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Calibrating Priestley-Taylor Model to Estimate Open Water Evaporation under Regional Advection Using Volume Balance Method-Case Study: Chahnimeh Reservoir, Iran

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Abstract: The objective of this study is to calibrate Priestley-Taylor (PT) model for estimating open water evaporation from an arid region reservoir called Chahnimeh. Chahnimeh Reservoir which is situated in the Sistan area in the southeast of Iran is being affected by regional energy advection during May to October. Therefore, common models of open water evaporation estimation such as PT require calibration. PT method was calibrated for Chahnimeh Reservoir using a volume balance method. Results showed that PT coefficient, α_{PT}, as a constant over the year varies between 2.47±0.09 and 1.20±0.03 for two different hydrologic conditions of dry and wet. It means that there is also an intra-annular variation in α_{PT}. Calibration of PT model also showed that α_{PT} is a time dependant variable and varies monthly. In other word there is an inter-annular variation. Inter-annular variation of α_{PT} showed that this coefficient varies from 1.56 to 3.16 against 0.67 to 1.95 for dry and wet conditions, respectively.

Key words: Open water evaporation, Priestley-Taylor, volume balance, regional advection, Chahnimeh reservoir

INTRODUCTION

The management of surface water resources such as reservoirs, wetlands and other freshwater ecosystems needs estimates of open water evaporation. Also, understanding open water evaporation is necessary in planning economic uses of these water resources. Open water evaporation serves as a convenient index of the evaporation demand of a particular climate (Linacre, 2004) and, plays an important role not only in the water budget of a lake, reservoir or wetland, but also in the energy budget.

Evaporation and transpiration are major components of the hydrologic cycle, where approximately 62% of precipitation over land is lost through these phenomena globally. Several difficulties arise when modeling evaporation of arid region free water bodies. In these open water bodies, evaporation is the major component of water balance which generally, has rarely been measured directly especially in developing countries (Vallet-Coulomb *et al.*, 2001). Huge amount of sensible heat flows from adjacent warm-hot dry lands (large amount of advection energy flux density) and increases the evaporation rate of free surface water bodies drastically. Therefore, it is very difficult to estimate evaporation of open water using ordinary methods.

Evaporation is estimated by numerous methods such as Penman and Priestley-Taylor (PT) models (Castellvi *et al.*, 2001; Daneshkar Arasteh, 2004). Priestley-Taylor formula is one the most used model to estimate open water evaporation in operational procedures such as reservoir management. It is presented for no or low advection conditions or on the base of the equilibrium assumption which is the theoretical lower limit of evaporation (Jacobes *et al.*, 2002; Li and Yu, 2007). This is the main restriction of using such a model in arid regions.

Priestley and Taylor coefficient is suggested, $\alpha_{PT} = 1.26$ for minimum advective condition with no edge effects (Eaton *et al.*, 2001). Pereira and Nova (1992) emphasized that the value of 1.26 is suitable for potential condition and invalid under advective conditions. The α_{PT} coefficient varies widely according to surface type and condition (vegetation type and soil moisture condition) and micrometeorological conditions such as strength of advection (Eaton *et al.*, 2001; Fisher *et al.*, 2005). Pereira (2004) reported that the α_{PT} parameter can be set equal to the inverse of the McNaughton-Jarvis decoupling factor. A wide range of values for α_{PT} has been determined for different types of terrains. Some of these suggested values are summarized in Table 1.

