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Estimation of effective precipitation for winter wheat in different regions of Iran using an Extended Soil-Water Balance Model

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Abstract

Estimated Effective Precipitation (Pe) in dryland areas is an essential element of water resource management. It represents the amount of precipitation available in the crop root zone to meet the needs of evapotranspiration. The current study compared different approaches for estimating Pe in different climatic zones of Iran. A two-layer soil–water balance (SWB) model was adopted based on the proposed approach in which a portion of the previous day's precipitation saved between the previous and current root-zone development is added to the Pe of the current day. To this end, we used three groups of data (meteorological, phenological, and soil characteristics data) related to 21 agro-meteorological stations representing arid, semi-arid, semi-humid, and humid regions of the country. The results of this study indicated that, in spite of data limitations, the new procedure performed appropriately in estimating that part of the wheat yield which could be explained by Pe only. Coefficients of determination (R^2) between annual precipitation and Pe ranged from 0.50 in the humid climatic zone to 0.82 in the arid climatic zone. Ultimately, using annual precipitation data collected from 181 Iranian synoptic stations and its correlation with Pe, the first annual Pe map of Iran was produced.

Keywords: Dryland wheat crop; Pe; Two-layer soil-water balance model; Iran

1. Introduction

Estimating effective precipitation (Pe) as a portion of the precipitation stored in the plant root zone to meet evapotranspiration requirements has always been a problem in agricultural water management (Tsai *et al*., 2005). A precise estimate of Pe is still needed, not only for planning and managing dryland wheat production (Cahoon *et al*., 1992), but also for risk management strategies for farms.

The term Pe has been defined differently by various applications (Hayes and Buell, 1955; Ogrosky and Mackus, 1964; Dastane, 1978; Jensen *et al*., 1990; Patwardhan *et al*., 1990; Mohammadi and Karimpour Reihan, 2008; Malekian *et al*., 2009).

Pe as used in this study is defined as, "That portion of total precipitation on a cropped area during a specific time period which is available to meet the potential evapotranspiration requirements in the cropped area" (Bos, 1980; Bos and Nugteren, 1974; ICID, 1978; Kopec *et al*., 1984).

As mentioned, this definition limits itself to the "cropped area". The amount of precipitation over fallow fields might be either very harmful or very beneficial for future crops (Bos *et al*., 2009). Carrying out valuable research on the effectiveness of precipitation is often very difficult, since it depends on many local conditions. From an agricultural view, the statement "during a specific time period" refers to the period between sowing and harvesting or the period between two sequential harvests. According to the definition, Pe is restricted to that part "which is available to meet the potential evapotranspiration requirement in the cropped area". Precipitation that passes through the ground reaches the crop's roots and may cause leaching of harmful salts. The salt leaching process may happen during a fallow period or a crop season or even through non-consumed irrigation water;

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however, the required water plays an important role in it. This role is not included in the definition of Pe (Bos and Nugteren, 1974).

Because of the high cost associated with direct measurements, estimates of the Pe component are often based on soil-water balance models (Campbell and Diaz, 1988; Patwardhan *et al*., 1990). Soil-water balance techniques characterize Pe for a given location. However, the accuracy of Pe estimates made using soil-water balance techniques depends on the accuracy of the input data, particularly climate and soil data.

Soil-water balances based on various acceptable approaches are widely used in agro-climatological studies. Such approaches act on a single soil layer corresponding with the root zone which gradually extends during the growing season (Tang *et al*., 1992). Although previously applied successfully in several regions (Laya *et al*., 1998; Ye and Van Ranst, 2002), the application of these single-layer soil-water balance approaches in semi-arid climates has shown serious shortcomings (Verdoodt and Van Ranst, 2003).

So far, numerous studies have been conducted to develop soil-water balance models for estimating the Pe component. Chin *et al*. (1987), for example, developed a soil-water balance model for the more effective use of precipitation in Taiwan. They reported the Pe rate for this area as ranging from 40% to 65% of precipitation.

In recent decades, researchers have also developed functional two-layer soil-water balance models for use in determining Pe components (Rao, 1987; Tang *et al*., 1992; Hajilal *et al*., 1998; and Panigrahi and Panda, 2003).

