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ESTIMATING THE POTENTIAL EVAPOTRANSPIRATION (PET) USING SATELLITE IMAGERY IN ARID LANDS

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Abstract

Evapotranspiration is one of the main sources of water loss in arid regions. Although FAO Penman-Monteith (FAO-PM) method is one of the accurate method to estimate potential evapotranspiration (PET). Nevertheless, it is a point-based method and requires several weather data such as radiation, wind speed, air humidity and temperature, which is not available in all regions. Therefore, this study is aimed to estimate PET equivalent to FAO-PM model using satellite data and Priestly-Taylor (PT) model in Yazd province, located in Central Iran. Daily net radiation and soil heat flux, which are used in PT method, were calculated using Landsat 5 data. Then, the net radiation data were integrated with ground data to estimate PET through PT equation. Although similarity between ground-based Priestly-Taylor (PT land) and satellite-based Priestly-Taylor (PT image) was observed, FAO-PM had higher PET values (RMSE=4.74 mmd^{-1}) compared to other methods in all climatic zones of the study area. Therefore, results of PT image method can be replaced with PT land results to estimate potential evapotranspiration, in regions with limitation or lack of weather data. Finally, linear regression model were used for presenting relationship between ground-based FAO-PM and PT land. For this purpose, 70% and 30% of ground data were used for modeling and testing, respectively at different Selianinov climatic zones of the study area. Maximu RMSE for modeled and test data were 4.6 and 2.93, respectively. The model output was applied on PT image to get the FAO-PM image with maximum RMSE of 3.67. It can be concluded that the defined regression equations for each climate zones in this study, can be used to convert values of satellite- based Priestly Taylor method (PT image) as independent variable (X) to equivalent of FAO-PM PET.

Key words: arid lands, FAO Penman- Monteith, potential evapotranspiration, Priestly- Taylor, remote sensing

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1. Introduction

Evapotranspiration (ET) is described as the combinition of of water evaporation from land surface and plant trenspiration from vegetation. Both evaporation and transpiration processes relies on air temperature, wind speed, relative humidity (i.e., vapour pressure deficit), and solar radiation (Zotarelli et al., 2009). Potential Evapotranspiration (PET) is the maximum amount of water that could be lost under a given set of atmospheric and soil conditions (Thornthwaite, 1944).

Potential evapotranspiration can be measured using direct and indirect methods. Direct method requires lysimeters preparation and installations of experimental plots in field, and it has the highest accuracy (Bernado, 1995). As direct measurement of the potential evapotranspiration is difficult and expensive, it is mostly calculated by indirect experimental methods using weather data (Jensen et al., 2016).

A large number of empirical methods for estimating evapotranspiration, such as Hargreaves Samani, Thornthwaite, Blaney-Criddel etc., have been developed during the last 50 years by using different climatic variables (Zotarelli et al., 2009). Allen et al. (1998) recommended the combined FAO-PM method, to estimate reference evapotranspiration. FAO-PM

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method with regards to measuring of lawn evapotranspiration by lysimeter, has been applied and experienced in different regions of the world and is selected as a standard method for estimating reference evapotranspiration (Pereira et al., 2002; Xing et al., 2008). This method of calculating of evapotranspiration is based on aerodynamic and energy balance concepts. FAO-PM method requires much field data, such as radiation, wind speed, air humidity and temperature, which is sometimes inaccessible in many regions. In addition, field data collecting is often expensive and non-repeatable (Bastiaanssen et al., 1998). Currently, the only method to obtain different variables with high spatial and temporal resolutions required for estimating evapotranspiration, is remote sensing techniques (Santos et al., 2009). Advances in different remote sensing-based ET estimation methods, is facilitated to estimation of the actual and potential evapotranspiration over a regional scale (Bastiaanssen, 2005). Measurement of evapotranspiration using remote sensing models have been widely studied at different time scales and various climate. Tasumi et al. (2003) compared results of remote sensing evapotranspiration estimation model using Surface Energy Balance Algorithm for Land (SEBAL), with Lysimeter evapotranspiration in semi-arid region of Idaho, USA during period of 2000-2003. Comparisons of SEBAL results with the measured results by lysimeter in semi-arid climates show good agreement. Sensitivity analysis resultstes show that the SEBAL model is precise without atmospheric correction. However, SEBAL results are somewhat impacted by differences in satellite images, weather data and operators.

Some PET commonly methods and estimated 10 days PET at three meteorological stations evaluated in Mongolian grassland (Tuya et al., 2006). Temperature based (Hargreaves-Samani and Penman-Monteith), radiation based (Makkink, and Priestley-Taylor) and mass transfer based (Dalton aerodynamic) PET methods were compared. Results show that the PET values estimated using the five methods were correlated with correlation coefficient varies from 0.60 to 1.0. Totally, the Penman-Monteith and Hargreaves-Samani methods are recommended for regional applications in the Mongolian grasslands. Maede et al. (2010) calculated ET in Taita, Kenya using three methods of estimating of evapotranspiration such as Hargreaves, Thornthwaite and Blaney-Criddle. In these models, surface temperatures calculated from MODIS and ASTER satellite data were used as inputs. FAO-PM model was applied as a reference to calibrate the models. Results showed that the Hargreaves model, which is derived from MODIS, is the best model in the region. Chandrapala and Wimalasuriya (2003) calculated actual 10-day ET in Sri Lanka using NOAA-AVHRR satellite and meteorological data of two consecutive years. Results showed that there are differences between the values estimated from satellite data and measured values during 10-day and monthly as 17% and 1%, respectively.

Surface Energy Balance model (SEBAL) and Monteith models were applied to calculated actual evapotranspiration and absorbed photosynthetically active radiation, respectively in a semi-arid region of Borkhar basin in Iran, using Terra/MODIS and ASTER LIA images (Mokhtari, 2005). Results showed no significant differences between estimated PET Penman-Monteith and SEBAL model for both sugar beet and maize. Sun et al. (2010) estimated actual ET in Nansi Lake wetland in China using Landsat 7, DEM, and meteorological data using SEBAL algorithms. Results of the algorithm were found to be similar to the ET obtained from the evaporation pan.

Chavez et al. (2007) estimated daily evapotranspiration values for 11-county area in the Texas High Plains, using Landsat images and a remote sensing based ET algorithm (Mapping Evapotranspiration at High Resolution Using Internalized Calibration or METRIC model), and meteorological data measured at four ET weather stations. Generally, daily ET results show that METRIC achieves well for the climate conditions of the Texas High Plains with prediction errors of 4-20%. A remote sensing based ET algorithm of METRIC, with Landsat images is applied to predict monthly and seasonal ET for water rights and ground water models in southern Idaho, southern California, and New Mexico (Allen et al., 2005). Results of daily and monthly ET measured by METRIC, lysimeter and traditional methods were comparred at different land covers. Results indicated that METRIC or similar methods are efficient, accurate, and inexpensive procedures to predict actual evaporation fluxes from irrigated lands. Gowda et al. (2008), was evaluated METRIC, as a remote sensing based ET algorithm, for mapping ET in the Texas High Plains, USA using two Landsat 5 TM images. The ET model was evaluated by comparing the predicted daily ET with derived soil moisture. Results proves that the METRIC have the potential for mapping of regional ET in the region. To estimate evapotranspiration in Brazil, Landsat satellite imagery and METRIC model, were applied (Falls et al., 2009). Results showed that the metric model can be used for estimating water consumption in irrigated agriculture in North East Brazil.

As mentioned above, most of the researches in field of satellite-based evapotranspiration focused on actual evapotranspiration. But, in many application such as drought assessment (AghaKouchak et al., 2015; Rind et al., 1990), crop yield estimation (Bennett and Harms, 2011) and climate changes (Liu et al. 2018), and estimation of potential evapotranspiration is important. Values of PET shows the amount of water that could potentially be lost to evaporation over a vegetated surface. However, due to the lack of sufficient and well distributed point data, recently efforts directed toward using satellite data for estimating PET (Huang et al. 2017; Kim and Hogue, 2008; Shwetha and Kumar, 2018). In adition to the combination of point based and satellite data (Majozi et al., 2017, Roy et al., 2017). Capability of sensor data in estimation of plant biophysical parameters has made provision of spatially distribution of PET estimation (Reyes-Gonzalez et al., 2018; Rahimian et al., 2014).