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Table 1: Suggested estimates of α_{PT} for different terrain types

Terrain type	Site location	α_{PT}	Source
Wetland	Trail Valley Creek, Northwest Territories, Canada	1.08	Eaton *et al.* (2001)
	Churchill Sedge Fen, Manitoba, Canada	1.18	
	Hudson Bay, Ontario, Canada	1.26	
	Lake Melville, Newfoundland, Canada	1.2	
	Lake Michigan, Indiana, USA	1.035	Soucha *et al.* (1996)
	Paynes Prairie, Florida, USA	1.0	Jacobs *et al.* (2002)
Tundra	Trail Valley Creek, Northwest Territories, Canada	1.04	Eaton *et al.* (2001)
	Trail Valley Creek, Northwest Territories, Canada	1.07	
	Churchill, Manitoba, Canada	1.08	
	Churchill, Manitoba, Canada	0.9	
	Scout Mountain, British Columbia, Canada	1.26	Saunders *et al.* (1997)
Forest	Havikpak Creek, Northwest Territories, Canada	0.77	Eaton *et al.* (2001)
	Churchill Spruce-Tamarack Forest, Manitoba, Canada	1.31	
	Puerto Viejo de Sarapiqui, Costa Rica	1.24	Loescher *et al.* (2005)
Shallow lake	Golf Lake, Churchill, Manitoba, Canada	1.31	Eaton *et al.* (2001)
	Northern Manitoba, Canada	1.35	
Deep lake	Great Slave Lake, Northwest Territories, Canada	1.92	Eaton *et al.* (2001)
	Lake Toba, Indonesia	1.28	Sene *et al.* (1991)
Dry land	Southern Supersite Tiger Bush (HAPEX-SAHEL)	1.287	Wang *et al.* (2004)

As it is shown in Table 1, α_{PT} values approach to unity in wetland areas. Eaton *et al.* (2001) represented α_{PT} values for five terrain types. They showed that α_{PT} values of less than unity to 0.77 are suitable for coniferous forests and values up to 2.32 for deep lakes. Wang *et al.* (2004) found a range of 1.1 to 1.4 for α_{PT} from HAPEX-SAHEL data sets. Flint and Childs (1991) reported values ranging from 0.7 to 1.6. For a study in the peatlands of Hudson Bay, α_{PT} was found to be 0.63.

Investigations on α_{PT} showed that it increases for dry surfaces. Chuanyan *et al.* (2004) reported from previous investigators a value as large as 1.57 under strongly advective conditions. Jensen *et al.* (1990) ascertained a value of 1.74 for arid and semiarid climates.

Chuanyan *et al.* (2004) used this value to model potential evapotranspiration in the semiarid regions of China, the Zuli River Basin, successfully, especially in areas with more homogeneous land cover. Xiaoying and Erda (2005) showed that PT-model underestimates crop evapotranspiration in annual and monthly scales especially when wind speed is high. In the modified approach, α_{PT} is a function of environmental variables. And a unique, physics-based functional form for the modified it has not been defined and must be determined empirically (Sumner and Jacobs, 2005).

It seems that in arid regions α_{PT} must be very different from common values because of large amount of energy advection. The Sistan plain in the southeast of Iran is one of those regions that experiences high amount of advection fluxes annually especially during summer time (May to October). In this study, calibrating PT model to estimate open water evaporation from the Chahnimeh Reservoir, the only regulated fresh water reservoir of Sistan area, using a water budget method is introduced.

MATERIALS AND METHODS

The Sistan Plain is one of those regions that experiences high amounts of advection fluxes when a regional continuous wind flow occurs annually especially during summer time (May to October). This seasonal wind is called the 120-day wind. The monthly average of maximum wind speed at 10 m height during this period is about 8 m sec^{-1} and in rest of the year is less than 2 m sec^{-1} with dominant direction of north to south and northwest to southeast. Sistan is an area subject to hydro-meteorological extremes, such as large floods and severe persistence droughts. There are not any considerable groundwater resources in this part of Iran and the annual precipitation is less than 60 mm, whereas records of class A evaporation pan shows annual evaporation of more than 4500 mm. The only water resource in this region is the Hirmand River, a trans-boundary river between Iran and Afghanistan (Fig. 1). The Hirmand is the tenth-largest river in Asia and drains much of Afghanistan. The main branch of the Hirmand forms the international boundary between Iran and Afghanistan. And, the Hirmand water right is the major geopolitical crises between the two countries. The Hirmand River flows to the interconnected wetland system of Hamuns with a total area of 4000 km^2 for full condition. Near the Iran and Afghanistan border line a reservoir has been constructed to supply water for domestic and agricultural activities within the Sistan Plain.

