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Comparison of artificial intelligence methods and empirical equations to estimate daily solar radiation

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ABSTRACT

In the present research, three artificial intelligence methods including Gene Expression Programming (GEP), Artificial Neural Networks (ANN) and Adaptive Neuro-Fuzzy Inference System (ANFIS) as well as, 48 empirical equations (10, 12 and 26 equations were temperature-based, sunshine-based and meteorological parameters-based, respectively) were used to estimate daily solar radiation in Kerman, Iran in the period of 1992–2009. To develop the GEP, ANN and ANFIS models, depending on the used empirical equations, various combinations of minimum air temperature, maximum air temperature, mean air temperature, extraterrestrial radiation, actual sunshine duration, maximum possible sunshine duration, sunshine duration ratio, relative humidity and precipitation were considered as inputs in the mentioned intelligent methods. To compare the accuracy of empirical equations and intelligent models, root mean square error (RMSE), mean absolute error (MAE), mean absolute relative error (MARE) and determination coefficient (R^2) indices were used. The results showed that in general, sunshine-based and meteorological parameters-based scenarios in ANN and ANFIS models presented high accuracy than mentioned empirical equations. Moreover, the most accurate method in the studied region was ANN11 scenario with five inputs. The values of RMSE, MAE, MARE and R^2 indices for the mentioned model were 1.850 MJ m^{-2} day^{-1}, 1.184 MJ m^{-2} day^{-1}, 9.58% and 0.935, respectively.

1. Introduction

Solar radiation is one of the most important parameters which is used to design solar systems (Mousavi et al., 2015), atmospheric energy balance studies, agricultural studies and meteorological forecasting (Ozgoren et al., 2012), solar energy applications (Janjai et al., 2011), determining irrigation water requirements and potential yield of crops (Almorox et al., 2013) and agronomy (Liu et al., 2015). But, despite the importance of the measurement of this parameter, solar radiation is not a routinely measured meteorological parameter as temperature or rainfall (Liu et al., 2015; Iziomon and Mayer, 2002; Almorox et al., 2005; Mubiru et al., 2007). Moreover, direct measurements of solar radiation have been faced many problems. Some of these problems are: calibration problems, problems with accumulation of dirt and water on the sensors (Rahimikhoob, 2010). Even, at stations where solar radiation is measured, there could be many days which radiation data are missing or lie outside the expected range due to the equipment failure and other problems (Hunt et al., 1998). These problems have been encouraged researchers to use the empirical models for estimating solar radiation (Menges et al., 2006; Ertekin and Evrendilek, 2007; Bakirci, 2009a; Sonmete et al., 2010; Besharat et al., 2013; Yao et al., 2014). Besharat et al. (2013) reviewed empirical models for estimating solar radiation. They classified existent models into four categories; sunshine-based, cloud-based, temperature-based and other meteorological parameters-based models. Then, they have carried out a case study in Yazd, Iran. Their results showed that sunshine-based models had the highest accuracy. Yao et al. (2014) evaluated 108 empirical models for estimation of solar radiation in Shanghai, China. They reported that polynomial models were the most accurate models between other used models. Das et al. (2015) applied 17 sunshine duration-based models (6 linear and 11 nonlinear models) in South Korea. They concluded that one of nonlinear model had the best performance which means that nonlinear relationship exist between sunshine duration and clearness index.

Beside the empirical equations, artificial intelligence methods are as a powerful tool to estimate meteorological parameters in non-linear systems such as solar radiation. In the recent years, artificial intelligence methods e.g. Gene Expression Programming (GEP), Artificial Neural Networks (ANN) and Adaptive Neuro-Fuzzy Inference System (ANFIS) have been used successfully in many engineering sciences (e.g. estimating the solar radiation).

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Nomenclature

H	Daily solar radiation (MJ m^{-2} day^{-1})
H_o	Daily extraterrestrial solar radiation (MJ m^{-2} day^{-1})
S	Sunshine duration (h)
S_o	Maximum possible sunshine duration (h)
T_{min}	Daily minimum air temperature (°C)
T_{max}	Daily maximum air temperature (°C)
T	Daily mean air temperature (°C)
RH	Daily mean relative humidity (%)
ST	Daily mean soil temperature (°C)
P	Precipitation (cm in empirical Eq. (25) and mm in empirical Eq. (35))
T_k	Daily mean absolute air temperature (°K)
w	Atmospheric precipitable water vapor per unit volume of air (cm)
H_{mod}	Daily estimated solar radiation corrected for systematic bias (MJ m^{-2} day^{-1})
Z	Elevation of the station (m in empirical Eq. (5) and Km in empirical Eqs. (13) and (16))
a to g	Calibrated coefficients of empirical equations
I_{gs}	Solar constant (1367 W m^{-2})
f	Eccentricity correction factor
ϕ	Latitude of the station (°)
w_s	Sunrise hour angle (°)
δ	Solar declination (°)
J	Julian day (starting from the first January)
P_s	Atmospheric pressure at the station (kPa)
P	Atmospheric pressure at sea level (kPa)
RMSE	Root mean square error (MJ m^{-2} day^{-1})
MAE	Mean absolute error (MJ m^{-2} day^{-1})
R^2	Determination coefficient
MARE	Mean absolute relative error (%)
μ	Membership function

