

## **Comparison of Several Evaporation Models Applied to Reservoir of the Saveh Dam, Iran**

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### **Abstract**

Knowing the rate of evaporation from surface water resources such as channels and reservoirs is essential for precise management of the water balance. However, evaporation is difficult to measure experimentally over water surfaces; several techniques and models have been suggested and used in the past for its determination. Few detailed evaporation studies exist for small lakes or reservoirs in arid regions of the world. In this study, monthly water balance evaporation values were for Saveh Lake(Iran) from 1995-2008 compared with class-A pan and pan coefficient was determined for study site. Daily data were obtained from IMO(Iran Meteorological Organization) weather station, located near the lake, for all of these years.. For all the years, evaporation rates were low in Winter and Fall and highest during the summer. However, the times and month of highest evaporation rates varied during the study period. For each method, evaporation rates determined using several alternate evaporation methods during the 14 years were compared with values from the Bowen-Ratio Energy-Budget(BREB) method, considered as standard. Values from the DeBruin, Priestley–Taylor, DeBruin–Keijman, and Penman methods compared most favorably with BREB-determined values. Differences from BREB values averaged 0.53, 0.17, 0.42, and 0.28 mm.d-1, respectively, and results were within 20% of BREB values during more than 94% of the monthly comparison periods for three last methods. All four methods require measurement of net radiation, air temperature, change in heat stored in the lake(thermal survey), and vapor pressure, making them relatively data intensive. Methods that rely only on measurement of air temperature, such as Pabadakis was relatively cost-effective options for measuring evaporation at this small lake; outperforming some methods that require measurement of a greater number of variables. Also, based on the BREB results, the mass transfer method coefficient was modified.

**Keywords:** Free Water Evaporation, Saveh Lake, methods Comparison.

## Introduction

Water scarcity occurs where there are insufficient water resources to satisfy long-term average requirements. It refers to long-term water imbalances, combining low water availability with a level of water demand exceeding the supply capacity of the natural system. Although water scarcity often happens in areas with low rainfall, human activities add to the problems in particular in areas with high population density, tourist inflow, intensive agriculture and water demanding industries. Losses of water in the supply network and from water reservoirs are often substantial in several water scarce regions in the world. For example in France and Spain as much as 30 % and 24%-34 % of water is lost before it reaches the consumer. In the future, it is likely that predicted climate change will exacerbate this situation in the most water scarce parts of the world. A combination of less precipitation and higher temperatures will further reduce the amount of water available and economic impacts may be high and affect several sectors. Low water availability and droughts have severe consequences on most sectors, particularly agriculture, forestry, energy, and drinking water providers. Activities that depend on high water abstraction and use, such as irrigated agriculture, hydropower generation and use of cooling water, will be affected by changed flow regimes and reduced annual water availability.

Evaporation estimates are needed in a wide array of problems in hydrology, agronomy, forestry and land resources planning, such as water balance computation, irrigation management, river flow forecasting, investigation of lake chemistry, ecosystem modeling, etc. Of all the components of the hydrological cycle, evaporation is perhaps the most difficult to estimate owing to complex interactions between the components of the land-plant-atmosphere system(Singh et al., 1997).

Also, Evaporation from Lakes and reservoirs is an essential factor in its water budget and one of the prime causes of the salinity variation and water losses. Estimates of evaporation from open water are increasingly required for several Environment Agency functions, particularly Water Resources and Ecology. Current methods of estimating open water evaporation vary between and, in some cases, within Regions; there is no generally adopted best method. In addition, there is often a mismatch between the accuracy of estimates produced by current methods (they are generally crude and subject to large uncertainties) and their significance in the calculations that are used as a basis for decision making.

Studies of open-water evaporation from fresh-water systems are biased toward the larger end of the size spectrum. Most have been conducted for reservoirs and larger lakes and relatively few have been conducted for smaller lakes and ponds. Most lakes, ponds, and wetlands are focal points for the hydrologic processes that occur over their drainage basins and in many parts of the world, where fresh-water resources are becoming limited, water managers need to quantify these hydrologic fluxes for increasingly smaller water bodies(Rosenberry et al, 2007).

Evaporation constitutes the dominant water loss from many free water surfaces. More recently, interest in lake evaporation has been spurred by a wide variety of research and management needs. For example, there is great interest in quantifying water budgets (of which evaporation is often a major component) of lakes in order to determine watershed water usage

requirements and hydrological regimes (Rosenberry and Winter, 1997). In addition, free water surfaces evaporation estimates are required for modeling regional groundwater flow and contaminant transport as well as global climate change (e.g. Restrepo et al., 1998; Sun et al., 1998; Bartlett et al., 2002). Open water areas in wetlands may vary in depth, expanse and duration depending on hydroperiod, climate, hydrogeomorphological setting and microtopography. The characteristics of open water areas that affect evaporation include depth of water, whether water is standing or flowing and water temperature. These factors influence how much energy the water will ultimately absorb, which in turn affects how much energy is subsequently available for evaporation. In addition to depth, water quality may also affect evaporation. For example, as salinity increases, evaporation rates decrease as a result of a reduction in the saturated vapor pressure (Oroud, 1995).

The methods for determining evaporation can be grouped into several categories, including: (i) empirical (e.g. Kohler et al., 1995), (ii) water budget (e.g. Guitjens, 1982), (iii) energy budget (e.g. Fritschen, 1966), (iv) mass transfer (e.g. Harbeck, 1962), (v) combination (e.g. Penman, 1948) and (vi) measurement (e.g. Young, 1947).

It is difficult to select the most appropriate evaporation measurement methods for a given study. This is partly because of the availability of many equations for determining evaporation, the wide range of data types needed and the wide range of expertise needed to use the various equations correctly. More importantly, objective criteria for model selection are lacking. Consequently, the conditions under which one evaporation method would be more suitable are not always spelled out (Singh et al., 1997).

The most common methods for measuring evaporation free water surfaces are the Bowen ratio energy balance (BREB) and eddy covariance (EC) methods. Although less commonly used, the surface renewal (SR) and LIDAR methods show some promise for improving evaporation measurements. Each of these methods has advantages and disadvantages. A common assumption in using these methods is that there is adequate 'fetch' (i.e. upwind distance having uniform features) required to ensure that the measurement is representative of the underlying surface and not contaminated by the flux from a distant surface. Because stability changes over the day, the fetch requirements also change. During daylight hours, when there is less stability and more turbulence, the fetch requirement is less than at night when the atmosphere is more stable (Drexler et al, 2004).

When using a BREB system, the surface is assumed to be horizontally homogeneous, resulting in only vertical energy transport. For free water surfaces we have this condition. The surface heat balance of a lake is governed by short-wave and long-wave radiations, latent heat and sensible heat flux, and by energy associated with the inflows and outflows (Henderson-Sellers 1986). In this study various terms of heat balance were measured either directly or by evaluating empirical formulations from the available data.

#### Study Area and climatic setting

Saveh Lake is situated in the Vaforghan Valley, about 150 Km southwest of the of the Tehran city on the Ghare-Chai river (Fig. 1). The lake is about 9 km<sup>2</sup> in area and is at an elevation of 1080 m above mean sea level.

One medium stream drain into the lake and a dam controls the outlet and maintains the lake at a higher and more stable stage than would naturally occur. More water flows from the lake to ground water than leaves the lake via the surface-water outlet. Annual precipitation(1995–2008) averages 230 mm. Average monthly temperature(1995–2008) ranges from 30 °C during July to 4.9 °C during January.

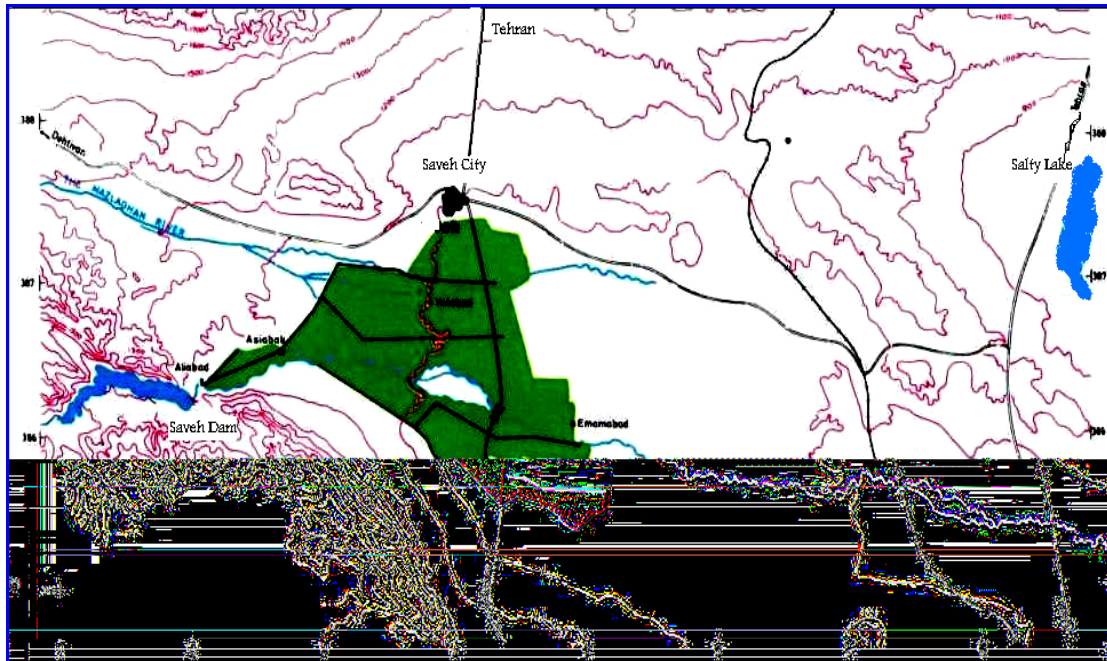


Figure 1 Location of Saveh Lake, including Agricultural supported Area and major physical features of the Lake drainage basin.

