage Error
Corrected Pan Evaporation	2539	-
Present Approach	2411	-5.0
Penman	1216	-52.1
Priestley Taylor	1787	-29.6
Penman Monteith	2024	-20.3
Kimberly Penman	2049	-19.3
Hargreaves	2371	-6.6

$$H = E_o + K. \quad \dots (14)$$

Penman assumed that the transport of vapor and the transport of heat by eddy diffusion are essentially controlled by the same mechanism; that is, atmospheric turbulence, the one being governed by $(e_s - e)$, the other by $(t_s - t)$.

Adopting the same assumptions, we obtain:

$$E_o = \frac{\Delta H + \gamma E_\infty}{\Delta + \gamma} \quad \dots (15)$$

where:

γ = Psychrometer constant = 0.485.

Δ = Slope of vapor pressure curve at t having a value obtained from the saturation pressure curve.

Thus, evaporation may be calculated with the aid of this procedure, where:

$$E_o = \Phi (t, h, U_2, n/d, R_A) \quad \dots (16)$$

Using this approach, the calculated evaporation rates and the measured ones for the experimental period are plotted in Fig. (3).

From Fig. (3), it is noted that the difference between the calculated and the measured values is very small. The percentage error using Penman's equation between the measured and calculated evaporation rates reached 52%, particularly in the dry season, while the error was reduced to 5% after using coefficients to suit the area.

Figure 4 shows the measured *versus* calculated evaporation rates using the aforementioned method. The correlation factor is 0.957, which shows a close agreement between the measured and the calculated values.

In comparison of different potential evapotranspiration equations, Table 1 gives a summary of the results.

All the calculated values stay below the measured values. Compared to the corrected pan measurements,

the recent study gave the best results with an average deviation of -5%. The second closest calculation was obtained with Hargreaves with an average deviation of -6.6%, while Penman showed a deviation of -52.1%.

CONCLUSION

Some difficulties appear in applying the methods of evaporation determination on evaporation from the Dead Sea surface.

These difficulties can be attributed either to the lack of data concerning Dead Sea balance or to the high aridity of the area.

In this study, direct measurement of evaporation at the site is used. An attempt is made to correlate evaporation rate with the meteorological data affecting the evaporation rate.

A close agreement of results is indicated, which emphasizes the validity of the present procedure for the evaluation of evaporation rates in regions of high aridity.

REFERENCES

- Eichinger, W.E. et al. 2003. Lake evaporation in arid environments. *Hydro Science and Engineering*.
- Einacre, E.T. 1993. Data sparse estimation of lake evaporation using a simplified Penman equation. *Agriculture and Forest Meteorology*.
- Ferguson, H.I. and Znamensky, V.A. 1981. Methods of computation of the water balance of large lakes and reservoirs, UNESCO, 19-66.
- Haque, A. 2002. Estimating actual areal evapotranspiration from potential evapotranspiration using physical models based on complementary relationships and meteorological data, *Bull. Eng. Geol. Env.* (2003), 57-63.
- Hargreaves, G.H. and Allen, R.G. 2003. History and evaluation of the Hargreaves evapotranspiration equation. *Journal of Irrigation and Drainage Engineering*, 129 (1): 53-63.
- Houghton, S.S. 1985. Handbook of applied meteorology, John Wiley, Canada, 550-560.
- Jacobs International, INC. 1979. Hydrology of the Dead Sea. Arab Potash Company.
- Measurement and estimation of evaporation in nature, Technical Note # 83, WMO, No.201. 1971.
- Morton, F.I. 1975. Estimating evaporation and transpiration from climatological observations. *J. App. Meteorol.*, 14 (4): 488-497.
- Penman, H.L. 1948. Evaporation in Nature, Proc. R. Soc., London, Ser.A.193, 366-388.
- Penman, H.L. 1948. Natural evaporation from open water, bare soil and grass, Proc. R. Soc., London, 120-146.
- Priestley, C.B. and Taylor, R.J. 1972. On the assessment of surface heat flux and evaporation using large scale parameters. *Monthly Weather Review*, 100: 81-92.
- Shuttleworth, W.J. 1993. Evaporation. Ch.4. Handbook of

hydrology. McGraw Hill.

Smith, K. 1964. A long period assessment of the Penman and Thornthwaite "*potential evaporation formulae*". *J. of Hydrology*, 2: 277-290.

Subramanya, K. 1984. Engineering hydrology, McGraw

Hill, New Delhi, 48-69.

Weib, M. and Menzel, L. 2008. A global comparison of four potential evapotranspiration equations and their relevance to stream flow modeling in semi-arid environments. *Advances in Geosciences*, 18: 15-23.