The Chahnimeh Reservoir comprises of four large depressions located north of the delta of Hirmand River in Sistan region. The geographical boundary of the region is from 30° 45' to 30° 50' northern latitude and 61° 38' to 61° 45' Eastern longitude. The average altitude is 500 m above mean sea level. An earthen dam lined with concrete

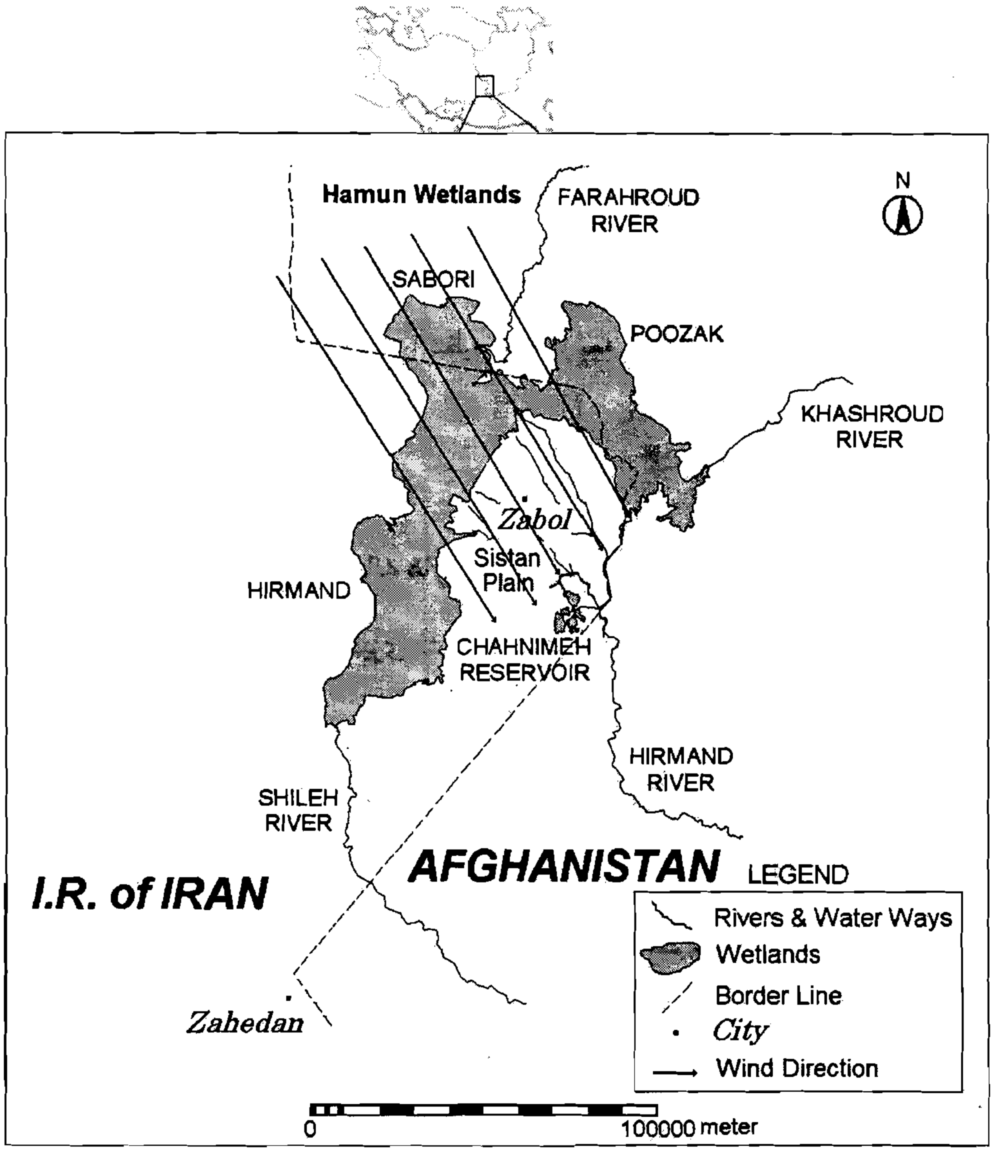

Fig. 1: Sistan plain in southeast of Iran

blanket has been constructed to close the depression in an appropriate elevation (Fig. 2). The outlet structure of irrigation canal is located on the dam.

This reservoir forms a continuous water body in the wet years and separates water bodies in dry years. The Chahnimeh Reservoir with a maximum capacity of approximately 630 mm^3 (MCM) and an area of over 47 km^2, provides fresh water to Zabol (center of Sistan region), Zahedan (center of Sistan and Baluchestan Province) and other adjacent inhibited areas of Sistan; in other words, the Chahnimeh Reservoir supplies domestic water for more than 1 million people residing in the region, as well as irrigation water to roughly 80,000 ha of farmlands in the region. Only half of the reservoir's capacity is considered live and the rest is the dead volume.

Chahnimeh hydrology has become the subject of many researches by planners and engineers to estimate open water evaporation and save water for the expanding population as well as the whole ecosystem. Numerous studies and projects were proposed to estimate evaporation from Hamun Wetlands and Chahnimeh Surfaces.

Most of the past studies in the region relied on the computation of evaporation using meteorological ground