Since a precise estimation of Pe is necessary for increasing agricultural production, the major objective of the current study was to design a soil-water balance model that provides a more accurate estimation of Pe; in addition, climate zoning of Iran based on Pe is presented. To this end, three different approaches of soil-water balance model were compared to choose the one that gives a more accurate estimate of Pe for wheat crops.

2. Material and methods

2.1. Study Area & Data

Iran is situated in southwestern Asia with an area of about 1648000 km^2 and stretches between 25°-45° N and 44°-64° E. It has a diverse climate because of its wide latitudinal area, the Elburz and Zagros mountain chains in its north and west, and the intensive elevation variability (from -25m in coastal regions of the Caspian Sea to 5600 m in the central Elburz mountains) (Ganji, 1968). Since the country lies in the arid belt of the northern hemisphere (30°-60° N), arid and semi-arid climates cover the majority of its area (Khalili, 2004; Bazrafshan and Khalili, 2013).

The data used in this study were divided into four types: weather, phenological, soil characteristics, and wheat yield data. Weather data include daily maximum (T_{max}) and minimum (T_{min}) temperatures, daily maximum (RH_{max}) and minimum (RH_{min}) relative humidity (%), daily precipitation [mm day^{-1}], wind speeds at 2 m height, and sunshine hours (SH) related to 21 agro-meteorological stations for the period of 1995 to 2009 and obtained from the Islamic Republic of Iran Meteorological Organization (IRIMO).

Phenological data include the planting and harvest dates in each year and dates of the beginning and end of each phenological stage of wheat.

Soil characteristics data include field capacity, permanent wilting point, and soil texture and structure collected from IRIMO and OPTIWAT (Optimization and Planning for Water Use in Agriculture) databases (Alizadeh and Kamali, 2007).

Wheat yield data, including sixteen years (from 1995-96 to 2009-10) of historical wheat (Triticum aestivum) yield data published by the Ministry of Jehad Keshavarzi (MJK) for Iran, were used to evaluate Pe estimated using different soil-water balance approaches.

Before using the weather data to estimate Pe, data reconstruction was required and performed using the normal-ratio method.

In order to generalize the results over Iran, monthly precipitation data of 181 synoptic stations for 1970-2005 were collected. Figure 1 shows the agro-meteorological and synoptic stations network of Iran.

2.2. Soil-Water Balance Model

Many models have been developed in order to characterize soil-water balance through the world. These models vary in some features such as terms of their time scale and degree of complexity, which is often determined for the specific purposes of the researchers.

Based on a comprehensive review from an agro-climatological perspective, such studies can be classified under two broad classes of modeling approaches that use soil profiles in different ways to formulate soil-water balance. In the first class, the entire soil or maximum potential root zone depth is represented as a single soil layer in modeling daily soil-water balance in order to calculate Pe. In the second class, the approaches simulate the dynamic processes of root growth, and root zone depth is represented as a single soil layer in modeling daily soil-water balance. They quantify Pe resulting from the interaction of various water balance components that influence soil moisture in the daily root zone.