### Purpose of the study

The water budget modeling is an important primary task in hydrologic studies of lakes and reservoirs. With the aid of the water budget equation, one can calculate the amount of free surface water evaporation(Schindler, 2001). This method was used to determine evaporation from the Saveh Reservoir in Markazi region, center of Iran. A detailed investigation showed that daily water budget survey is not appropriate because of extreme fluctuation of water surface. Therefore, monthly time steps were selected to form the water budget equations. The water budget equation was used to calculate pan coefficient. A regression model was formed to determine the coefficients. In this study several methods of evaporation determination applied for a small lake in arid region of Iran and results compared with BREB, as a standard method.

### Methods and models

#### The bowen Ratio Energy budget method for evaporation estimation

All of the evaporation measurement methods ultimately are based on the energy balance equation, which accounts for all the sources and losses of energy that are available for vaporizing water. The BREB method for calculating Open-water evaporation, which relates net transfer of energy into

and out of the water body to changes in energy storage can be stated as(Bowie et al., 1985):

$$Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} + Q_v - Q_e - Q_h - Q_w + Q_b = Q_x \quad (1)$$

where:

- $Q_s$  incoming short-wave radiation;
- $Q_r$  reflected short-wave radiation;
- $Q_a$  incoming long-wave radiation;
- $Q_{ar}$  reflected long-wave radiation;
- $Q_{bs}$  long-wave radiation emitted from the body of water;
- $Q_v$  net energy advected to the body of water;
- $Q_e$  energy used for evaporation;
- $Q_h$  energy conducted from the water as sensible heat;
- $Q_w$  energy advected from the body of water by the evaporated water;
- $Q_b$  heat transfer to the water from the bottom sediments;
- $Q_x$  change in energy content of the body of water.

All terms are expressed in watts per square meter( $w.m^{-2}$ ). Moreover, exchanges of energy occur through precipitation, withdrawal of evaporated water, chemical and biological reactions in the water body, conversion of kinetic to thermal energy. These energy fluxes are small enough to be omitted. In many cases, and especially in large and deep lakes, the components  $Q_v$  and  $Q_b$  are enough small to be neglected. Many researchers agree that omitting the energy budget components with small values does not significantly affect the results(Bolsenga, 1975, Myrup et al., 1979, Stauffer, 1991, Sturrock et al., 1992, Sacks et al., 1994, dos Reis and Dias, 1998 and Winter et al., 2003). In this case, equation(1) takes the following form:

$$Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} - Q_e - Q_h - Q_w = Q_x \quad (2)$$

Three terms of equation(1) that are not directly measured,  $Q_e$ ,  $Q_h$ , and  $Q_w$ , were determined as functions of the evaporation rate by using the following relations:

$$Q_e = \rho.E_{eb}L \quad (3)$$

$$Q_h = R.Q_e \quad (4)$$

$$Q_w = \rho.c.E_{eb}(T_e - T_b) \quad (5)$$

where:

- $\rho$  density of evaporated water( $kg.m^{-3}$ );
- $E_{eb}$  energy budget evaporation rate( $cm/day$ );
- $L$  latent heat of vaporization of water( $j/kg$ );
- $R$  Bowen Ration(dimensionless);
- $c$  specific heat of water( $j.kg^{-1}.^0k^{-1}$ );
- $T_e$  temperature of the evaporated water( $^0C$ );
- $T_b$  arbitrary base temperature( $^0C$ ).

By selecting an arbitrary base temperature of  $0^{\circ}C$  and Presume  $T_e$  to be equal to the water surface temperature( $T_0$ ),  $T_e - T_b$  equals the surface water temperature  $T_0$  (Winter and Rosenberry, 1992). Latent heat of vaporization depends on water temperature according to (Orlob, 1981):

$$L = 2.5 - 0.0024T_0 \quad (6)$$

where  $T_0$  is water surface temperature( $^{\circ}C$ ) and  $L$  is expressed in  $Kj/g$ .

The Bowen ratio is the ratio of sensible to latent heat and is calculated from Harbeck et al.(1958):

$$R = \frac{c.P(T_0 - T_a)}{100(e_0 - e_a)} \quad (7)$$

where:

$c$  empirical constant that determined by Bowen(1926) to vary from 0.58 to 0.66(dimensionless);

$T_0$  temperature of the water surface( $^{\circ}C$ );

$T_a$  temperature of the air( $^{\circ}C$ );

$e_0$  vapor pressure of saturated air at the temperature of the water surface( $Kpa$ );

$e_a$  vapor pressure of the air( $Kpa$ );

$p$  atmospheric pressure( $Kpa$ );

100 conversion factor to give pressure in kilopascals.

Atmospheric pressure( $Kpa$ ) was calculated from the relationship to altitude( $m$ ) of the lake by equation proposed by Jensen et al.(1990):

$$P = 101.3 \left[ \frac{293 - 0.0065H}{293} \right]^{5.26} \quad (8)$$

To calculate evaporation rate by using the energy budget method for a specific interval of time, equation can rewritten as following form:

$$E_{eb} = \frac{Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} + Q_v + Q_b - Q_x}{L(1 + R) + T_0} \quad (9)$$

Energy budget components

The short-wave(Solar) Radiation incident at the lake's water surface( $Q_s$ ) may be measured directly using a pyranometer or may be related to the hours of sunshine by the equation(Allen et al., 1998):

$$Q_s = (a + b \frac{n}{N})Q_0 \quad (10)$$

in which  $n/N$  is the ratio of actual to theoretical daily sunshine hours,  $Q_0$  is the upper(outer limits of the atmosphere) solar radiation( $w.m^{-2}$ ) and  $a$  and  $b$  are constants dependent on latitude.

According to studies, for the position of saveh dam,  $a = 0.28$  and  $b = 0.4$ . Actual daily sunshine hours( $n$ ) is acquired from daily sunshine data, while the terms  $N$  and  $Q_0$  are calculated as a function of latitude and day of

the year with the chain equations proposed. The reflected short-wave radiation( $Q_r$ ) from the water surface is given by:

$$Q_r = a_s Q_s \quad (11)$$

where  $a_s$  is the reflectivity of short-wave radiation of water, usually taken as  $a_s = 0.07$ .

The incoming long-wave(atmospheric) radiation( $Q_a$ ) is approached by the equation:

$$Q_a = \varepsilon_a \sigma (T_a + 273)^4 \quad (12)$$

where  $\sigma$  is the Stefan-Boltzmann constant( $5.67 \times 10^{-8} Wm^{-2}K^{-4}$ ) and  $\varepsilon_a$  is the atmospheric emissivity.

A number of equations exists for estimating  $\varepsilon_a$ , usually depending on vapor pressure, air temperature and cloud cover. We use the graphic data of Raphael(1962) formulated by Henderson-Sellers(1986) as follow:

$$\text{for } n/N \leq 0.4 \quad \varepsilon_a = 0.87 - \frac{n}{N} (0.175 - 29.92 \times 10^{-4} e_d) + 2.693 \times 10^{-3} e_d \quad (13)$$

$$\text{for } n/N \geq 0.4 \quad \varepsilon_a = 0.84 - \frac{n}{N} (0.1 - 9.973 \times 10^{-4} e_d) + 3.491 \times 10^{-3} e_d \quad (14)$$

The above equations combine the impact of vapor pressure and cloud cover and yield good results for both cloudless and cloudy conditions(Henderson-Sellers,1986).

The reflected long-wave radiation( $Q_{ar}$ ) from the water surface is given by:

$$Q_{ar} = a_a Q_a \quad (15)$$

where  $a_a$  is the reflectivity of long-wave radiation of water, usually taken as  $a_a = 0.03$ .

The back radiation( $Q_{bs}$ ) follows the same formulation as  $Q_a$ , but the atmospheric temperature is replaced by the water surface temperature( $T_0$ ) and the emissivity is independent from water composition and fixed at  $\varepsilon_b = 0.97$  (Robinson et al., 1972; Bowie et al., 1985).