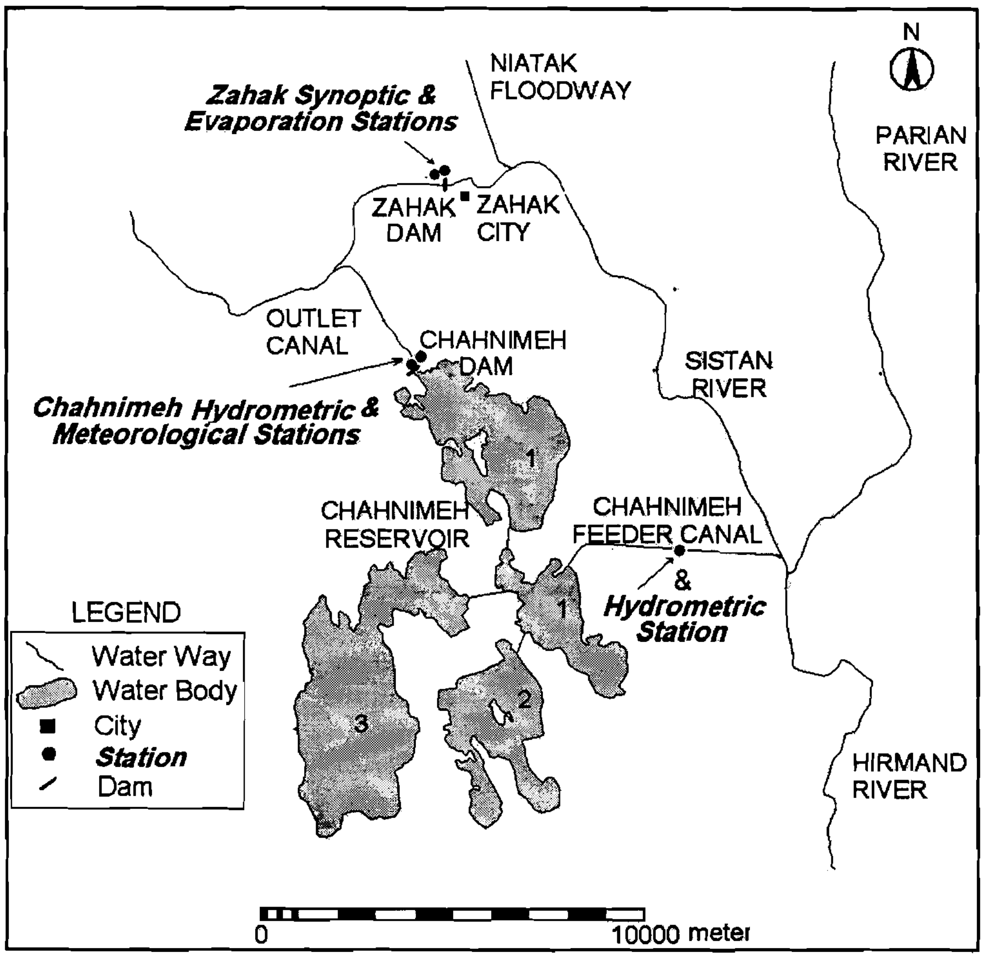

Fig. 2: Chahnimeh Reservoir and measuring sites

station data but some of them are on the base of remote sensing and application of satellite imagery.

Daneshkar Arasteh *et al.* (2005) according to a statistical point of view showed that evaporation from Chahnimeh Reservoir belongs to two hydrological conditions, one for those years that Hamun Wetlands are full of water (wet condition or HG2) and the others for which Hamuns are approximately dried (dry condition or HG1). In Daneshkar Arasteh *et al.* (2005) study, Hamuns open water area with more than 75% of the area was taken as wet condition and in the rest of time it was taken as dry. They showed that this statistical separation is fully adapted with climatic conditions of the area. During wet conditions agricultural activities and irrigated area is maximized and wetlands and irrigated area have the same effects on Chahnimeh Reservior evaporation. Figure 3 shows average monthly open water evaporation from Chahnimeh Reservoir and its deviation using water budget of the reservoir.