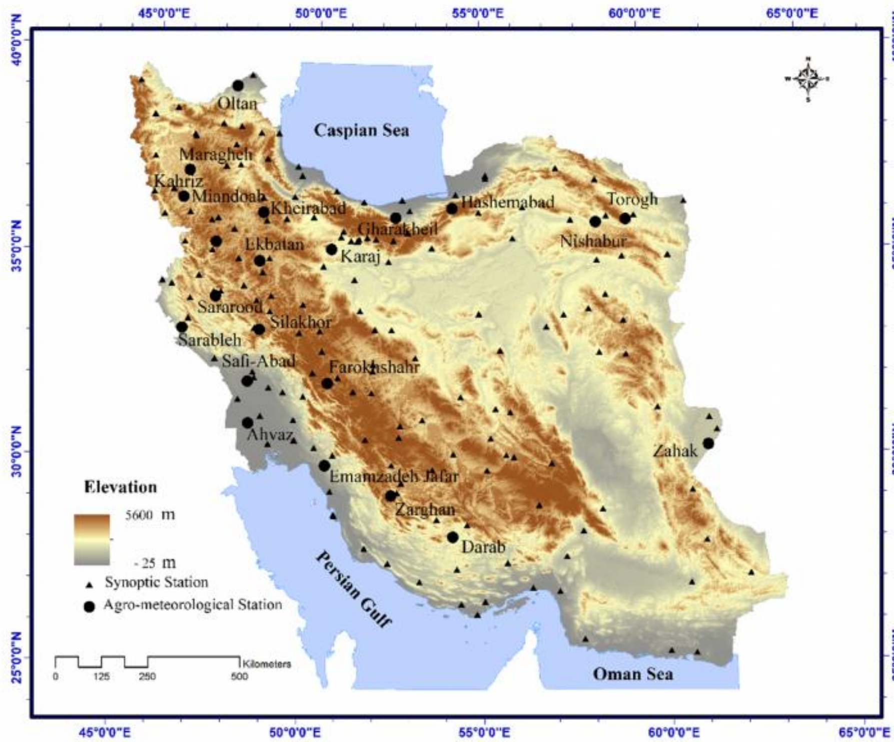

Fig. 1. Iran's geographical map displaying topography and location of the stations of interest

In this study, a two-layer soil-water balance model formulated by Rahimi *et al*. (2012) was used to estimate Pe during crop growth length. One layer is called "active layer" in which the root grows at any given time "t", and losses of both evapotranspiration and infiltration can occur. The second one is called "passive layer". It is exactly below the active layer which is defined as maximum root depth-root depth achieved in day of "t" after sowing with only an infiltration event. In this model, it is assumed that, in addition to the portion of the precipitation retained on the current day root zone, that portion of the previous day's precipitation saved between the previous root-zone and current root-zone is added to Pe on the current day. Schematic diagrams of three different approaches in determining Pe and deep percolation are depicted in Figure 2.

Components of this soil-water balance model are presented below.

The soil moisture content of the active layer (MC1) at the end of each day of "t" is computed as:

$$MC_{1(t)} = MC_{1(t-1)} + ISM_{(t)} + R_{(t)} - Q_{(t)} - ET_{(t)} - P_{1(t)} \tag{1}$$

$$P_{1(t)} = \begin{cases} 0 \quad if \quad MC_{1(t-1)} + \mathrm{ISM}_{(t)} + \mathrm{R}_{(t)} - \mathrm{Q}_{(t)} - \mathrm{ET}_{(t)} \le \mathrm{K}_{1(t)} \\ MC_{1(t-1)} + ISM_{(t)} + R_{(t)} - Q_{(t)} - ET_{(t)} - K_{1(t)} \end{cases} \tag{2}$$

where MC_1 is the soil moisture content in layer l, R is precipitation, Q is runoff, ISM is incremental soil moisture due to daily root extension, ET is evapotranspiration, P_1 is the percolation out of layer 1, K_1 is available water holding capacity (FC-PWP) of layer 1, and $MC_{1(t-1)}$ is soil moisture content in the active layer at the end of the previous day (i.e., beginning of the current day t). All terms are expressed in mm day^{-1}.

The initial soil moisture content for the first day of the season was calculated using moisture content at field capacity (Θ_{FC}) and moisture content at wilting point (Θ_{WP}).

Conditions for the passive root zone were similar to those of the active layer except that there were no losses. Soil moisture content of layer 2 at the end of any day of "t" is given by:

$$\mathrm{MC}_{2(t)} = \mathrm{MC}_{2(t-1)} - \mathrm{ISM}_{(t)} + \mathrm{P}_{1(t)} - \mathrm{P}_{2(t)} \tag{3}$$