Liu et al. (2013), assessed seven commonly used potential evapotranspiration methods for selecting appropriate ETo equations for weather stations with limited climate in Beijing, China. Results showed that the two methods of vapour pressure deficit or VPD-based and VPD-radiation performed well in ETo estimation. Considering of climate data limitation, the calibrated Turc, VPD-based and VPD-radiation-combined methods can be replaced for complex Penman Monteith method in Beijing. To estimate monthly potential evapotranspiration (ET0) at Pantnagar, India, two temperature-based approaches (Hargreaves and Thornthwaite) and two radiation based approaches (Priestley-Taylor and Turc) were used (Nikam et al., 2014). Turc method was the best method, having lowest RMSE and high coefficient of determination (r=0.792) on monthly time period. The Priestley-Taylor was the best for spring season with lowest error. All the methods show weak results for summer season, compared to other seasons. The main objective of this study was to develop a satellite-based PET model that estimates PET equivalent to the ground-based FAO-PM model in Yazd province. Since FAO-PM model requires several climate parameters which are not regularly available in the study area, daily net radiation was obtained using satellite data Landsat 5 data. Then, regression models were defined for different climate zones to convert values of satellite- based Priestly-Taylor method to equivalent of FAO-PM potential evapotranspiration.

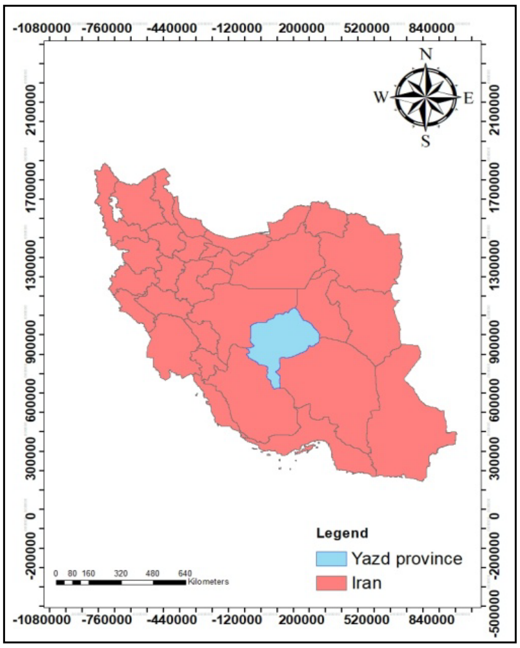
2. Material and methods

2.1. Study area

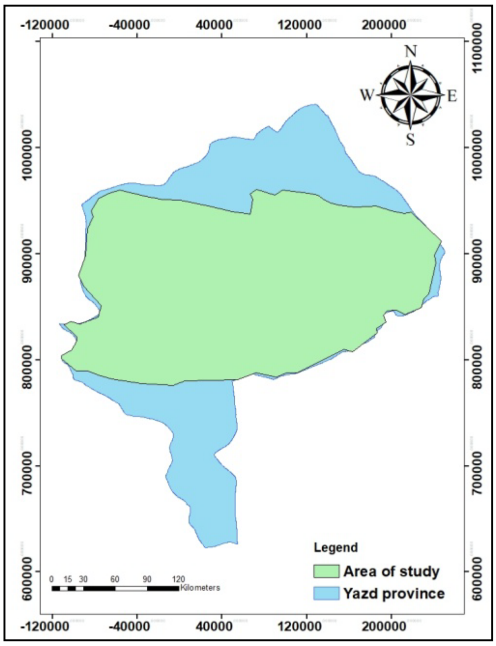
Yazd province (the study area), which is located in the central part of Iran, comprises 50,052 km². It is situated between 52° 44.91 ' to 56° 39.8' E longitude and 30° 57.5' to 32° 38.3' N latitude (Fig. 1). The elevation of the study area ranges from 4075 m.a.s.l. at the Shirkooh summit to 970 m.a.s.l at the Siahkooh playa (Zare, 2009). High variability in spatial and temporal of rainfall and prolonged periods of droughts are a characteristic of the Yazd province.

According to the last 64-year meteorological data in Yazd weather station, the mean annual precipitation is about 60 mm, with a high coefficient of variation of about 45%. The proportion of winter precipitation to total precipitation is 55%, primarily falls from winter storms moving eastward from the Mediterranean. Average annual temperature of Yazd is 19.1°C between 1953 and 2017, while this amount was 18.8°C for the normal period of 1961-1990. During 1953-2017, maximum and minimum average relative humidity in Yazd were 54.2% (January) and 17.6% (July), respectively.

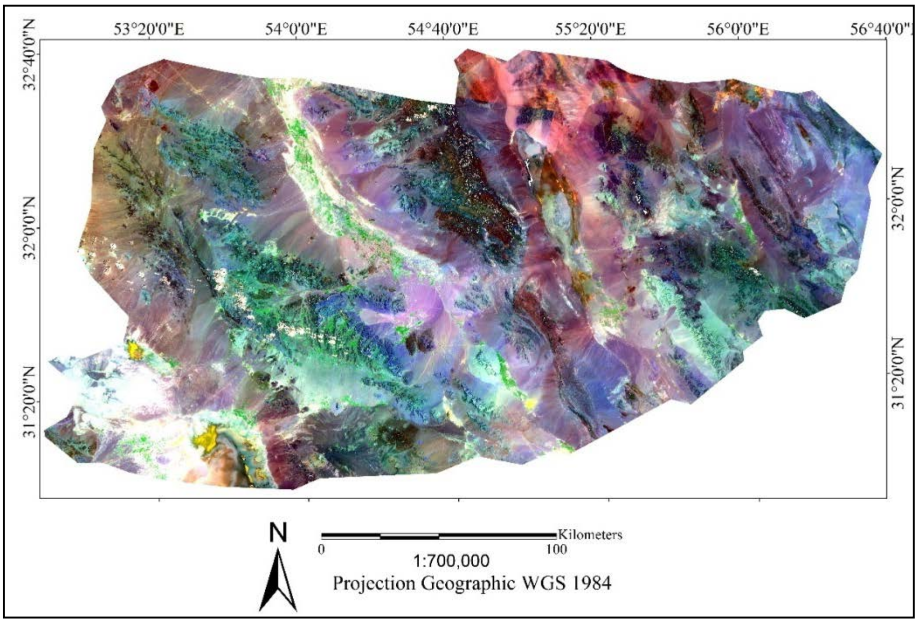
Vegetation density of the study area, similar to other arid lands, is very low and rarely reaches 30%. The negative effect of reduction in vegetation cover is visible when it reaches to less than 20%. Due to lack of the permanent or even seasonal surface water in the study area, the groundwater sources supply necessary water for different purposes (Zare, 2009).



(a)



(b)



(c)

Fig. 1. Location of the study area in: (a) Iran, (b) Yazd province, and (c) Landsat image

2.2. Data

Satellite data of this study were consisted of 12 Landsat 5 Thematic Mapper (TM sensor) images captured on years of 2009, 2010 and 2011. Two Landsat 5 TM scenes with paths/row of 161-162/38 covers the entire study area. The wavelength range for the TM sensor is from visible, through mid-IR, into the thermal-IR portion of the electromagnetic spectrum. Bands1 to 5 and 7 of the Landsat 5 has spatial resolution of 30 meters. The resolution of the thermal infrared band is 120 meters. Since potential ET estimation is mostly important during spring and summer, Landsat images acquired in these seasons were collected for the study. Table 1 shows characteristics of the six paired mosaic Landsat 5 images used in this study.

Climate parameters of air temperature, wind speed, sunny hours and relative humidity, have been used based on the specific date of each image, i.e. on a daily basis for the years of 2009, 2010 and 2011, at 30 synoptic, climatology and rain-gauge stations, located in different parts of the Yazd province. As a sample, Table 2 shows some climate parameters of Yazd weather station for time period of the four Landsat images have been used in this research. Land use/cover in the study area (Fig. 2) consists of bare land, rangeland, farmland (irrigated), afforestation, sand dune (Zare, 2009). Flowchart of adopted methodology of this research is shown in Fig. 3.