The 14-day mean change in energy content of the body of water( $Q_x$ ) is calculated from:

$$Q_x = \frac{\rho \cdot c}{a_s} \sum_z \left( \frac{\Delta T(z)}{\Delta t} a(z) \cdot \Delta z \right) \quad (16)$$

where  $\overline{a_s}$  is lake surface area,  $\Delta T(z) = T_{t+7}(z) - T_{t-7}(z)$  is the 14-day(centered) change in daily mean lake temperature at depth  $z$ ,  $\Delta t$  number of days in energy budget interval(converted to seconds),  $a(z)$  is lake area at depth  $z$ , and  $\Delta z$  is layer thickness.

Lake area is estimated from a hypsometric curve of saveh lake(generated from a bathymetric map) in conjection with lake level data(available roughly every 2 weeks).

## The water Budget

The water budget modeling is an important primary task in hydrologic studies of lakes and reservoirs. With the aid of the water budget equation, one can calculate the amount of free surface water evaporation. The water budget of Saveh lake is presented by:

$$(I + R + G) - (E + O) = S \quad (17)$$

where the terms are the time average of:  $I$  = surface inflow of drainage water,  $R$  = rainfall on the free water surface,  $G$  = groundwater exchanges from and to the lake,  $E$  = evaporation,  $O$  = surface outflow, and  $S$  = change in water storage.

Since the lake is with no apparent groundwater exchanges from and to the lake, Equation (17) reduces to:

$$(I + R) - (E + O) = S \quad (18)$$

## Pan Evaporation

The use of pans of water for measuring evaporation dates back to the 18th century. It is easy to understand their intuitive appeal as they measure open water evaporation in a visible way. However, despite numerous studies, it is very difficult to use data from pans except in specific circumstances.

Hounam (1973) carried out a review of methods for estimating lake evaporation from measurements of pan evaporation and much of the following is drawn from this source. Measurements of pan evaporation can rarely be used directly as estimates of evaporation from a water body due to differences in size between the pan and the water body and, possibly, differences in the overlying air. Winter(1981) suggests that the use of data from pans located some distance away from the water body can result in considerable errors. This method presented by:

$$E = K_p \cdot E_p \quad (19)$$

where  $E$  is the mean evaporation rate from the water body,  $E_p$  is the mean evaporation rate of the pan,  $K_p$  is an empirical constant. Pan coefficients are simply the ratio of the water body evaporation to pan evaporation.

Numerous coefficients have been reported in the literature, although most apply to the US Class A pan. However, the coefficients are generally specific to the pan type, its location and the nature of the water body. In addition, they may vary with time. This variation with time takes account of the lag, due to heat storage, in large water bodies whereas the pans are too small for any lag effect. Lapworth also found a strong monthly variation in the pan coefficients which varied between 0.47 and 1.18 for the US Class A pan. Winter(1981), in a hypothetical study, suggested errors of 10% for measurement errors, 50% for application of pan coefficients and 15% for areal averaging.

## Other applied methods

Several of the most commonly used and widely applied evaporation methods were selected for comparison with BREB values; methods also were selected to represent a range of method complexity with regard to data requirement (Table 1). Although many of these methods were developed to calculate potential evapotranspiration, because the evaporating surface of Saveh Lake is open water, they are assumed here to represent evaporation.



Evaporation methods are grouped in Table 1 according to method type. Combination methods include an available-energy term and an aerodynamic term. Combination methods are the most data intensive and require measurement of some or all of the terms  $Q_n$ ,  $Q_x$ ,  $T_a$ ,  $U_2$ , and  $e_a$ .

Mass transfer methods require measurement of  $U_2$ ,  $T_0$ ,  $T_a$ , and  $e_a$ . The mass-transfer Dalton-type method requires an empirical coefficient that is site dependent. BREB data are used to determine the mass-transfer coefficient. The last three methods listed in Table 1 require measurement only of  $T_a$ . Two of the methods also require a determination of day length for the latitude of the study site.

Table 1 Methods for calculation of evaporation(E), the results from which are compared to results from the BREB method, in  $\text{mm}\cdot\text{d}^{-1}$ .

Method	Reference	Equation	Developed for
<b>Combination group</b>			
Priestley–Taylor	Stewart and Rouse (1976)	$E = \alpha \frac{s}{s + \gamma} \frac{Q_n - Q_x}{L\rho} \times 86.4$	Periods of 10 d or greater
deBruin–Keijman	deBruin and Keijman (1979)	$E = \frac{s}{0.85s + 0.63\gamma} \frac{(Q_n - Q_x)}{L\rho} \times 86.4$	Daily
Penman	Brutsaert (1982)	$E = \frac{s}{s + \gamma} \left( \frac{Q_n - Q_x}{L\rho} \right) \times 86.4 + \frac{\gamma}{s + \gamma} (0.26(0.5 + 0.54U_2)(e_s - e_a))$	Periods greater than 10 d
deBruin	deBruin (1978)	$E = 1.192 \left( \frac{\alpha}{\alpha - 1} \right) \left( \frac{\gamma}{s + \gamma} \right) \frac{(2.9 + 2.1U_2)(e_s - e_a)}{L\rho} \times 86.4$	Periods of 10 d or greater
<b>Dalton group</b>			
Mass transfer	Harbeck et al. (1958)	$E = (NU_2(e_0 - e_a)) \times 10$	Depends on calibration of N
<b>Temperature group</b>			
Papadakis	McGuinness and Bordne (1972)	$E = 0.5625(e_s \text{ max} - (e_s \text{ min} - 2)) \left( \frac{10}{d} \right)$	Monthly

$\alpha = 1.26$  = Priestley–Taylor empirically derived constant, dimensionless,  
 $s$  = slope of the saturated vapor pressure–temperature curve at mean air temperature ( $\text{Pa } ^\circ\text{C}^{-1}$ ),  
 $\gamma$  = psychrometric ‘‘constant’’ (depends on temperature and atmospheric pressure) ( $\text{Pa } ^\circ\text{C}^{-1}$ ),  
 $Q_n$  = net radiation ( $Q_s - Q_r + Q_a - Q_{ar} - Q_{bs}$ ) ( $\text{W m}^{-2}$ ),  
 $Q_x$  = change in heat stored in the water body ( $\text{W m}^{-2}$ ),  
 $L$  = latent heat of vaporization ( $\text{MJ kg}^{-1}$ ),  
 $\rho$  = density of water ( $998 \text{ kg m}^{-3}$  at  $20^\circ\text{C}$ ),  
 $N$  = mass-transfer coefficient (used 0.01644 for Mirror Lake),  
 $U_2$  = windspeed at 2 m above surface ( $\text{m s}^{-1}$ ),  
 $e_0$  = saturated vapor pressure at temperature of the water surface (mb),  
 $e_s$  = saturated vapor pressure at temperature of the air (mb),  
 $e_a$  = vapor pressure at temperature and relative humidity of the air (mb),  
 $T_a$  = air temperature  
 $d$  = number of days in month,  
 $e_s \text{ max}$  and  $e_s \text{ min}$  = saturated vapor pressures at daily maximum and minimum air temperatures (Pa).  
 The multipliers 10 or 86.4 that appear in several equations are to convert output to  $\text{mm d}^{-1}$ .

### Data sources and quality

Daily data of air temperature, relative humidity, atmospheric pressure, sunshine hours, rainfall, pan evaporation, and wind speed were acquired from the weather station adjacent the study site. As mentioned before, shortwave radiation was related to the hours of sunshine by the equation proposed by Allen et al.(1998)(Fig. 2).

Longwave radiation was also calculated by aid of daily air temperature and sunshine hours and the graphic data of Raphael(1962) formulated by Henderson-Sellers(1986)(Fig. 2). Lake area is estimated from a hypsometric

curve of Saveh Lake(generated from a bathymetric map for year 2003) in conjunction with lake level data(available roughly every 2 weeks)(Fig. 3).

For calculating the  $Q_x$  component of BREB method, we should have thermal profile and the water surface temperature of the lake, but there are a few and discontinues measurement of this parameters only for some months of study period. For this purpose, we found that the data of the thermometers exist in the body of the dam(for the stability studies of the dam) are comparable very well with the discontinuous measured data.