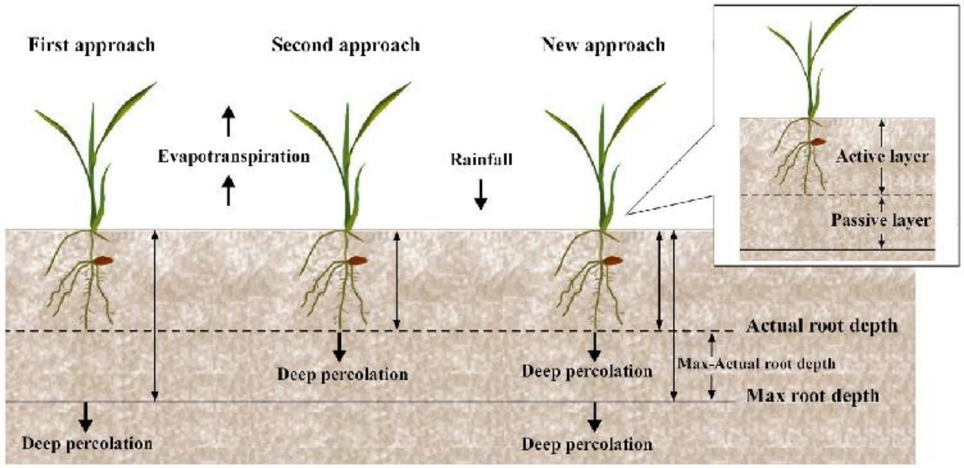

Fig. 2. Representation of three different approaches in determining Pe and deep percolation

$$P_{2(t)} = \begin{cases} 0 \quad if \quad MC_{2(t-1)} - ISM_{(t)} + P_{1(t)} \leq K_{2(t)} \\ MC_{2(t-1)} - ISM_{(t)} + P_{1(t)} - K_{2(t)} \end{cases} \tag{4}$$

where MC_2 is soil moisture content in layer 2, P_2 is deep drainage out of layer 2, K_2 is available water holding capacity of the layer 2, and $MC_{2(t-1)}$ is soil moisture content of the passive layer at the end of the previous day. All terms are expressed in mm day^{-1}.

2.2.1. Root growth model

Root growth value was estimated by the following sigmoidal root growth model (Borg and Grimes, 1986):

$$RD_{(t)} = RDM[0.5 + 0.5\sin(3.03(DAS/DTM) - 1.47)] \tag{5}$$

Where $RD_{(t)}$ is root depth attained at any day after sowing (DAS), RDM is maximum root depth, DTM = DAS to maximum root depth. All terms are in mm day^{-1}. The maximum rooting depth of winter wheat ranges from 0.8 m in heavy-textured soils to 1.2 m in light-textured soils (Rickert *et al*., 1987). Based on assumption, the rooting depth will be constant after achieving its maximum depth at the end of mid-stage (Lashari *et al*., 2010).

Based on soil evaporation at first day, the depth of the active layer was assumed to be 150 mm. Moreover, its water holding capacity and soil moisture contents increased with the advancement of roots, while consequently the capacity and soil moisture contents of layer 2 decreased by an equivalent amount. Available water holding capacity for layer 1 was given as:

$$\text{if} \quad RDM > RD_{(t)}$$
$$K_{1(t)} = K_{1(t-1)} + (K_{2(t-1)} \times DRD)/(RDM - RD_{(t)}) \tag{6}$$

Where,

$$DRD = RD_{(t)} - RD_{(t-1)} \tag{7}$$

DRD is the daily increase in root depth [mm day^{-1}].

Available water holding capacity of passive layer was computed by:

$$K_{2(t)} = K_{2(t-1)} - P_{1(t)} + P_{2(t)} \tag{8}$$

Daily increment in soil moisture (ISM) gained through root extension was given by:

$$\text{if} \quad RDM > RD_{(t)}$$
$$ISM_{(t)} = (MC_{2(t-1)} \times DRD)/(RDM - RD_{(t)}) \tag{9}$$

2.2.2. Runoff Model

Runoff was estimated using the SCS method, which is based on curve number and was developed by the US Department of Agriculture (USDA) Soil Conservation Service (SCS, 1972).

2.2.3. Evapotranspiration Models (ET)

In this paper, evapotranspiration was calculated by the modified Penman-Monteith equation which is a simple representation of the physical and physiological factors governing the process in order to estimate ET_o (Allen *et al*., 1998).

Crop ET (ET_c) is defined as ET applicable to a specific plant other than the reference crop. ET_c can be calculated for a specific plant material by applying a crop coefficient (K_c) and a coefficient which is considered as water stress (K_S) using the following equation (Allen *et al*., 1998):

$$ET_c = ET_o \times K_{ci} \times K_{Si} \tag{10}$$

Where, K_{ci} and K_{Si} are daily crop coefficient and water stress coefficient, respectively. Both ET_o and ET_c are in mm day^{-1}.