Daneshkar Arasteh (2004) developed a remotely sensed model to estimate Hamun Wetlands surface evaporation named HRSE (Hamun Remotely Sensed Evaporation model). Daneshkar Arasteh (2005) used HRSE to partition energy balance components in Sistan area. He showed advection has a value of nearly equal to net radiation in this part of the world, an amount that has almost never been seen anywhere. It seems that Sistan area and Hamun Wetlands are very unique with many catastrophes. Daneshkar Arasteh and Tajrishy (2006) used HRSE to estimate open water evaporation and vegetation cover evapotranspiration from Hamun Wetlands.

A standard meteorological station is located on the northern bank of the reservoir next to the outlet of the Chahnimeh Dam. Daily records of meteorological data including min, max, wet and dry temperature, pan evaporation, wind speed and direction could be found for more than 12 years (since 1994), in this station. Data from

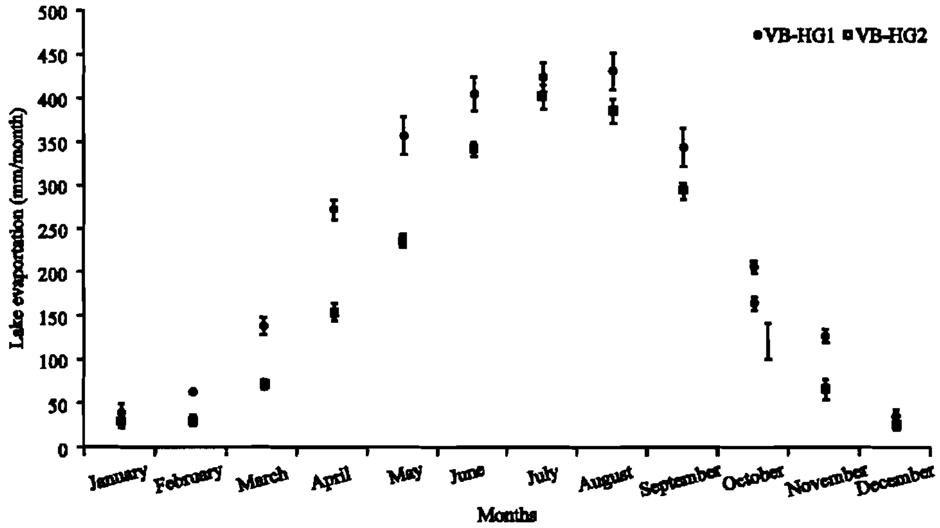

Fig. 3: Chahnimeh monthly evaporation (Daneshkar Arasteh *et al.*, 2005)