2.3. Albedo

Surface albedo is considerd as the ratio between reflected (shortwave) radiation and the incoming radiation reaching earth. It is measured in solar effective wavelength range of 0.3 to 3µm and calculated from corrected reflectance value using linear model. Surface albedo can be estimated from Landsat 5 spectral bands (Liang et al., 2003) (Eq. 1):

$$\alpha = (0.293 * band1 + 0.274 band2 + 0.233 * band3 + 0.156 * \\ * band4 * 0.033 * band5 + 0.011 * band7 \quad (1)$$

where: α is surface albedo.

2.4. Daily net radiation

Before calculating of potential evapotranspiration using satellite- based Priestley-Taylor method, daily net radiation is calculated using (Eq. 2) (Mokhtari, 2005):

$$R_{net-day} = (T_{a-day}(1-1.1\alpha).R_a) - 110\frac{T_{sw}}{11.5741} \quad (2)$$

where: $R_{net-day}$ is daily net radiation$[MJm^{-2}d^{-1}]$, R_a = Daily shortwave radiation at top of atmosphere; which are calculated in weather stations $[MJm^{-2}d^{-1}]$; T_{a-day} is atmosphere daily transmissivity [-]; α =is Wide-band surface albedo [-]; T_{sw} is atmospheric transmission capacity $[m^2d\,Mj^{-1}]$, calculated using (Eq. 3) (Mokhtari, 2005):

$$T_{sw} = \frac{312}{R_a + 11.5741} \quad (3)$$

where: R_a is Daily shortwave radiation at top of atmosphere, which are calculated in weather stations; T_{a-day} is atmosphere daily transmissivity; α =is Wide-band surface albedo, T_{sw} is atmospheric.

Atmospheric daily transmissivity can be calculating by applying the (Eq. 4):

$$T_{a-day} = (0.25 + 0.5n / N) \quad (4)$$

where: *n/N* is the relative sunshine duration.

Due to the differences in *n/N* values at each weather stations in the study area, numerical values of this ratio were interpolated for each used image dates. Inverse Distance Weighting (IDW) method was selected as the best method of interpolation of data, since its RMSE value was the lowest compared to other interpolation.

2.5. FAO Penman-Monteith equation (FAO-PM)

The FAO-PM equation for calculating potential evapotranspiration can be expressed as (Allen et al., 1998) (Eq. 5):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (5)$$

where: *ETo* is reference evapotranspiration [mm/day]; *Rn* is net radiation at crop surface [$m^2d\ Mj^{-1}$]; *G* is soil heat flux density [$m^2d\ Mj^{-1}$]; T is mean daily air temperature at 2 m height [°C]; u_2 is wind speed at 2 m height [ms^{-1}]; e_s is saturation vapour pressure [kPa]; e_a is actual vapour pressure [kPa]; $e_s - e_a$ is saturation vapour pressure deficit [kPa]; Δ is slope vapour pressure curve [kPa $°C^{-1}$]; γ is the psychrometric constant [kPa $°C^{-1}$].

Table 1. Characteristics of the Landsat 5 images used in the study

Image name	*Paired mosaic images*	*Acquisition Date*	*Cloudy cover (%)*	*Time*
LT51620382009154KHC00 LT51610382009131KHC00	Spring, 2009	03/06/2009 11/05/2009	0 0	06:44:48.42663 06:38:13.46863
LT51620382009186KHC00 LT51610382009195KHC00	Summer, 2009	05/07/2009 14/07/2009	0 0	06:45:23.66875 06:39:21.81713
LT51620382010125KHC00 LT51610382010118KHC00	Spring, 2010	05/05/2010 28/04/2010	1 1	06:47:32.00969 06:41:21.70831
LT51620382010189KHC00 LT51610382010198KHC00	Summer, 2010	08/07/2010 17/07/2010	0 0	06:47:14.96825 06:41:02.03588
LT51620382011128KHC00 LT51610382011089KHC00	Spring, 2011	08/05/2011 30/03/2011	0 2	06:46:19.04706 06:40:21.85125
LT51620382011288KHC00 LT51610382011297KHC00	Summer, 2011	15/10/2011 24/10/2011	0 0	06:44:44.34381 06:38:29.01506

Table 2. Climate parameters of the Yazd weather station

Date	*Temperature (°C)*	*Wind speed(m/s)*	*Sunny hours*	*Relative humidity (%)*
28/04/2010	24.4	11	10.2	16
05/05/2010	22.9	8	12.2	23.5
08/07/2010	33.9	8	12.3	10.5
17/07/2010	36.3	4	10.1	12

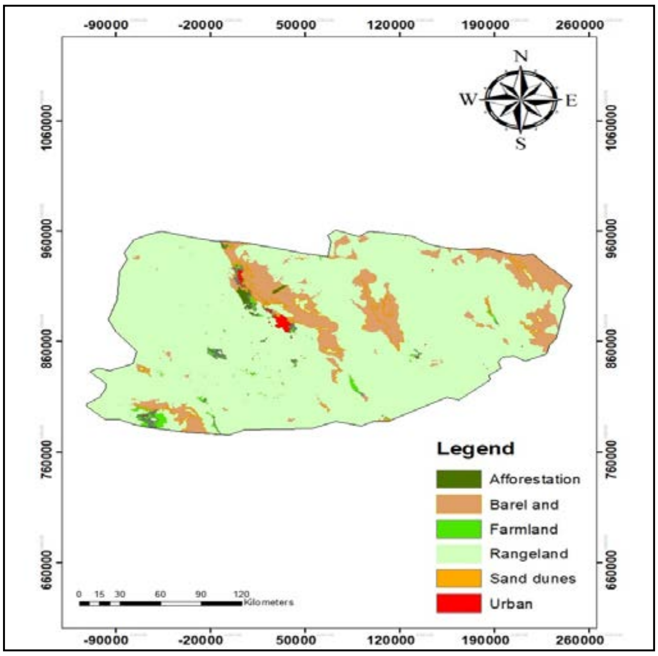


Fig. 2. Land cover map of the study area

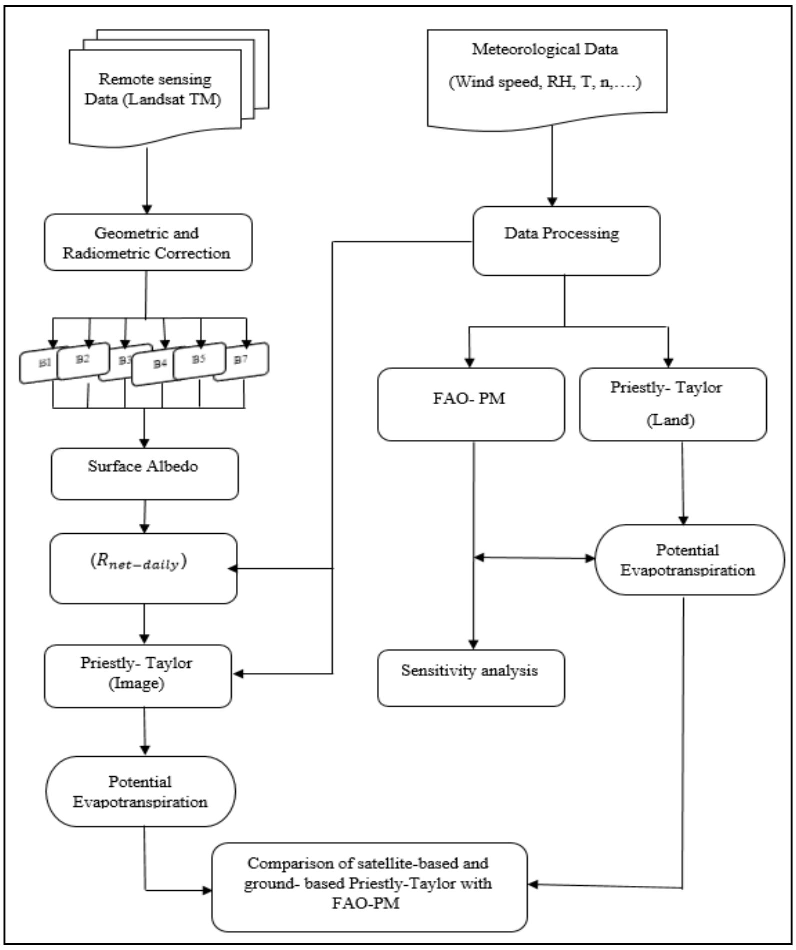


Fig. 3. Flowchart of adopted methodology

The FAO-PM method applies standard climatic data according to the methodology provided by the Allen et al., (1998) in FAO Irrigation and Drainage Paper No.56 guideline.