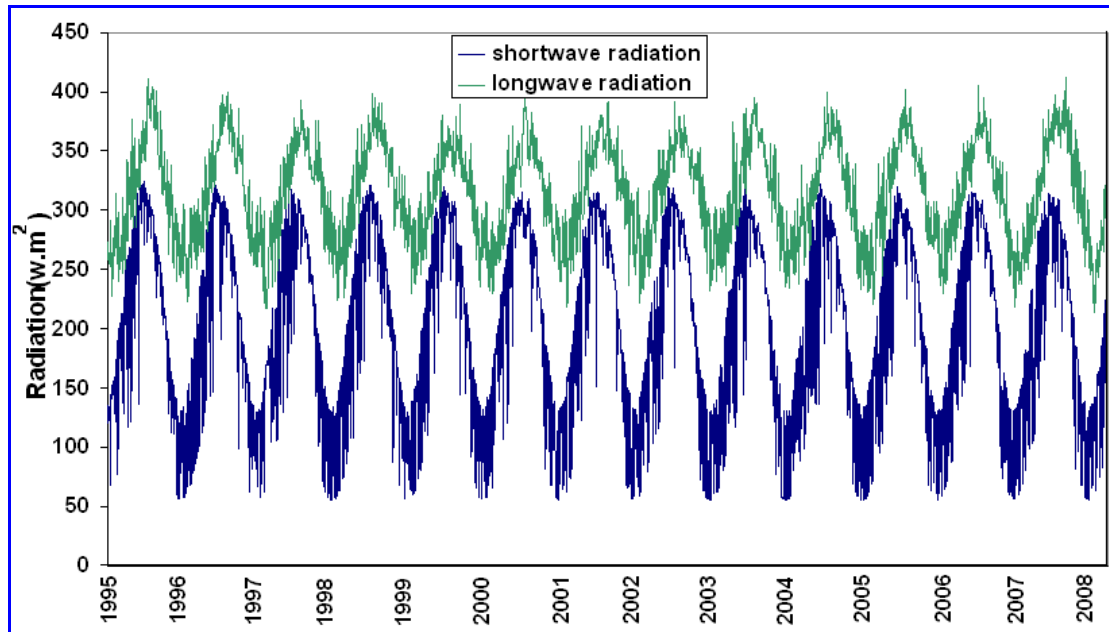


Figure 2 Daily shortwave and longwave radiation calculated by use of daily sunshine data.

With the absence of the continuous and reliable data for water surface temperature and the thermal profile, we applied those thermometers data and energy-budget periods were determined as the time interval between successive thermometers processing. Finally,  $Q_x$  was determined as the difference in heat stored between the beginning and end of each energy-budget period.

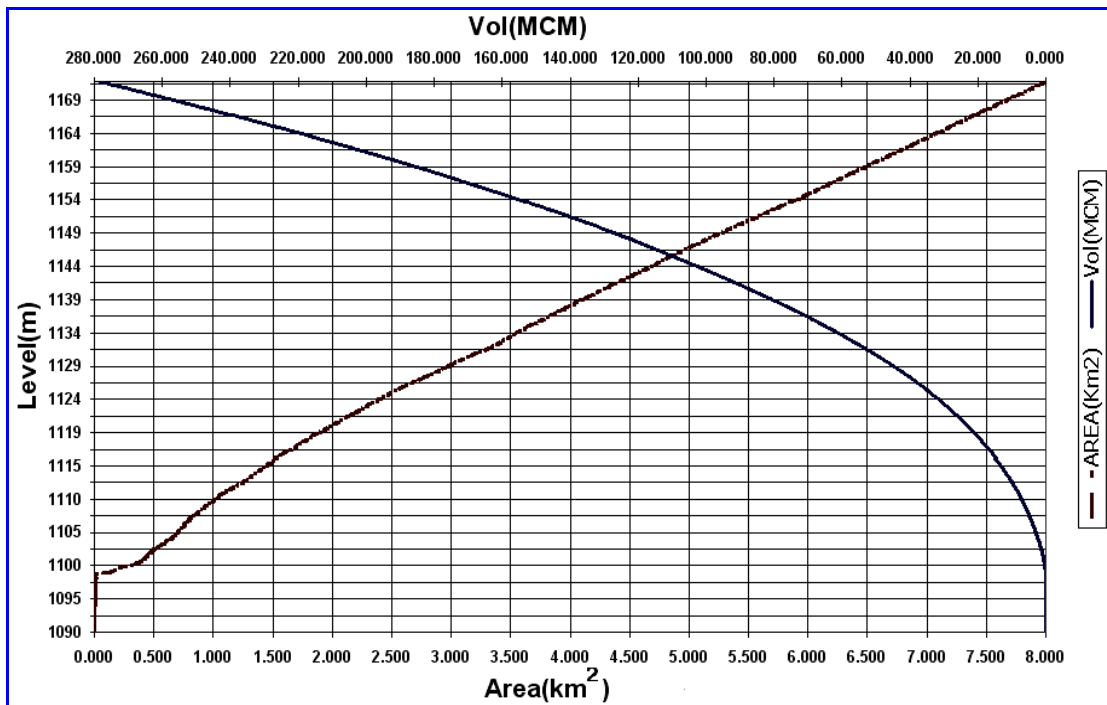


Figure 3 Bathymetric map of Saveh Lake for year 2003.

In order to reconstruct the daily water surface temperature, a mathematical relationship trendline(Regression) was created between water surface temperature and daily air temperature data(Fig. 4, Fig. 5).

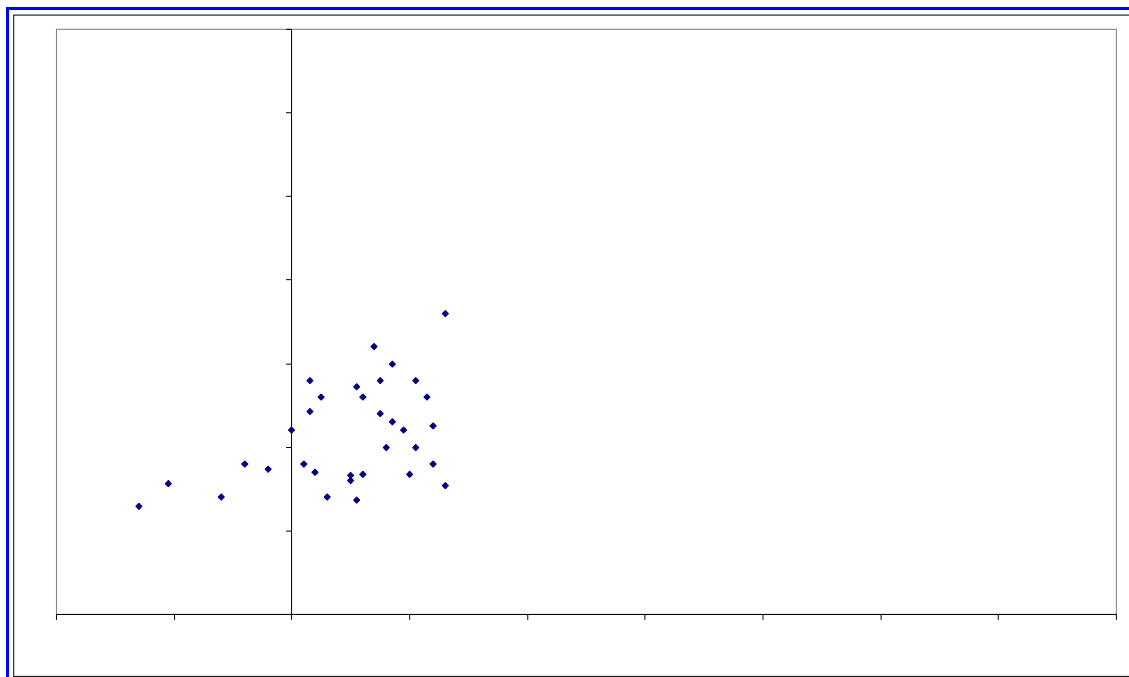


Figure 4 Mathematical relationship trendline(Regression) between water surface temperature and daily air temperature data.

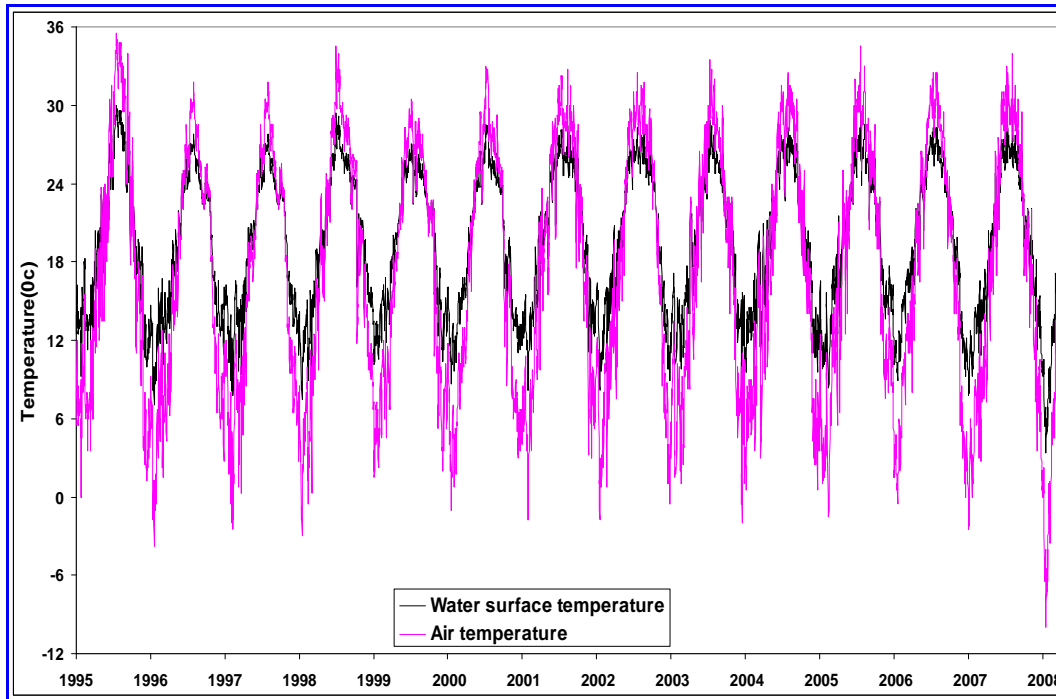


Figure 5 Reconstructed daily water surface temperature.