However, conducted studies in the field of solar radiation estimation using GEP are rare. Reddy and Ranjan (2003) estimated solar radiation in 13 locations in north and south of India using existent meteorological data and geographical coordinates. They used Angstrom-Prescott, Hargreaves, Supit and Van Kappel models and ANN technique. It is concluded that ANN was the most accurate model. Tymvios et al. (2005) predicted solar radiation using ANN and Angstrom-Prescott linear model at Athallasa in Cyprus radiometric station. ANN model with inputs of sunshine duration, maximum possible sunshine duration and maximum temperature had the highest accuracy. Ozgoren et al. (2012) by considering 10 different scenarios from monthly meteorological parameters and also geographical coordinates estimated monthly solar radiation in 31 stations in Turkey using ANN and MNLR (Multiple Non-Linear Regression). The results showed that ANN with full inputs was the best model. Landeras et al. (2012) compared the ability of three artificial intelligence techniques including GEP, ANN and ANFIS with two empirical equations of Hargreaves–Samani and Mahmood and Hubbard to estimate solar radiation in four stations in Basque region in northern Spain. They developed used artificial intelligence techniques based on five different defined scenarios using different combinations of extraterrestrial radiation, minimum and maximum air temperatures, day of the year and corrected clear sky solar radiation. The results indicated that ANN structure with four inputs of extraterrestrial radiation, minimum and maximum air temperatures, day of the year and 10 neurons in the hidden layer was the most accurate model among studied models. Citakoglu (2015) compared the accuracy of ANN, ANFIS, MLR (Multiple Linear Regression) to estimate monthly solar radiation with four empirical equations including Angstrom, Abdalla, Bahel and Hargreaves–Samani in 163 stations in Turkey. In the mentioned research, 11 different combinations of month number, extraterrestrial radiation, relative humidity, mean air temperature as well as geographical coordinates were considered as inputs for ANN, ANFIS, and MLR models. The results showed that the estimation accuracy of ANN was greater than ANFIS, MLR and used empirical equations in the studied region. Piri and Kisi (2015) compared the ANFIS, NN-ARX (neural network auto regressive model with exogenous inputs) and empirical models in two Iranian stations, Zahedan and Bojnurd. ANFIS models are found to perform better than other methods. Mohammadi et al. (2015a) applied ANFIS and six empirical equations to estimate daily solar radiation in Tabass, Iran by using day of the year parameter as a sole input. The results revealed the superiority of ANFIS model.

From literature review, it is concluded that conducted studies in the field of the use of GEP for estimation of solar radiation are rare. Therefore, the objectives of the present study are: 1) evaluate the performance of 48 empirical equations including 10 temperature-based, 12 sunshine-based and 26 different meteorological parameters-based models, 2) investigating the capability of artificial intelligence methods including Gene Expression Programming (GEP), Artificial Neural Networks (ANN) and Adaptive Neuro-Fuzzy Inference System (ANFIS) and 3) comparative analysis of empirical equations with intelligent methods for estimating daily solar radiation in Kerman, Iran.

2. Material and methods

2.1. Study area and meteorological data

In the present study, Kerman was selected. Kerman is located in the southeast of Iran which has latitude, longitude and altitude of 30° 15′ N, 56° 58′ E and 1753.8 m, respectively. Kerman's climate based on the aridity index (AI) (defined by UNEP (1993)) is arid. Fig. 1 shows the location of the studied region.

The required daily meteorological data were minimum air temperature, maximum air temperature, mean relative humidity, precipitation, sunshine duration and actual solar radiation. The mentioned data were collected from Islamic Republic of Iran Meteorological Organization (IRIMO) in the period of 1992–2009 from Kerman station. 75% and 25% of data were used in calibration (training) and validation (testing) processes, respectively. Daily statistical characteristics including minimum (X_{min}), maximum (X_{max}), mean (X_{mean}) and standard deviation ($X_{st.dev}$) for used climatic data are seen in Table 1.

2.2. Checking the quality of recorded solar radiation values

On the basis of mentioned problems in introduction section, recorded solar radiation values using Pyranometer may be out of expected range. Therefore, solar radiation data should be controlled. To determine the incorrect solar radiation values, the daily clearness index (K_T) was computed and the values which were out of range of $0.015<K_T<1$ were eliminated (Jiang, 2009; Mohammadi et al., 2015a, 2015b). It should be noted that clearness index is the ratio of observed daily solar radiation to daily extraterrestrial radiation ($K_T=H/H_o$).