2.6. Priestley–Taylor (PT) potential evapotranspiration

Different methods are proposed to calculate potential evapotranspiration, each of them is different somewhat on the base of required data. If temperature and net radiation data are available, Priestley-Taylor method (Eq. 6) is the best method for calculating of potential evapotranspiration. This method is simplified based on the Penman and it is replaced as the Penman equation aerodynamic component with an empirical coefficient, which is known as Priestley Taylor parameter (Priestley and Taylor, 1972) (Eq. 6):

$$ET_0 = \alpha \frac{\Delta}{\Delta + \gamma}\left(\frac{R_{net-day} - G}{\lambda}\right) \quad (6)$$

where: ET_o is reference evapotranspiration (mm/day); is a dimensionless coefficient with a proposed empirical value of 1.26 (Priestley and Taylor, 1972); Rn and G are the net radiation and the soil heat flux density [$m^2 d\ Mj^{-1}$]; Δ is slope vapour pressure curve [KPa $^{\circ}C$]; γ is a psychrometric constant [KPa $^{\circ}C$]; λ is the latent heat of vaporization [$MJKg^{-1}$], which is estimated from the (Eq. 7):

$$\lambda = (2.501 - [2.361 * 10^{-3})T \quad (7)$$

where, T is daily air temperature [°C].

To estimate potential evapotranspiration according to the Priestley Taylor method, γ and Δ, were calculated in the same way of the FAO-PM method according to the guideline provided by Allen et al. (1998), for each day of images. However, in estimated method of ground- based Priestley Taylor (PT land), net radiation is calculated according to the guideline provided by Allen et al. (1998), and to estimate the PET of satellite- based PT method (PT image), Eq. (2) is applied.

2.7. Sensitivity analysing of the effective parameters to estimate PET using FAO-PM method

Minimum and maximum air temperature, relative humidity, wind speed and sunny hours are main parameters for estimating potential evapotranspiration using FAO-PM method (Chen et al., 2005). On the other hand, measuring and recording of the above mentioned variables are subjected to systematic and human errors. Therefore, it is necessary to evaluate the impact of changes in these parameters of the FAO-PM method. To evaluate sensitivity of the FAO-PM method, increase and decrease values of the main input parameters in estimating of potential evapotranspiration, such as the maximum and minimum air temperature (T_{max} and T_{min}), relative humidity (RH), wind speed (Ws) and sunshine hours (n), were considred in to the FAO-PM model, in three change intervals of ±10, ± 20 and ±30%.

2.8. Evaluation of the different methods for calculating PET

Several parameters of evaluation included correlation coefficient (R), standard deviation (SD), Mean Absolute Error (MAE), Root Mean Square Error (RMSE), Maximum Absolute Error (MAXE) and Standard Error of the Estimate (SEE) were used to evaluate FAO-PM method by Priestley-Taylor methods (Eqs. 8-11):

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|O_i - E_i| \quad (8)$$

$$MAXE = MAX\,|O_i - E_i| \quad (9)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(O_i - E_i)^2}{n}} \quad (10)$$

$$SEE = \sqrt{\frac{\sum_{i=1}^{n}(O_i - E_i)}{n-1}} \quad (11)$$

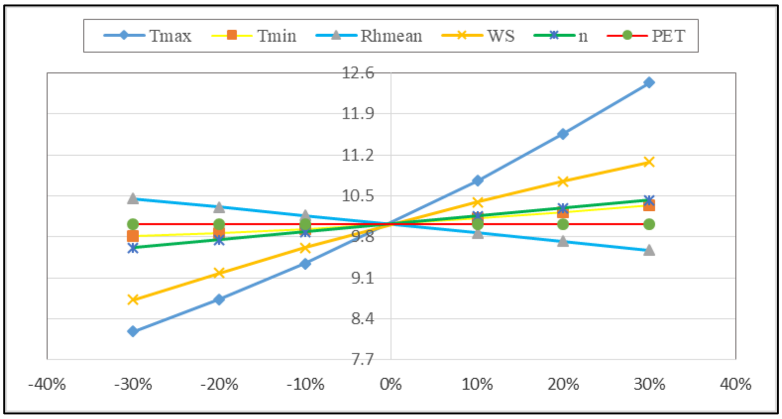
where: O_i is Potential evapotranspiration estimated using FAO-PM Method [mm/day]; E_i: Potential evapotranspiration estimated using PT method [mm/day]; *n*: total number of data [-].

3. Results and discussion

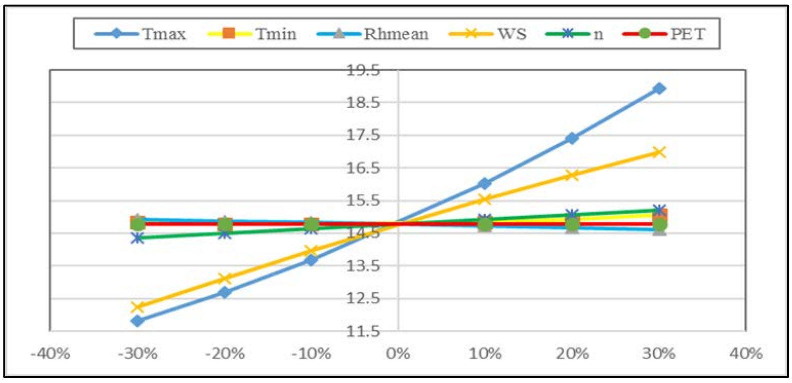
3.1. Sensitivity analysis

Sensitivity analysis results of the effective parameters in estimating of potential evapotranspiration in FAO-PM method (T_{max}= maximum air temperature [°C], Ws= wind speed [ms^{-1}], n= sunshine hours [h], RH= relative humidity [%] and (T_{min}) = minimum air temperature [°C]), were analyzed. Investigation of the sensitivity analysis indicated that the mostly sensitivity parameters in FAO-PM method are concerned to maximum air temperature (T_{max}), and wind speed (Ws), respectively. But effect of maximum temperature parameter is more than the minimum air temperature. Also the sensitivity of the maximum air temperature and wind speed parameters in summer is more than spring.

The most sensitive parameters were observed in spring 2009 and summer 2010. As an example, the results of sensitivity analysis of the FAO-PM method (Changes ±10%, ±20% and ±30% in climatic parameters of the Tmax, Tmin, RH, WS, and n) in spring and summer of 2010 in Yazd weather station are shown in Fig. 4.



(a)



(b)

Fig. 4. Results of sensitivity analysis of the FAO-PM method (Changes ±10%, ±20% and ±30% in climatic parameters of the Tmax, Tmin, RH, WS, and n) in: (a) spring and (b) summer of 2010 in Yazd weather station

3.2. Potential evapotranspiration

Daily net radiation was calculated for each of the selected days, using satellite images and its value is extracted for each of weather station located in the study area. Location of the selected weather station is shown in Fig. 5. Potential evapotranspiration is calculated by Priestley-Taylor method. Figs. 6-7 show the estimated potential evapotranspiration for each of these stations for one day in spring and summer of 2009, 2010 and 2011 respectively, using FAO-PM method, satellite-based Priestley-Taylor (PT image) and ground- based Priestley-Taylor (PT land) methods. According to the Fig. 7, the highest amount of potential evapotranspiration is occurred at Ebrahim Abad station in summer 2010 (FAO-PM method) and at Chah Afzal station in summer 2009 (PT method).

Comparing analysys of the three methods of estimating of potential evapotranspiration, shows that the amount of potential evapotranspiration in summer is more than spring due to the increase in air temperature. FAO-PM method has greater amount of estimated PET than the other two methods in all weather stations.