### Results and Discussion

The Daily values of the parameters of Equation(18) and Daily values of pan evaporation from the Class A Pan were obtained from the Water Resources Management Department of IRAN. According to figure 6, from the Daily average values of pan evaporation for the study period(1995-2008), evaporation is low for the first 60 days(two months) of the year and then has significant rise until middle days of the year following by downfall during the rest of the year.

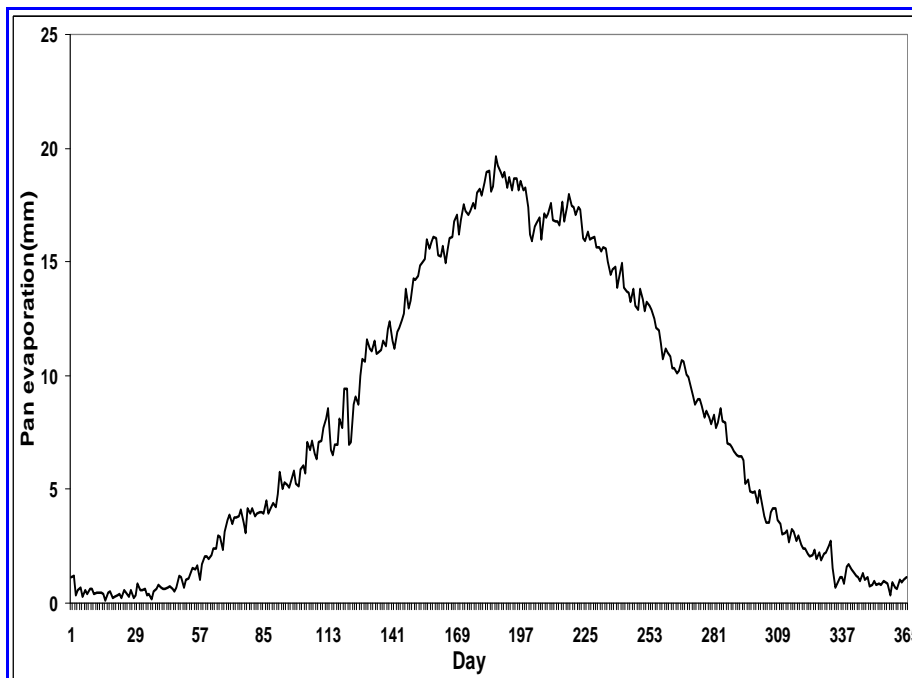


Figure 6 Daily average values of pan evaporation for study period(1995-2008).

Monthly and yearly evaporation values from water balance and pan evaporation are presented in table 2 and 3, respectively. Based on the statistical summary of monthly averages shown in this tables, maximum evaporation values for both methods occurred for July, August, and June, respectively and winter months have minimum values of evaporation. Also, maximum and minimum yearly evaporation values were not simultaneous for two methods.

Table 2 Monthly and yearly water balance of the Saveh Lake for the study period(mm).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Sum
1995	34	19	30	72	101	223	319	321	234	126	90	85	1654
1996	39	26	41	52	83	221	242	300	185	149	72	86	1496
1997	26	21	47	64	114	152	247	272	187	152	81	46	1409
1998	22	37	41	111	124	240	296	233	207	155	107	59	1632
1999	46	29	63	83	135	241	257	239	189	131	68	51	1532
2000	31	38	54	67	171	227	280	234	201	105	51	37	1496
2001	23	26	50	105	157	222	284	252	212	164	64	40	1599
2002	26	31	52	84	122	240	270	261	231	152	74	43	1586
2003	29	37	47	69	123	164	274	250	225	134	82	35	1469
2004	20	25	59	89	110	225	247	261	221	141	89	49	1536
2005	29	39	41	81	124	213	287	259	229	155	78	71	1606
2006	23	48	54	103	134	242	298	264	209	108	65	27	1575
2007	29	31	49	71	129	251	257	262	210	139	77	52	1557
Ave	29	31.5	48.5	82	126	220	274	262	211	139	76.5	52	1551.5

Table 3 Monthly and yearly pan evaporation of the Saveh Lake for the study period(mm).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Sum
1995	87	79	78.4	234	299	401	419	427	394	244	199	84	2947
1996	94	57	68.4	113	225	393	427	529	376	232	179	131	2824
1997	85	91	89.5	79.6	211	399	539	484	377	252	183	41	2832
1998	81	30	29	164	219	364	518	430	355	163	62	40	2456
1999	12	7.9	7.3	90.4	283	487	514	487	446	300	98	30	2761
2000	20	0	0	171	423	583	656	538	437	189	72.9	25	3116
2001	35	6.4	21	228	388	490	583	512	450	335	139	47	3232
2002	20	0	31.4	146	255	510	611	614	522	372	132	19	3233
2003	13	8.8	41.1	132	216	309	538	504	364	240	104	30	2500
2004	15	55	90.2	142	217	431	512	546	424	201	68.5	12	2713
2005	15	19	100	165	306	418	558	504	384	265	74.3	58	2867
2006	6.2	5.8	92.5	169	329	434	571	535	368	208	73.9	19	2811
2007	0	0	36.7	120	228	422	513	469	327	197	145	52	2509
Ave	37	28	53	150	277	434	535	506	402	246	118	45	2831

According to equation(19) and by calculating the yearly water balance evaporation values by the equation(18), yearly and average pan coefficient values were calculated(Table 4). Based on the statistical summary shown in this tables, this coefficient is between 0.48 for 2000 and 0.66 for 1998(with average of 0.55).

Table 4 Yearly and average pan coefficient for the study period.

	Pan evaporation	Water balance	Pan Coefficient
1995	2947	1654	0.56
1996	2824	1496	0.53
1997	2832	1409	0.5
1998	2456	1632	0.66
1999	2761	1532	0.55
2000	3116	1496	0.48
2001	3232	1599	0.49
2002	3233	1586	0.49
2003	2500	1469	0.59
2004	2713	1536	0.57
2005	2867	1606	0.56
2006	2811	1575	0.56
2007	2509	1557	0.62
Ave	2831	1549	0.55

Further, In this study results are presented as differences between monthly average evaporation rates determined by the alternate equations and evaporation determined by the energy budget values were made for 14 years during 1995-2008. Differences were calculated by subtracting the energy budget values from the values derived from the alternate equations; therefore calculated values greater than energy budget values(overestimates) are positive and those less than energy budget values(underestimates) are negative on the graphs. BREB evaporation rates ranged from 0.8 to 11.5 mm d<sup>-1</sup> and averaged  $4.4 \pm 0.25$  mm d<sup>-1</sup> during the 14-year study period(Fig. 7).