The effects of both crop transpiration and soil evaporation were integrated into a single crop coefficient. Allen *et al*. (1998) divided the growing period into four general growth stages, namely initial, crop development, mid-season, and late season stages that describe crop phonology or development. The three K_c values corresponding to Kc_{ini}, Kc_{mid}, and Kc_{end} according to Alizadeh and Kamali (2007) for winter wheat were considered to be 0.3, 1.15, and 0.25 respectively.

Daily K_c (K_{ci}) values were computed using the following:

$$\begin{aligned} &Kc_i = Kc_{ini} && L_1 \le i < L_2 \\ &Kc_i = Kc_{ini} + (Kc_{mid} - Kc_{ini})((i - L_2)/(L_3 - L_2)) && L_2 \le i < L_3 \\ &Kc_i = Kc_{mid} && L_3 \le i < L_4 \\ &Kc_i = Kc_{mid} - (Kc_{mid} - Kc_{end})((i - L_4)/(L_5 - L_4)) && L_4 \le i \le L_5 \end{aligned} \quad (11)$$

Where L_1 is day of year (DOY) at the beginning of the initial stage, L_2 is DOY at the beginning of the crop development stage, L_3 is DOY at the beginning of the mid-season stage, L_4 is DOY at the beginning of the late season stage, and L_5 is DOY at the end of the growing season.

2.2.4. Effective Precipitation (Pe)

Pe was estimated using the following equation:

$$P_e = (MC_{1(t)} - MC_{1(t-1)}) + ET_C \quad (12)$$

Where $MC_{1(t)}$ is the soil moisture content of layer l, $MC_{1(t-1)}$ is the soil moisture content in the upper layer at the end of the previous day and beginning of the current day i, and ET_c is the daily crop evapotranspiration. All terms are expressed in mm day^{-1}.

3. Results and Discussion

The authenticity of the proposed soil-water balance model compared with previous approaches was tested using the wheat yield data from different climatic zones of Iran.

Three different approaches of soil-water balance were carried out for the various growing seasons of different stations in Iran which have different climates, namely “arid”, “semi-arid”, “semi-humid”, and “humid” (based on the De Martone climatic classification).

The results for the three different approaches (“without considering deep percolation up to the maximum root depth”, “considering deep percolation after the actual root depth”, and “accounting for the water stored between the actual and maximum root depths”) are plotted in Figure 3.

The approach proposed to estimate the variations in dryland wheat crop that could be justified by Pe was more efficient than the other two approaches. (The values of R2 for the proposed approach were higher than those for the other two approaches.)

The calculation of Pe plays a major role in the optimal usage of water resources, particularly because of its inherently linkage to productivity under dryland conditions. Figure 4 shows the coefficient of determination (R2) of annual precipitation against Pe in the four climate zones of Iran. Satisfactory correlations between annual precipitation and Pe were found in all climates, with R2 values ranging from 0.50 to 0.82. Furthermore, it can be inferred that the average Pe-growing season precipitation ratio at stations with an arid climate was 0.84% and for stations in semi-arid, semi-humid, and humid areas was 0.80%, 0.62%, and 0.53% respectively. Moreover, Zahak station (de Martonne aridity index 1.5) with the average of 0.95%, and Gharakheil station (de Martonne aridity index 28.5) with the average of 0.51% had the maximum and minimum Pe-growing season precipitation ratio during the statistical period.

In general, as the de Martonne aridity index increases, the portion of precipitation contributed to dryland wheat crop. In other words, moving from an arid region toward a more humid region, the Pe-growing season precipitation ratio decreases, whereas Pe increases.

Since the dryland farming areas have a significant effect on the agriculture-oriented segment of Iran’s economy, preparing a climate zoning map based on Pe for dryland wheat crops was one of the main aims of this study. To this end, the precipitation data from 181 synoptic stations of the country was collected and used to generate the annual precipitation map. For the first time, the Pe map of Iran was prepared in the current study using the equations obtained from an assessment of relationships between annual precipitation against Pe for the four climate zones of Iran and the De Martonne classification map of Iran. Figure 5 shows the Pe map of Iran for the years 1970-2005.