Results of potential evapotranspiration from satellite- based Priestley-Taylor (PT image) and ground- based Priestley-Taylor (PT land) unlike the FAO-PM, are very similar and close to each other. Therefore, to estimate potential evapotranspiration in regions with lack of weather data, results of PT image method can be replaced by PT land results.

3.3. Relationship between estimated PET FAO-PM and estimated PET ground- based Priestley Taylor (PT land) methods in different temporal and spatial

Statistical results of estimated potential evapotranspiration using FAO-PM and ground- based Priestley Taylor at different times and on three climates zones is shown in Table 3. The correlation coefficient for SSA, AA and A climate zones are 0.59, 0.57, and 0.51, respectively, which are statistically significate at 1% level. The slight semi-arid climate (SSA), while having the highest correlation (r=0.59), has the lowest error indicators such as RMSE and MAE (3.43 and 2.48 mm/day, respectively). Potential evapotranspiration rate in SSA climate zone is less than two other climate zones. Map of the Selianinov climate zones of the study area is shown in Fig. 8. According to climatic Selianinov classification method, the study area is grouped in three classes of Absolutely-Arid (AA), Arid (A), and Slight Semi-Arid (SSA).

FAO-PM Method estimates the amount of potential evapotranspiration more than PET Priestley-Taylor method (Fig. 9). The estimated PET FAO-PM and PT land methods, regardless of climatic characteristics, at different times and regions are statistically significant at 1% level. Values of error indicators of MAE, RMSE and SEE were 3.77, 4.74 and 1.95 (mm/day), respectively.

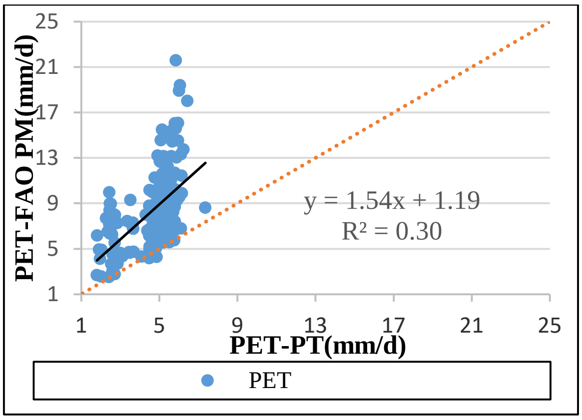


Fig. 9. Relationship between PET FAO-PM and PT Land, without considering climate parameters

3.4. Modelling and testing

Potential evapotranspiration values of the FAO-PM and ground- based Priestly-Taylor (PT land) were calculated at two seasons for three years in all weather stations located in three climatic zones of AA, A and SSA. Among all weather stations in each climate zone (AA = 90, A = 48 and SSA=42), 70 percent of stations were selected for modelling and the remain (i.e. 30%) were chosen randomly, for testing by FAO-PM method. The correlation coefficient (r) for linear regression equations of modelling and testing stages were 0.66, 0.59 and 0.70, for climate zones of AA, A and SSA, respectively, and were statistically significant at 1% level. According to Table 4, correlation coefficient in testing stage is increased in all three climate zones, compared with modelling stage, and amount of error is also decreased. Slight semi- arid climate (SSA) has the highest correlation and lowest error, compare with the other two climate zones. MAE and RMSE for this climate zone were 1.98 and 2.47 mm/day, respectively, in testing stage.

3.5. Relation between PET of FAO-PM and satellite-based Priestly Taylor method

To investigate the relationship between PET of FAO-PM and PT image, linear regression defined based on two field methods have been used in the three climate zones (Table 5). In these equations, PET of PT image is introduced as independent variable (X) and PET of FAO-PM (modeled with image) is defined as dependent variable (Y). Then, some statistical indicators between modeled PET image and actual values of FAO-PM have been calculated (Fig. 6).

Maps of potential evapotranspiration modelled with image (belong to spring and summer of 2009, 2010 and 2011) for the three climatic zones of AA, A and SSA is shown in (Figs. 10, 11 and 12). According to the (Fig. 11), maximum amount of potential evapotranspiration modelling with image is 14.94 mm/day for summer 2010, which is observed in arid climate zone.

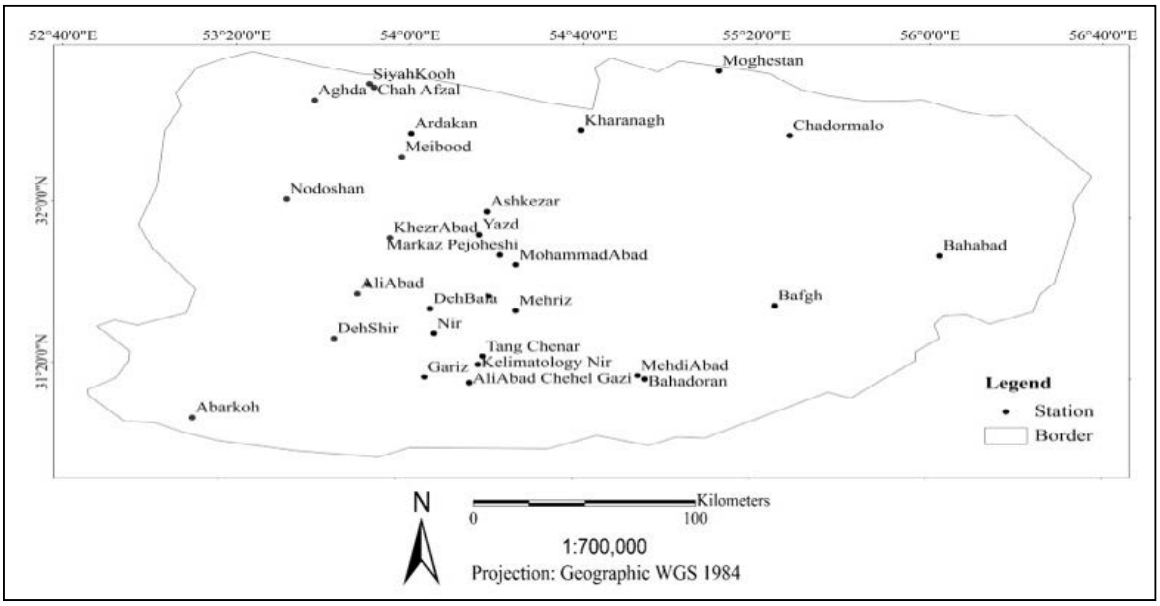
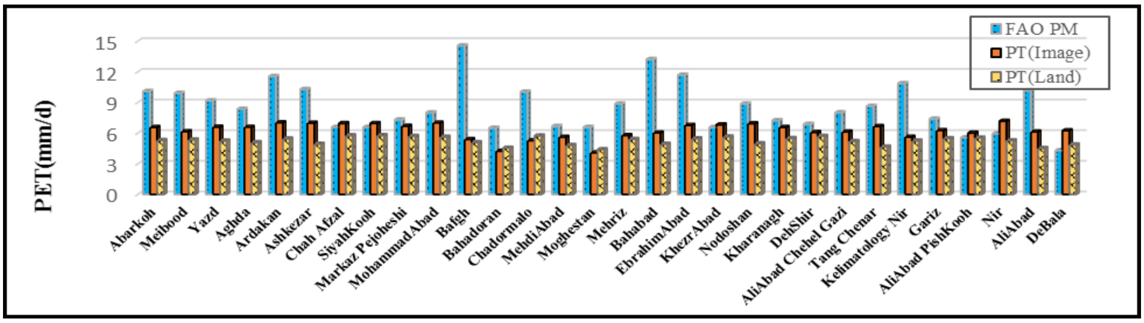
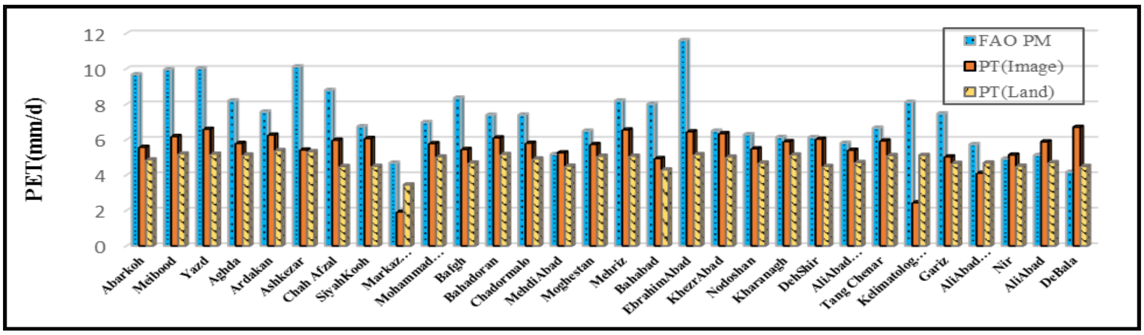