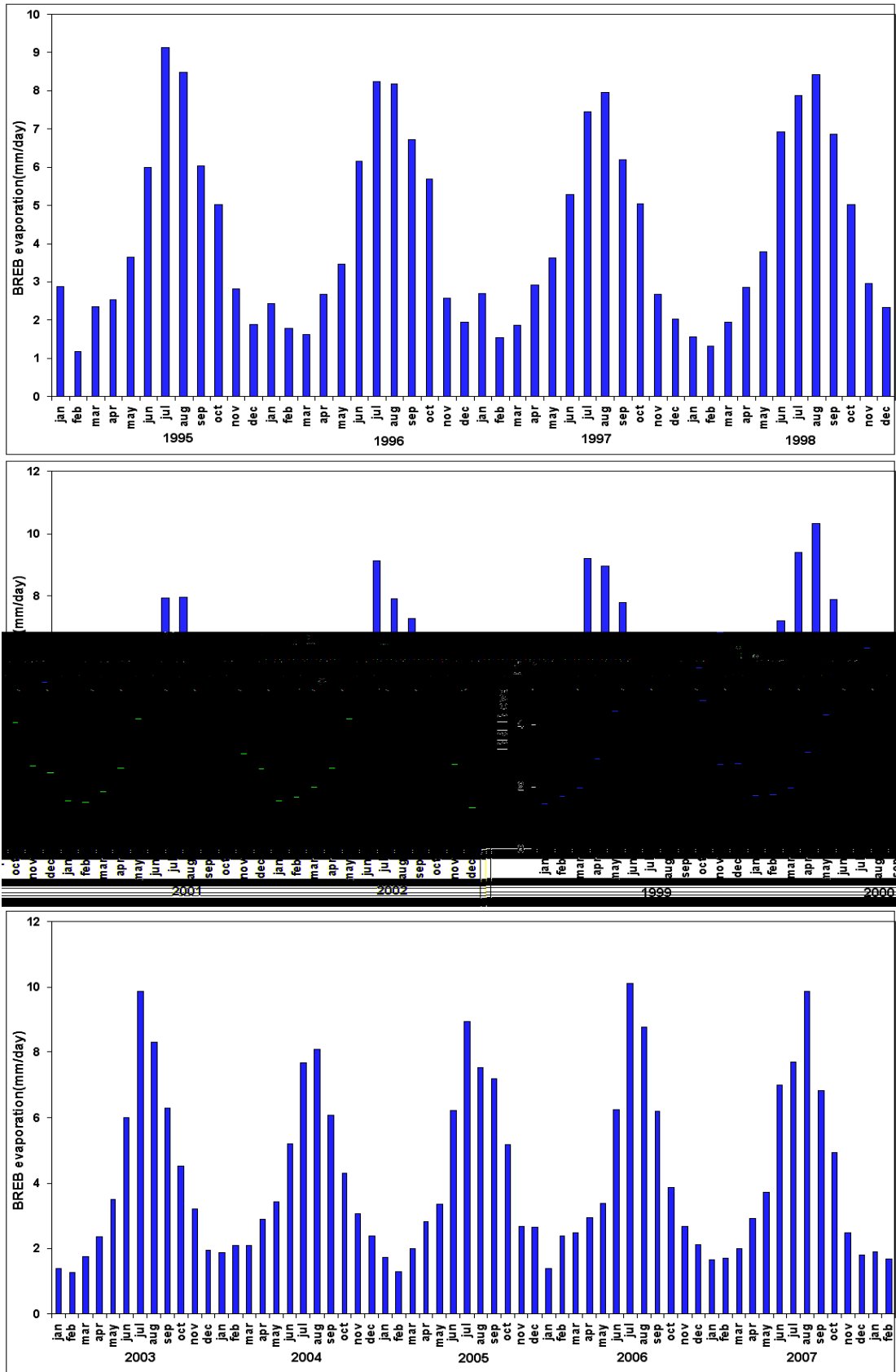
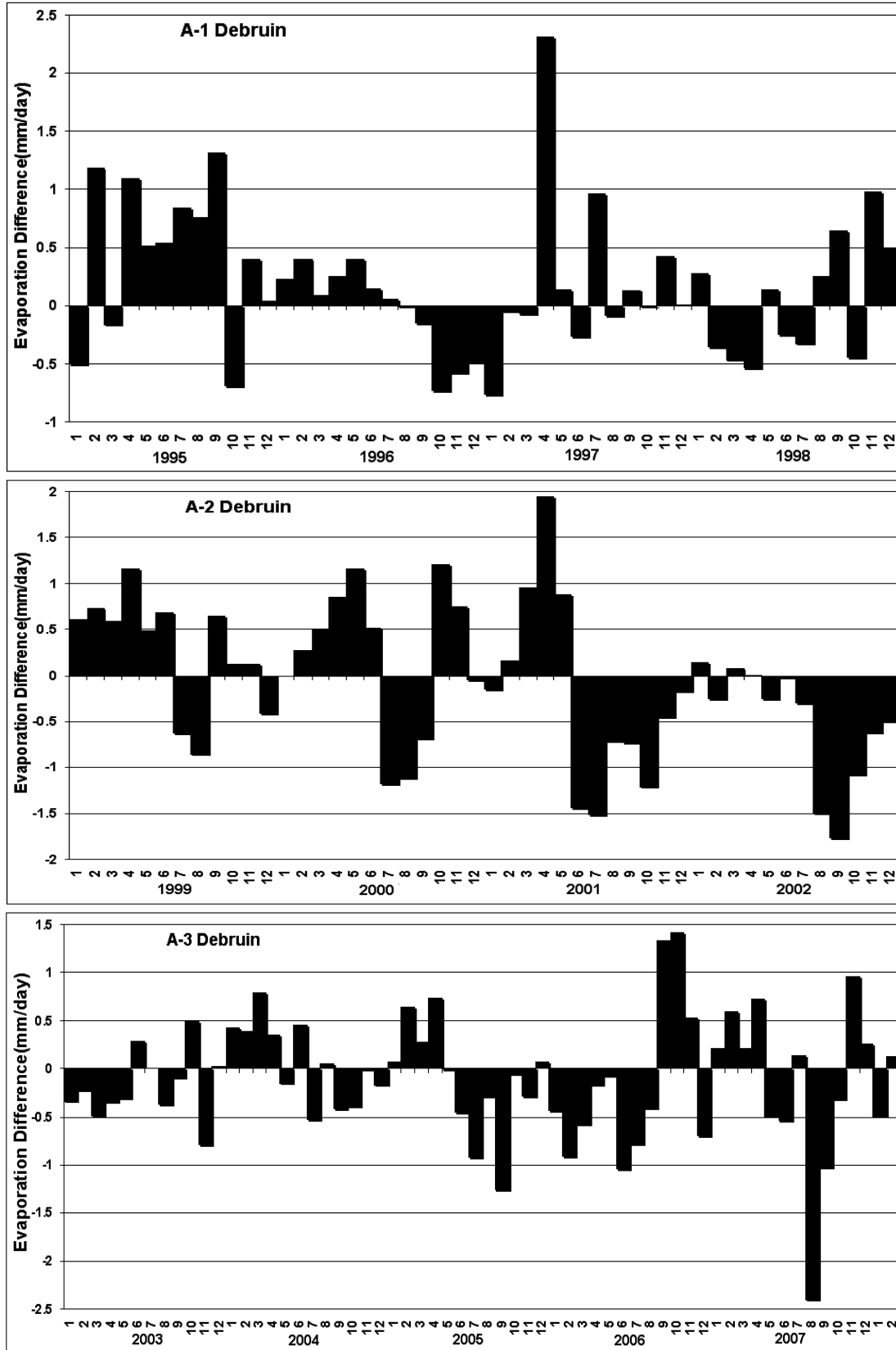
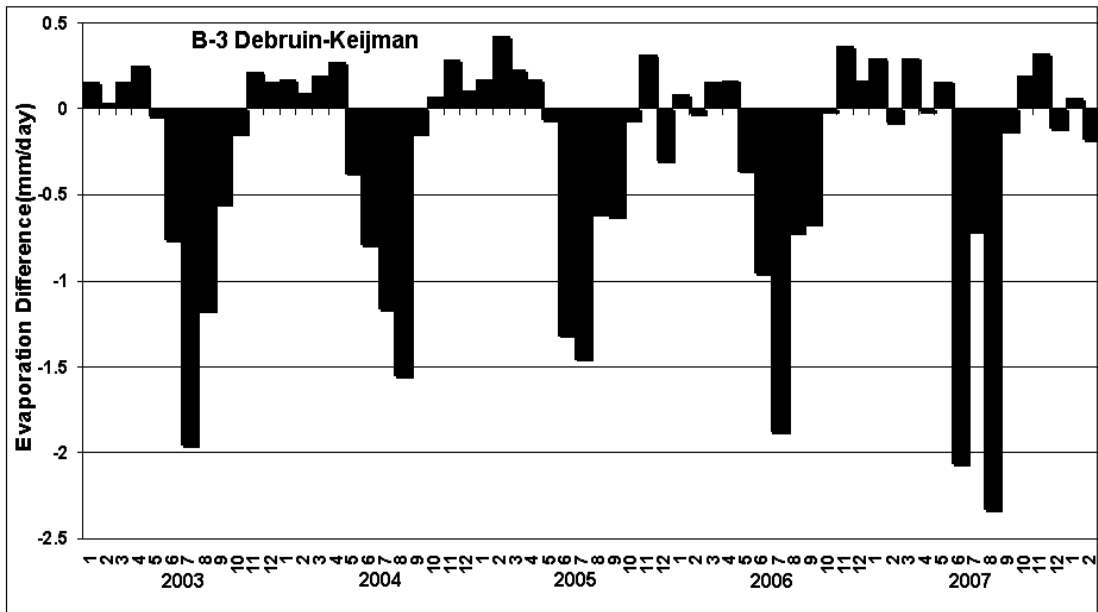
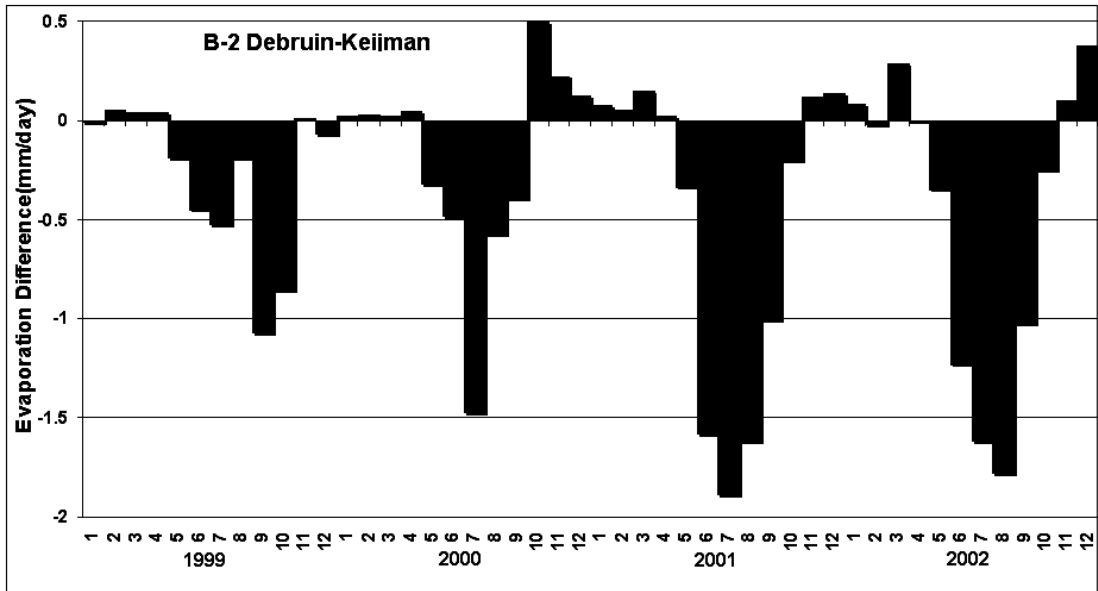
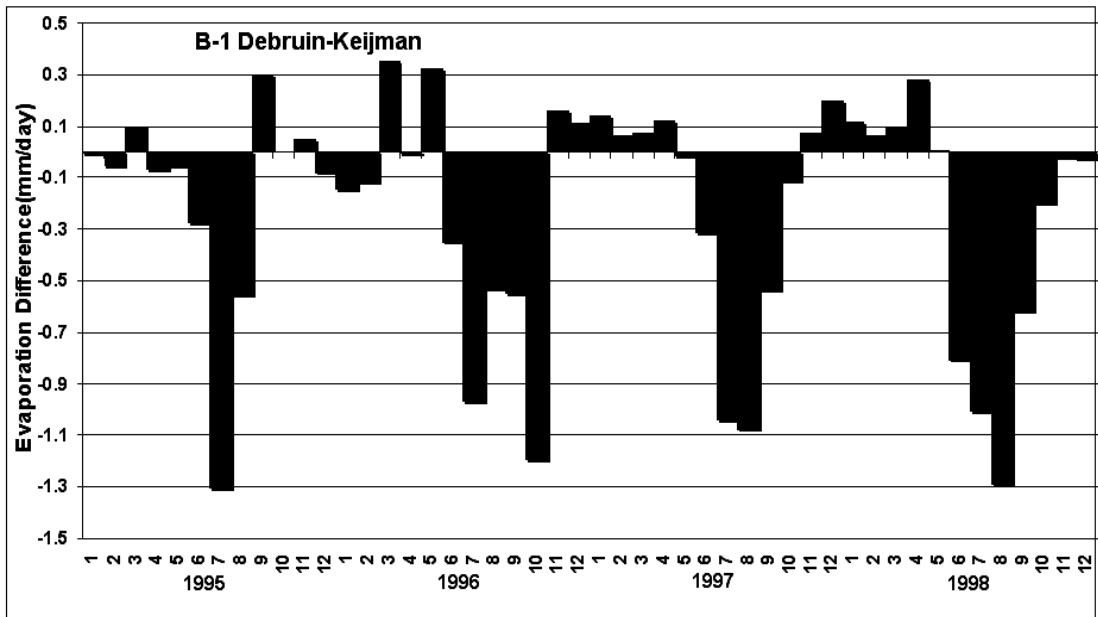