4. Conclusion

In many areas around the world where irrigation is not possible or practicable, the lack of sufficient water in the root zone of the soil can cause great problems. The ability to manage precipitation in order to gain sufficient yields and remain economically viable is a controversial issue. The scientific literature introduces two main approaches for estimating Pe using a soil-water balance model. With some assumptions, another approach for estimating Pe based on a soil-water balance model has been proposed in this study. These approaches were compared in different

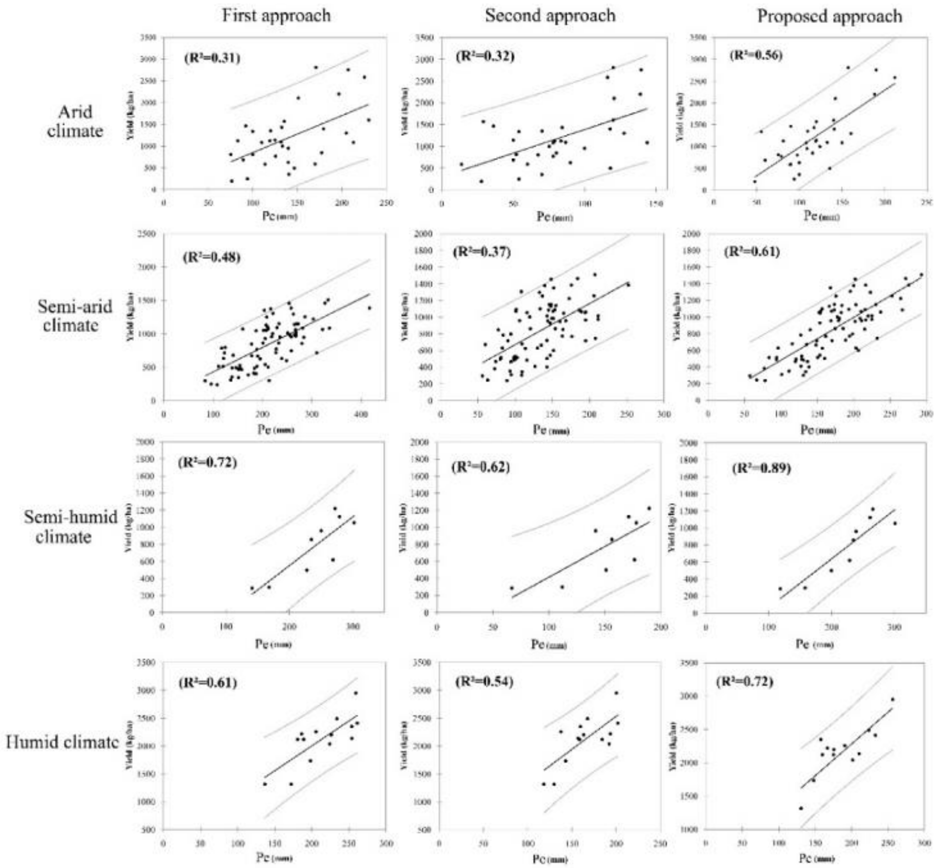

Fig. 3. Scatter plot of estimated Pe (mm) against crop yield (kg/ha) using different approaches for testing the accuracy of the proposed approach in different climatic zones of Iran (gray lines show the 95% confidence interval)