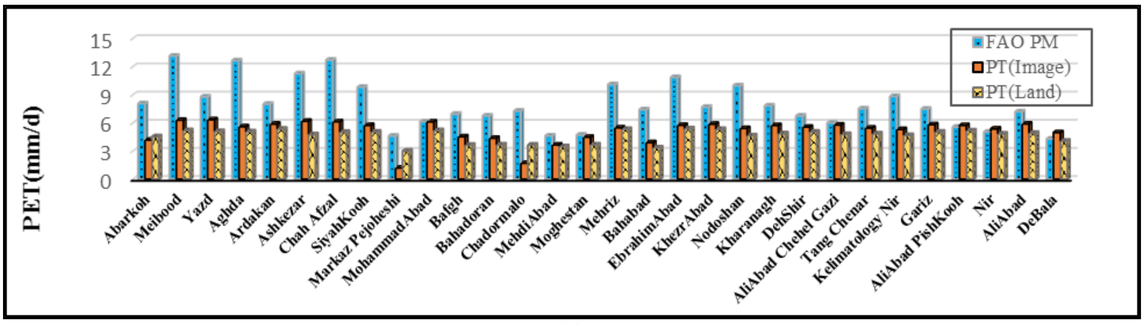
Fig. 5. Location of the selected weather stations



(a)



(b)



(c)

Fig. 6. Estimated PET for the selected stations using satellite and based Priestley Taylor (PT image and PT land) and FAO-PM in: (a) spring 2009, (b) spring 2010, and (c) spring 2011

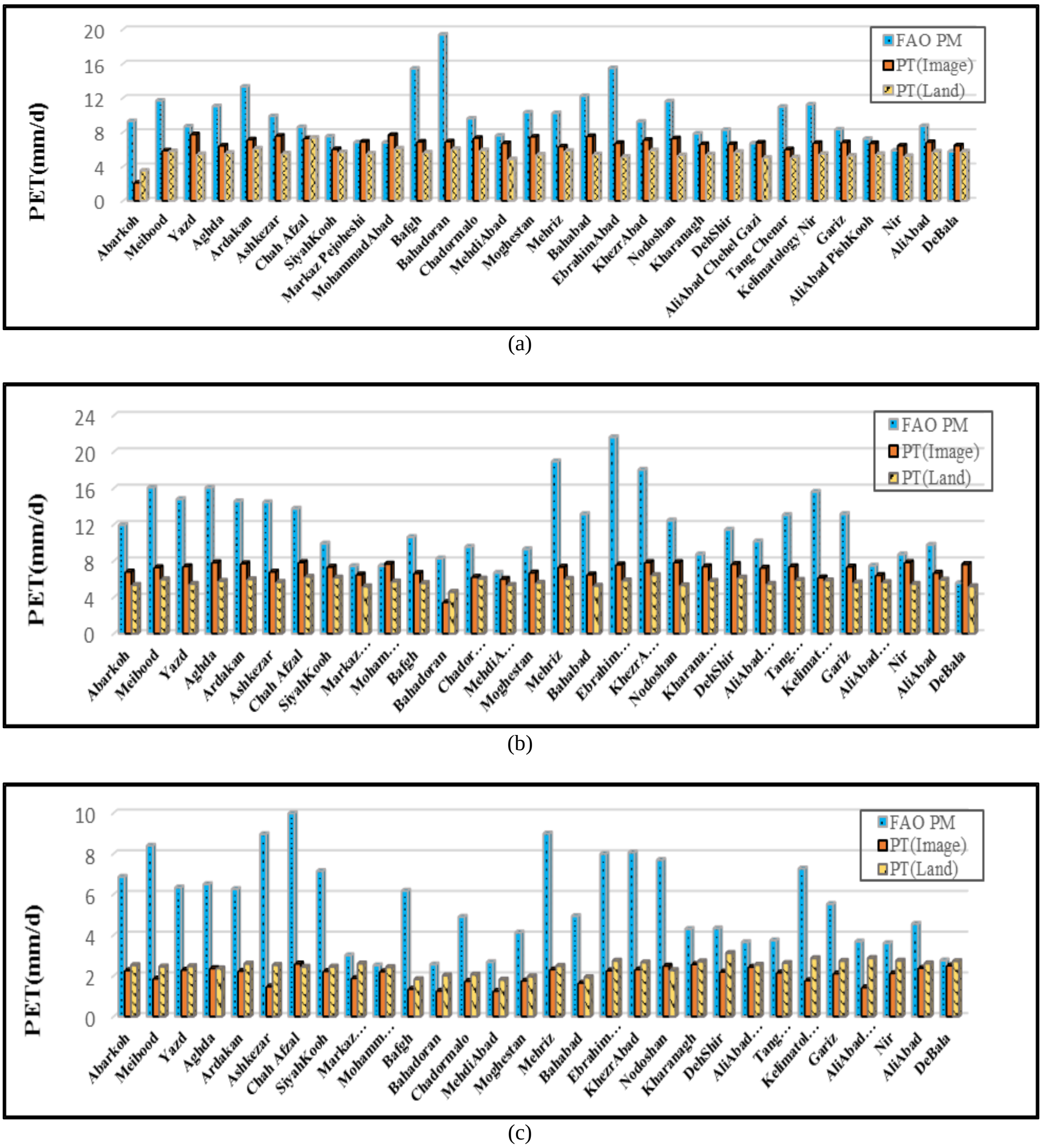


Fig. 7. Estimated PET for the selected stations using satellite and based Priestley Taylor (PT image and PT land) and FAO-PM in: (a) summer 2009, (b) summer 2010, and (c) summer 2011

Table 3. Statistical parameters of relationship between FAO-PM and PT (land) estimated PET methods at three climate zones

Climate Zone	*Equation*	*R*	*SD*	*MAXE*	*MAE*	*RMSE*	*SEE*
AA*	Y=1.45x+ 1.90	0.57	2.71	13.32	4.03	4.85	2.02
A	Y=1.66x+ 1.24	0.51	3.27	15.75	4.41	5.45	2.12
SSA	Y=1.68x- 0.77	0.59	2.34	9.74	2.48	3.43	1.59

Absolutely-Arid (AA), Arid (A), Slight Semi-Arid (SSA)

Table 4. Statistical parameters of linear regression equations of modelling and testing stages for FAO- PM and PT land methods

Climatic zone	*Stage*	*Equation*	*R*	*MAE*	*RMSE*	*SEE*
AA*	Modeling	Y=1.45X+ 1.90	0.57	3.79	4.60	1.96
	Testing		0.66	1.91	2.72	0.80
A	Modeling	Y=1.66X+ 1.24	0.51	4.46	5.55	2.14
	Testing		0.59	2.31	2.93	-0.14
SSA	Modeling	Y=1.68X- 0.77	0.59	2.61	3.36	1.64
	testing		0.70	1.98	2.47	0.05

Absolutely-Arid (AA), Arid (A), Slight Semi-Arid (SSA)