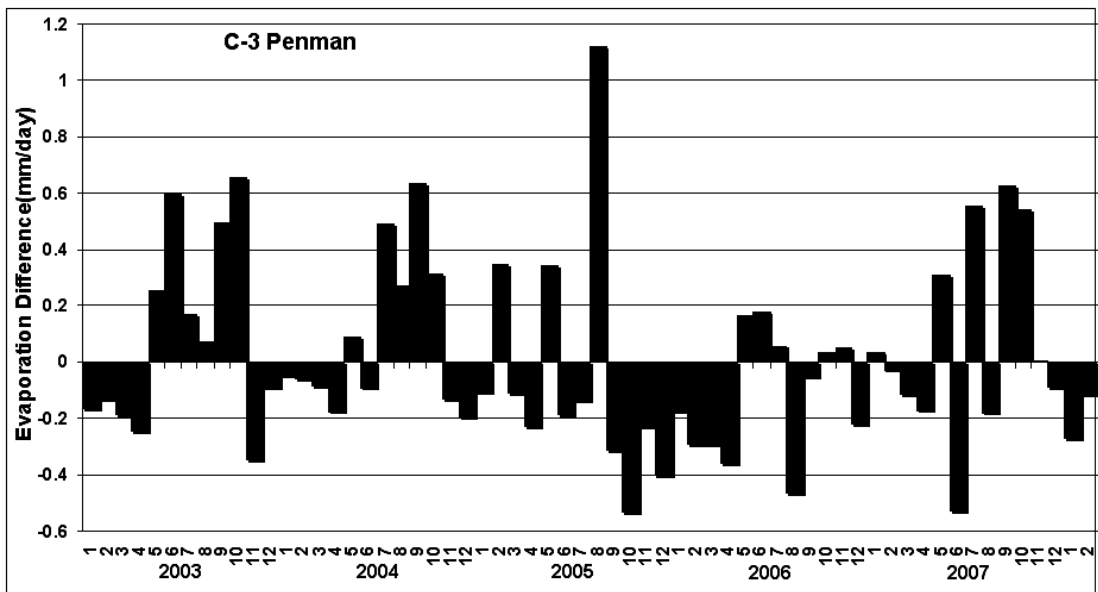
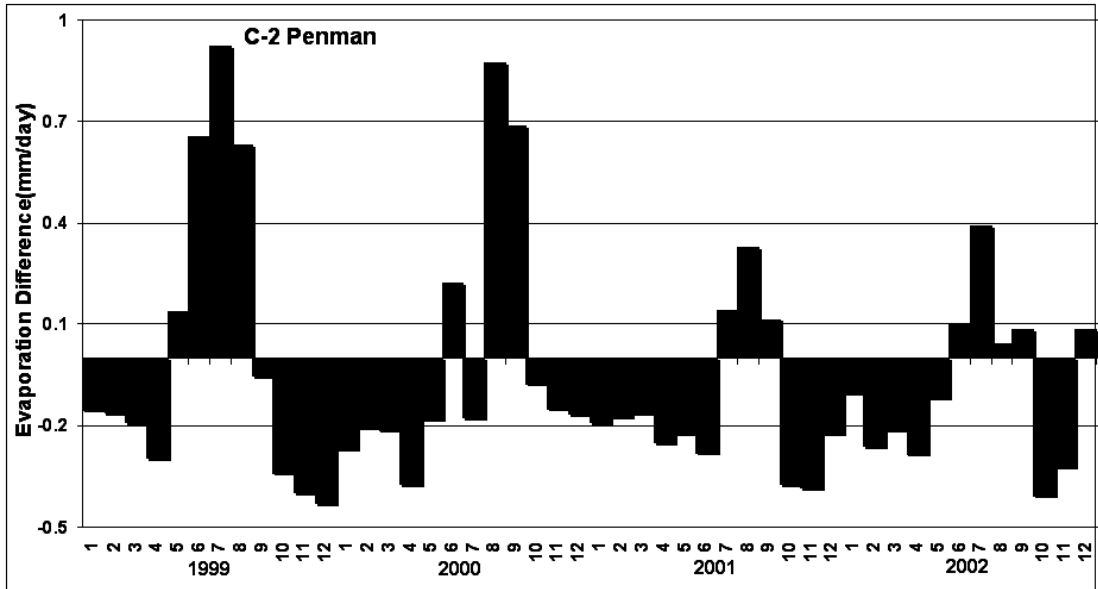
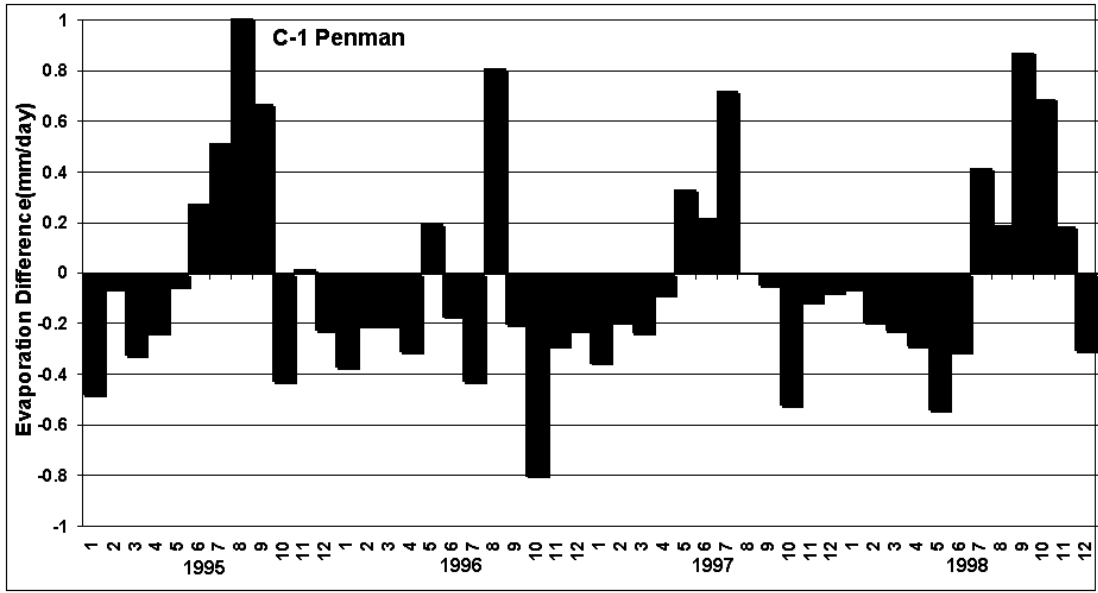
Figure 7 Daily evaporation from Saveh Lake( $\text{mm d}^{-1}$ ) averaged per month, as determined by the BREB method(1995-2008).