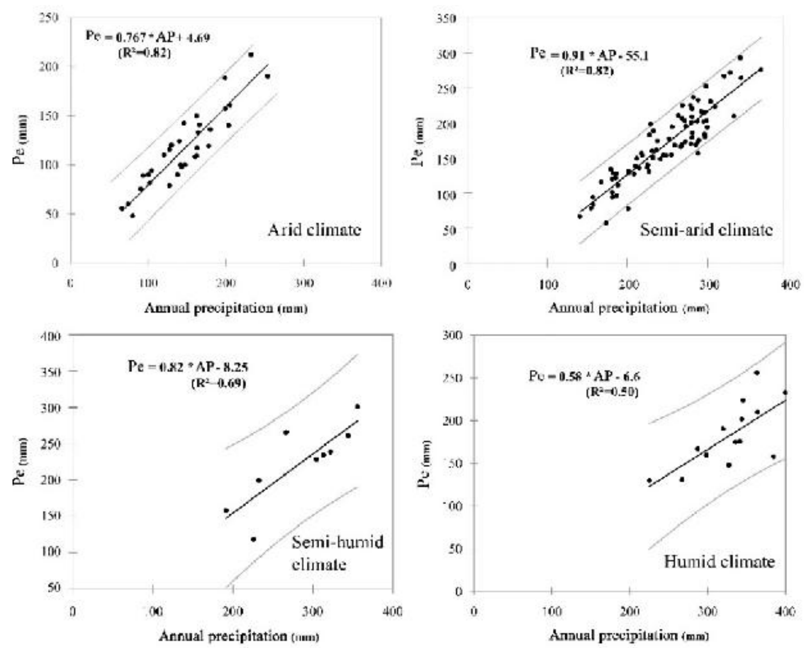

Fig. 4. Relationship between estimated Pe by proposed approach and the annual precipitation in different climatic zones of Iran (gray lines show the 95% confidence interval)

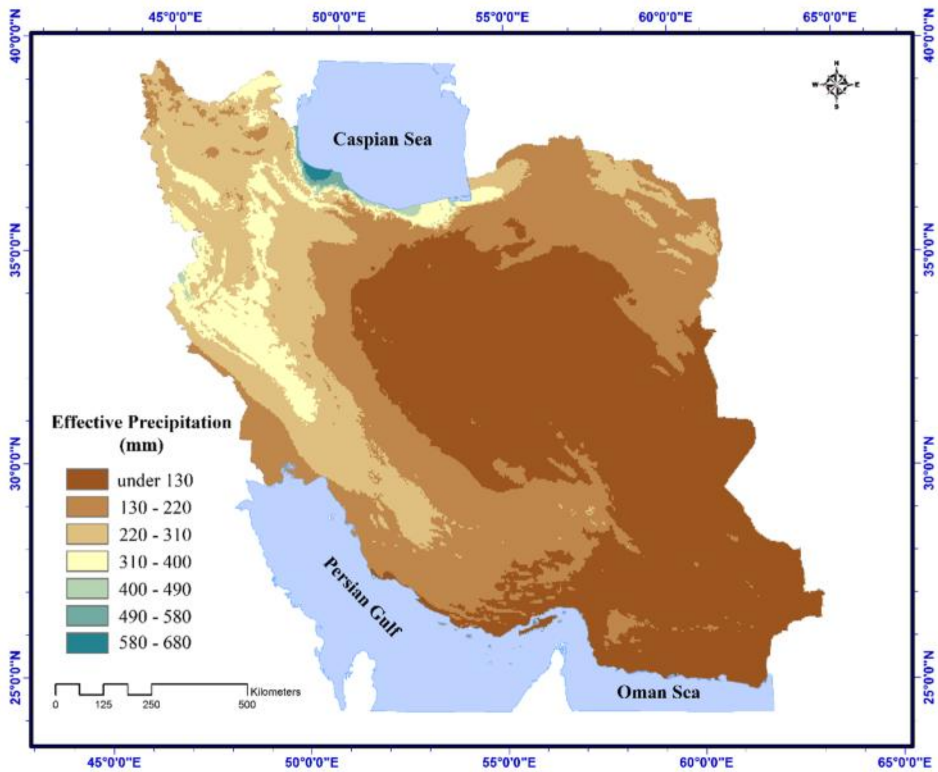

Fig. 5. Classification map of Pe in dryland wheat crop in Iran

climatic zones of Iran. The major advantage of the approach proposed in this study over previous approaches is that a portion of the previous day's precipitation saved between the previous and current root-zone development is added to the Pe on the current day. Testing annual Pe data series estimated by three different approaches against wheat yield data series in each of four climates revealed that the proposed approach has acceptable accuracy for estimating Pe in dryland wheat crop compared with the other approaches. Therefore, this method can be used as an efficient tool in computer-based programs developed for the agricultural risk management of dryland areas.

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