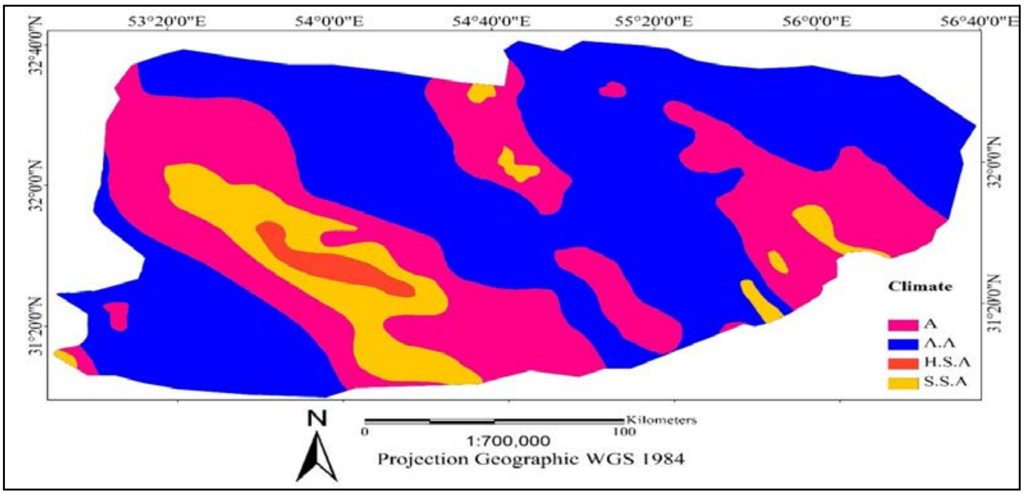


Fig. 8. Map of the Selianinov climate zones of the study area [Arid (A); Absolutely-Arid (AA); High Semi-Arid (HSA), and Slight Semi-Arid (SSA)]

Comparing results of these maps (Figs. 10-12) with actual PET values of FAO-PM (Fig. 6 and 7), indicates that in modelled PET image, amount of evapotranspiration is more than actual amounts of FAO-PM, as shown in (Fig. 13).

Negative sign in SSE values probes the mentioned subject. As shown in (Fig. 13) and (Table 5), the absolutely arid climate zone (AA) has the highest correlation and the lowest amount of statistical indicators among the other two climatic zones. However, AA and SSA climate zones shows close correlation, but SSA owned lower error (RMSE= 3.04 mm/day) than A climate zone. Results of potential evapotranspiration from satellite- based Priestley-Taylor (PT image) and ground- based Priestley-Taylor (PT land), are very similar and close to each other. Considering these similarity, results of the modelling and testing stages for two methods of FAO-PM and PT land, and comparing actual values of potential evapotranspiration of FAO-PM method with estimated PET modelled images in different climate zones, potential evapotranspiration can be measured by applying the Priestley Taylor method using satellite images in different regions of the Yazd province and even in areas with no weather stations or with imitated climate data.

The defined regression equations in this study for each climate zones can be used to convert values of PT image method as independent variable (X) to equivalent of FAO-PM potential evapotranspiration. Estimated potential evapotranspiration in Yazd province, shows that the PT land and PT image methods calculates PET lower than FAO-PM method, that is in agreement with Jacobs et al. (2004), that indicated that the Priestley-Taylor and Penman methods were estimated PET more than FAO-PM method, in a study on a wet meadow in Florida (USA). Turk and Mackink methods do almost as well as FAO-PM method.

The most important vaiables in estimating of PET in Yazd province are maximum air temperature, and wind speed, considering sensitivity analysis of the input parameters in the FAO-PM. In addition, impact of these parameters in summer is more than spring. Therefore, using temperature-based equations are more precise in estimating of PET in Yazd province. Results of climate input variables sensitivity analysis for Penman-Monteith model using the Sobol' method in the south of France showed that ETo is mainly governed by wind speed in winter and solar radiation in summer (Bois et al., 2007).

Because of a rapid increase in the average air temperature of the study area in summer, PET have been increased rather than spring season. This increase in absolute arid region (AA) was more than arid (A), and slight semi-arid (SSA) regions. Average of potential evapotranspiration by FAO-PM method were 8.25, 8.20 and 6.70 mm/day for climate zones of AA, A and SSA, respectively. As it is previously mentioned, correlation coefficient (r) for linear regression equations of FAO-PM and PT land for testing stage has been increased, but RMSE and SSE values have been decreased from 5.44 and 2.14 mm/day in modelling stage to 2.93 and -0.14 mm/day in testing stage, respectively.

4. Conclusions

Results of potential evapotranspiration from satellite- based Priestley-Taylor (PT image) and ground- based Priestley-Taylor (PT land), are very similar. Therefore, it is possible to estimate potential evapotranspiration using the Priestley-Taylor method, that only requires solar radiation and air temperature data, and then with replacement of the existing equations in modelling stage, finally achieve to the equivalent FAO-PM potential evapotranspiration. Defined regression equations for each climate zones in this study, can be applied to convert values of satellite-based Priestly Taylor method (PT image) as independent variable (X) to equivalent of FAO-PM PET.

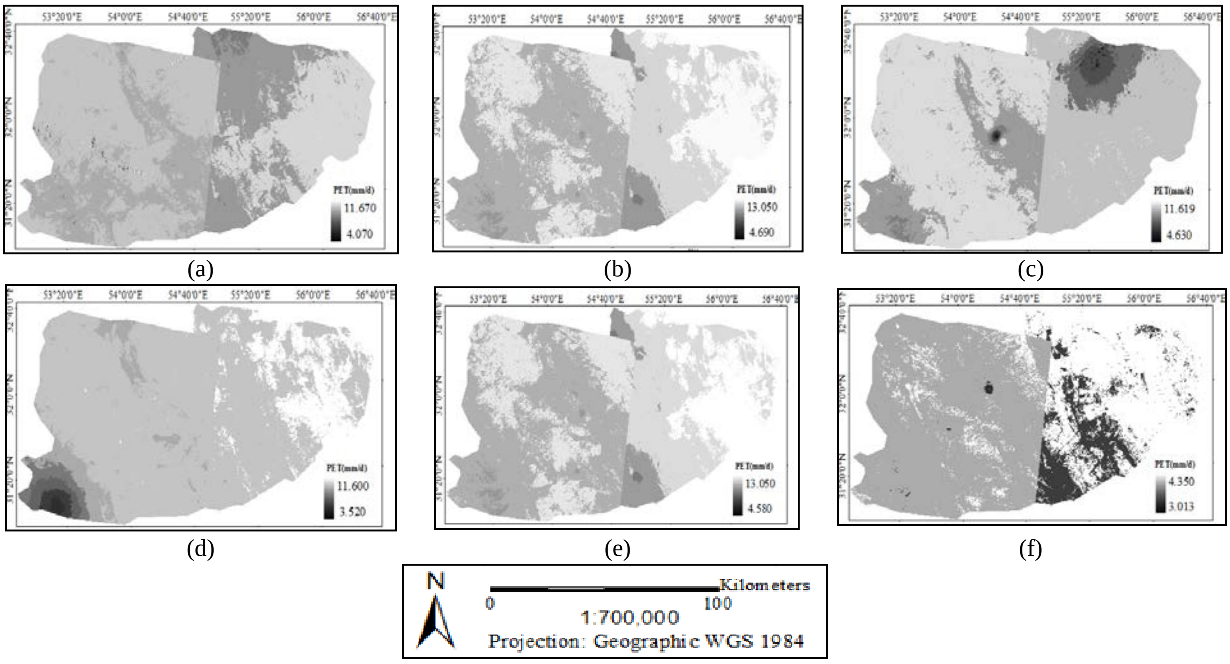


Fig. 10. Map of modeled image of potential evapotranspiration for climates zones of Absolutely-Arid (AA), in: (a) spring 2009, (b) spring 2010, (c) spring 2011, (d) summer 2009, (e) summer 2010, and (f) summer 2011