Maximum monthly rates were not consistent among years and occurred during July of 1995, 1996, 2000, 2001, 2003, 2005 and 2006, and during August of 1997, 1998, 1999, 2002, 2004 and 2007. Many of the alternate approaches for determining evaporation compared well with the BREB monthly values(Fig. 8).













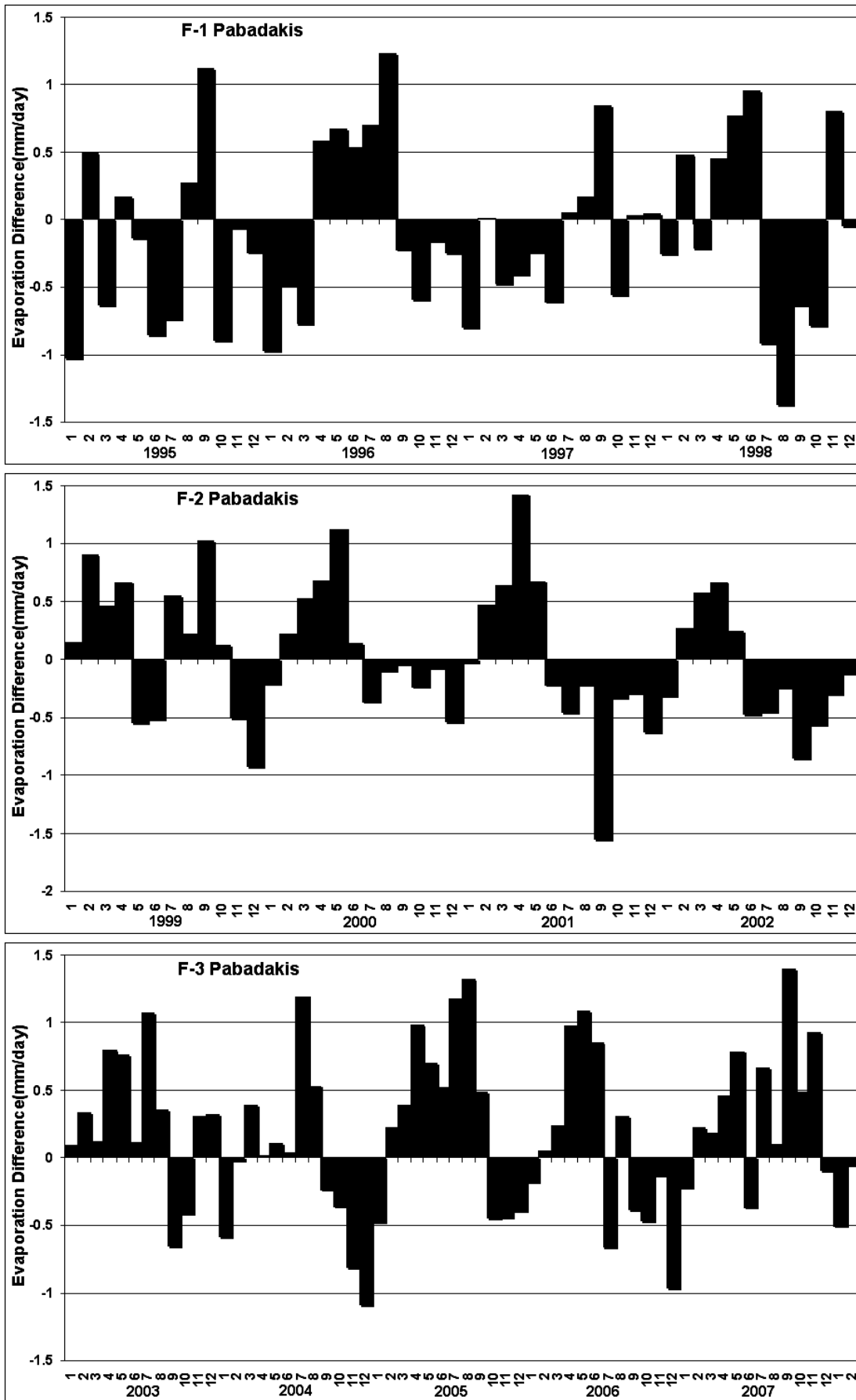


Figure 8 Difference in calculated evaporation between alternate evaporation methods presented in Table 1 and BREB values( $\text{mm d}^{-1}$ ).

Four of the alternate methods (Priestley–Taylor, Pabidakis, Penman, mass transfer) provided evaporation values that were within  $1.5 \text{ mm d}^{-1}$  of the BREB values for all of the monthly comparison periods. Three of the four combination methods (Penman, Debruin, Priestley–Taylor) also had a positive bias that was seasonal; overestimates of evaporation occurred during Spring months, and smaller overestimates or underestimates often occurred during winter and fall months (Fig. 8A,C, and D). Debruin-Keijman method often had a negative bias that was seasonal; underestimates of evaporation occurred during summer and fall months, and overestimates often occurred during the rest of the year months (Fig. 8B). Priestley–Taylor values were within  $0.5 \text{ mm d}^{-1}$  of BREB values during 153 of 165 monthly comparison periods (92.7%), Debruin values during 101 of 165 (61.2%), Debruin-Keijman values during 117 of 165 (71%), and Penman values during 139 of 165 (84.2%) periods.

Values generated with the mass-transfer method had zero bias, as would be expected since the mass-transfer coefficient (0.017) was calibrated to BREB values (Fig. 8E). Considering their simplicity, values from the method that requires measurement of  $T_a$  only compared surprisingly well with the BREB standard. Values from the Pabidakis method provided more consistent inter-annual and seasonal comparisons with BREB values (Fig. 8F).

#### Costs and accuracy of measurement and estimation methods

Whether or not a researcher should attempt to measure wetland ET directly or use one of the combination equations depends to a large extent on the cost of the instrumentation required as well as its accuracy and complexity.

Several of the “simplified” methods that were compared with the BREB method are not substantially different and require as many, or nearly as many, measured variables, reducing their value for studies that are searching for a less expensive means for estimating evaporation. The Priestley–Taylor, deBruin–Keijman, and Penman methods provided evaporation estimates that most closely compared with BREB values. Of these three, the Penman method requires the greatest number of variables. This method requires the same number of variables as the BREB method; it eliminates the need to measure water-surface temperature (and calculated vapor pressure at the water surface) with the tradeoff that requires that windspeed be measured. Therefore, the Priestley–Taylor and deBruin–Keijman methods are the most cost effective of these combination methods, requiring measurement of only  $T_a$ ,  $Q_n$ , and  $Q_x$ . However,  $Q_x$  remains a prohibitively expensive variable for many budgets, due to high labor costs. One potential solution, however, is to deploy strings of relatively inexpensive temperature recorders in several locations in the lake-water column (Rosenberry et al, 2007). The remaining combination method (deBruin) did not compare well with BREB values and requires measurement of  $T_a$ ,  $e_a$ , and  $U$ , making it a poor choice for use at Saveh Lake.

The Mass transfer method is the next most complex, requiring measurement of  $T_0$ ,  $T_a$ ,  $e_a$ , and  $U$ . This method requires a locally determined mass-transfer coefficient. The Pabidakis method that requires measurement of only  $T_a$  compared surprisingly well with BREB values. If that level of accuracy is sufficient, this may be the most cost effective of the methods compared for this study.

## Summary and Conclusions

Evaporation methods that include available-energy and aerodynamic terms (combination methods) provide the best comparisons with BREB evaporation measured at Saveh Lake. Three of the four combination methods (Priestley– Taylor, DeBruin–Keijman, Penman) provided values that were within 20% of BREB values during more than 94% of the energy-budget periods. Although small relative to other energy terms, inclusion of advected energy associated with rainfall, ground-water and surface-water fluxes, and energy conducted to or from the lake sediments, in the net radiation term improved evaporation estimates when compared with BREB values. Other temperature-only method also compared remarkably well with BREB values. Given its simplicity, temperature-only method, such as Papadakis, is cost effective and provide evaporation estimates that are more accurate than several more complex methods.

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