Zahak first order meteorological station, located 5 km North of the reservoir is also used for control and completion of Chahnimeh station data. Zahak station began to record from 1992. In Zahak meteorological station sun shine hour and shortwave radiation flux density are collected in addition to normal data of Chahnimeh station. All of parameters measured hourly.

Daily inflow and outflow are measured at two ordinary hydrometric stations. Inflows are measured in Jarikeh, a station equipped with a water level recorder, a telepheric bridge, a 4 m height stage and a standard AOTT current meter. Water surface levels in the Chahnimeh feeder canal are measured continuously and inflow volume integrated and reported daily since 1986.

Outflows are measured at the outlet of the dam with a 4 m height stage at upstream of the outlet weir, twice a day. Lake surface level is also measured twice a day by a set of eight numbers of 1 m height stages. Daily pumping volumes of the Zabol and Zahedan Pumping Plants are determined on the basis of their rating curves.

In this research, an eleven-year duration from May 1994 to September 2004 is considered, in which dry, normal and wet spells are included. Water budget of Daneshkar Arasteh *et al.* (2005) study was considered and free water evaporation was determined for the whole water year. This water budget on the base of a Volume balance Equation (VB) for five day periods was used. Meteorological data of Chahnimeh and Zahak stations were also used to model free water evaporation by PT method. To calibrate α_{PT}, ratio of evaporation rates from equilibrium method and VB was determined.

RESULTS AND DISCUSSION

As mentioned earlier, it seemed that common models require calibration before application in the study area. Figure 4 and 5 show the free water evaporation from Chahnimeh using the VB and PT methods before calibrating for two wet (HG2) and dry (HG1) hydrological conditions for May to October period. As it is shown from Fig. 4, PT model estimates free water evaporation less than true evaporation for dry years during May to October when the 120 day wind blows a warm dry wind blowing over the reservoir. In other words, PT method underestimates open water evaporation from Chahnimeh surface within the periods that Hamun Wetlands are approximately dried. Therefore, it requires calibration for these periods.

But, Fig. 5 shows relatively good estimations. Slope of trend lines for the relation between VB and PT results are 0.51±0.02 and 1.05±0.03, respectively for hydrological conditions of HG1 and HG2. These values show that during dry condition, PT model under predicts the evaporation rate about 50%.

Therefore, α_{PT} values (ratio of evaporation rates from equilibrium method and VB) varying between 2.47±0.09 and 1.20±0.03 for those conditions, respectively. It is shown that when Hamun Wetlands are full of water, Chahnimeh Reservoir acts similar to many other lakes and reservoirs all around the world and PT method leads to reasonable estimates for open water evaporation. But, during the periods in which Hamun Wetlands are dried this method underestimates the evaporation rate and evaporative behavior of the Chahnimeh Reservoir changes. It is clear that under dry conditions the