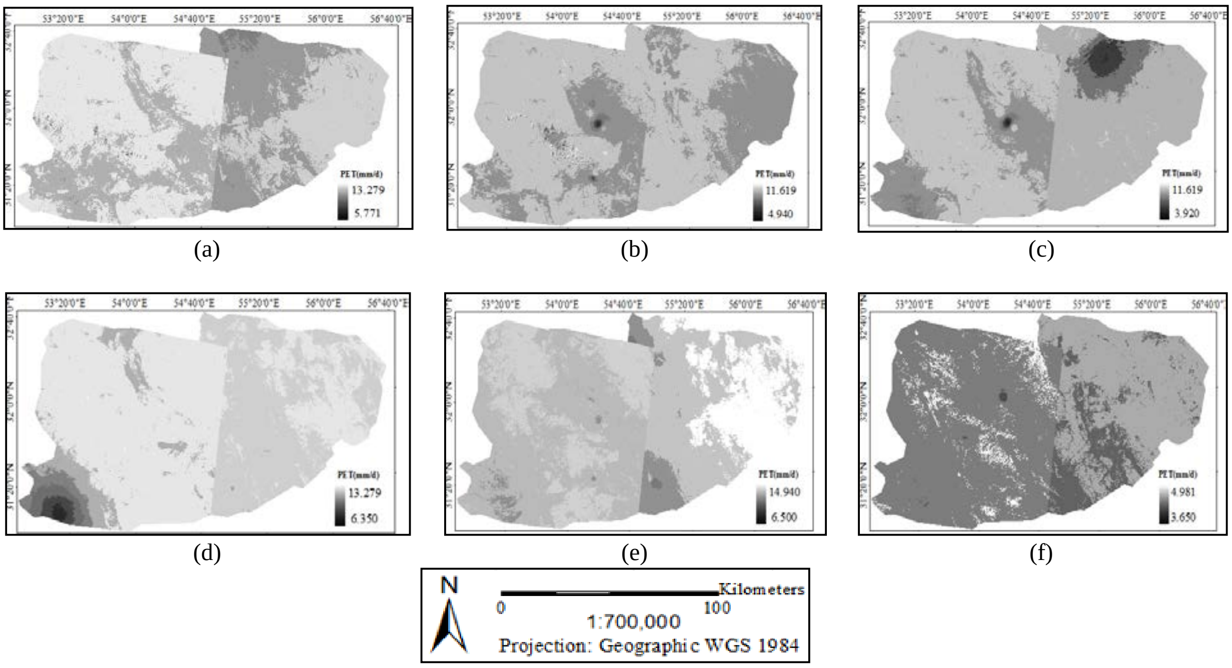
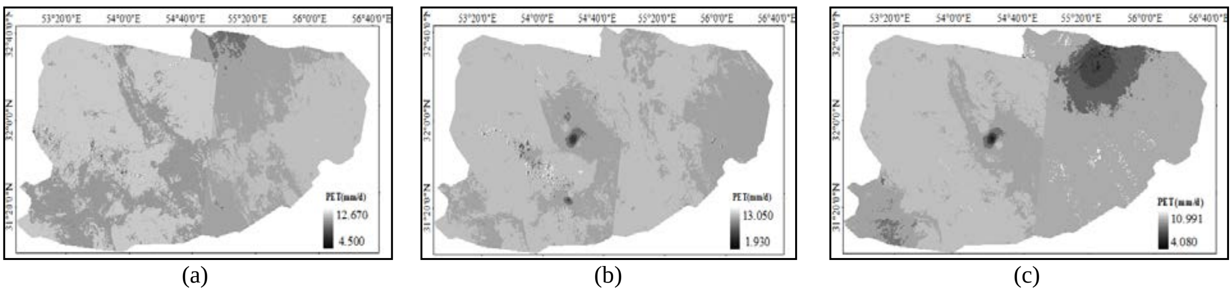


Fig. 11. Map of modeled image of potential evapotranspiration in climates zones of Arid (A), in: (a) spring 2009, (b) spring 2010, (c) spring 2011, (d) summer 2009, (e) summer 2010, and (f) summer 2011



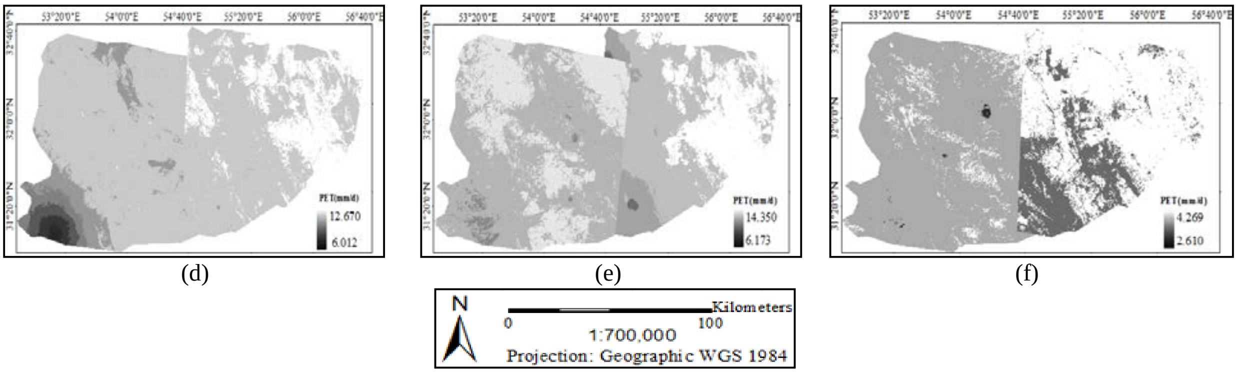


Fig. 12. Map of modeled image of potential evapotranspiration for climates zones of Slight Semi-Arid (SSA), in: (a) spring 2009, (b) spring 2010, (c) spring 2011, (d) summer 2009, (e) summer 2010, and, (f) summer 2011

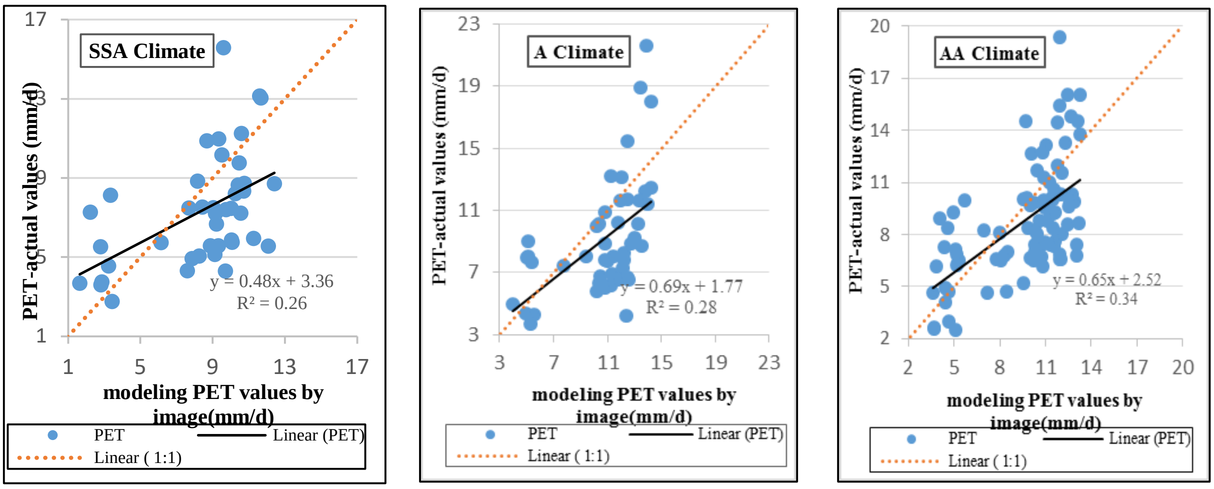


Fig. 13. Relationship between actual values of PET of FAO-PM with values of the PET modeled image in three climate zones of AA, A and SSA according to the line adaptation (1:1)

Table 5. Statistical indicators of relationship between the actual values of potential evapotranspiration FAO-PM and modelled image in three climate zones of Absolutely-Arid (AA), Arid (A), Slight Semi-Arid (SSA)

Climate	*R*	*SD*	*MAXE*	*MAE*	*RMSE*	*SEE*
AA	0.58	2.81	7.44	2.47	2.94	-0.94
A	0.53	3.34	8.19	3.11	3.67	-1.30
SSA	0.51	2.89	6.51	2.56	3.04	-1.02

As direct measurement of the potential evapotranspiration is difficult and expensive, it is mostly calculated by indirect experimental methods using weather data. FAO-PM as an accurate and frequently used method requires much field data which is sometimes inaccessible in many regions, and or is not agreement with development and extension in that basin. In addition, field data collecting is often expensive and non-repeatable.

Therefore, remote sensing techniques which are known as an appropriate tool to obtain different variables with high spatial and temporal resolutions, can be used to estimate evapotranspiration as the precision as the FAO-PM estimate in arid regions with no weather stations or limited climate data.

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