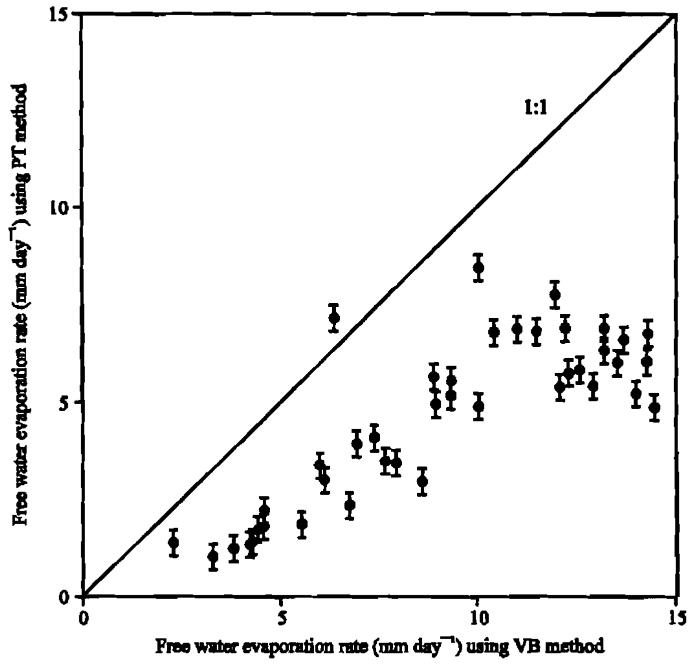

Fig. 4: Comparison between free water evaporation from Chahnimeh Reservoir measured by volume balance (VB) and estimated by Priestley-Taylor (PT) methods for dry hydrological condition (HG1) from May to October

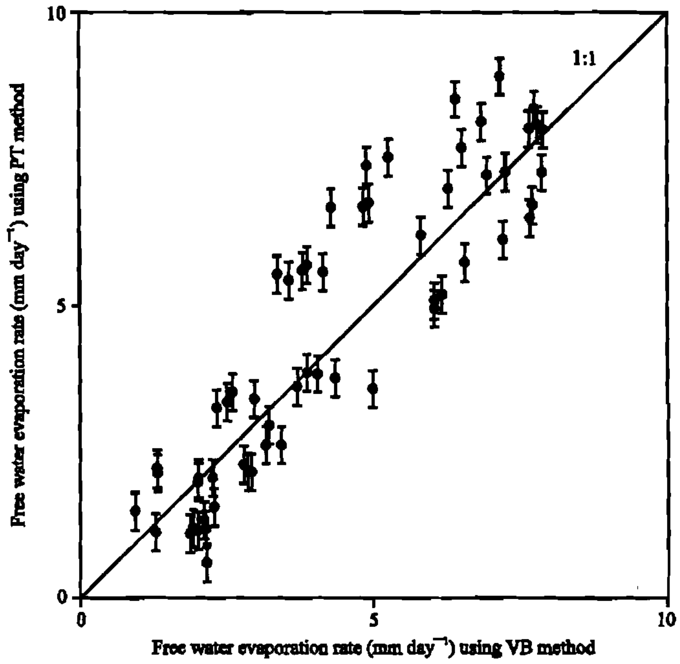

Fig. 5: Comparison between free water evaporation from Chahnimeh Reservoir measured by volume balance (VB) and estimated by Priestley-Taylor (PT) methods for wet hydrological condition (HG2) from May to October

coefficient is increased about two times of normal conditions (2.47±0.09). The value of α_{PT} for HG2 conditions (1.20±0.03) is similar to ones for other lakes and reservoirs around the world such as those summarized by Eaton *et al.* (2001).

Using free water evaporation rate from Chahnimeh surface determined by VB method as the given variable to PT model and using meteorological data, coefficient of α_{PT} was calibrated for monthly time scale. Figure 6 shows temporal variation of α_{PT} within May to October for two

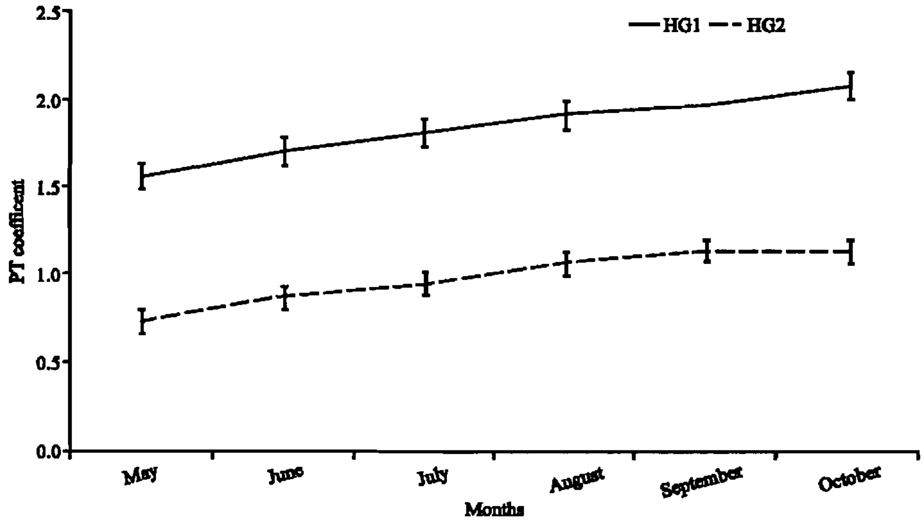

Fig. 6: Monthly variation of α_{PT} for Chahnimeh Reservoir

statistically homogeneous groups or hydrologic conditions.

Figure 6 shows, α_{PT} varies from 0.73 to 2.10 during May to October. For the HG1 group, it is larger than the HG2 group (1.56 to 2.10 for HG1 against 0.73 to 1.13 for HG2). It is observed that from May to October, in which the 120 day warm wind blows and regional energy advection occurs, the Chahnimeh Reservoir experiences conspicuous rise in α_{PT}.

From Fig. 6, one could find that the evaporation from the reservoir decreases to a little more than 70% of equilibrium evaporation rate, for May for the HG2 group and approaches to unity for wet conditions. A similar behavior is seen for the HG1 group but it is less intense. Figure 6 also shows that the decrease in α_{PT} in the HG2 group is more than that of the HG1 group in similar months. The reason should be sought in the air content of sensible heat. The HG1 group is related to dry years, during which Hamun Wetlands do not usually have any water. Therefore, as the 120 day wind blows, it carries an enormous amount of energy as sensible heat from upstream middle latitudes and desert lands of Iran's central plateau to Sistan region and highly influences the evaporation from the reservoir surface and augments it seriously. Whereas during the HG2 years, a part of this energy is consumed for evaporating from the surface of the Hamun Wetlands as the wind first flows over the wetlands water bodies with an area of 4000 km^2 during the wet years. In other word, advected sensible heat transfers to latent heat over Hamun Wetlands. On the other hand, the elimination of sensible heat over the Hamun Wetlands and evaporation from their surfaces increase the regional relative humidity and this causes a decrease in vapor pressure deficit. Both factors decrease the evaporation from the surface of the Chahnimeh Reservoir.

As Sene *et al.* (1991) confirmed, α_{PT} = 1.26 is equivalent to suggesting that, on average, for a water surface, the aerodynamic term of a combination model such as Penman equation contributes 21-22% of the total evaporation whereas in Chahnimeh Reservoir, obtained values for α_{PT}, showed a higher aerodynamic term. This larger term is related to the 120 day wind and transferring large amount of energy by air flow. Unfortunately, there were no proper equipments to measure sensible heat displacement in the study area.

CONCLUSION

Evaporation is the most important unknown factor in the water budget of the Chahnimeh Reservoir, Sistan region, Iran. This study showed that during the year from May to October (when the 120 day warm wind blows through the Sistan), α_{PT} increases due to increase in advected sensible heat. This increase in the α_{PT} is less in the wet years in which nearby the Hamun Wetlands are approximately full of water against dry conditions which their area decreases dramatically. It was shown that common well known models such as Priestley-Taylor requires calibration in the area. Calibration showed the Priestley-Taylor coefficient is time dependent and affected by season and existence of water in Hamun Wetlands.

Further study of the other methods such as mass transfer and energy budget are highly recommended. And also, it is recommended to carry an investigation on energy advection distribution and atmospheric circulation in the Sistan area and its influence on water surface evaporation. But, first of all, it is needed to equip the hydrometric and meteorological stations with required measuring devices as well as a floating energy balance station on the reservoir.

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