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Prediction of soil temperatures for shallow geothermal applications in Turkey

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ABSTRACT

In this study, soil temperatures at different depths in Turkey's different regions were investigated theoretically. Soil temperature data are critical for different research interests such as ecology, biology, technique processes, forestry, agriculture, energy, food sector, ground heat exchanger applications, thermal energy storage applications, and so forth. This investigation gives information related to the prediction of soil temperature's dependence with depth and time especially for shallow geothermal applications. Soil temperature values depend on a great deal of varied parameters such as thermal conductivity, short term climatic conditions and moisture content. The main issue is that despite these temperatures are extremely important values, they can not be obtained in a short time. Due to this reason, we study a mathematical model related to the prediction of soil temperature. Within this context, 81 cities and their approximately 300.000 data, both, monthly air and soil temperatures between 1960 and 2015 were studied and finally seven regions in Turkey were investigated and final average soil temperature values were achieved. Measured data taken from the Izmir State Meteorological Station, and predicted soil temperatures at depths of 5 cm, 10 cm, 20 cm, 50 cm, and 100 cm were analyzed for each region in Turkey according to data obtained fifty years ago. Finally, at depths of 5 cm, 10 cm, 20 cm, 50 cm and 100 cm, the maximum average percentage errors in Turkey were 16%, 14.8%, 13.5%, 14.4%, 13.9% respectively. In conclusion, we evaluate the relationship between ambient air temperatures and soil temperatures in terms of depths from 5 to 3000 cm.

1. Introduction

In today's world, renewable and sustainable energy resources is pretty necessary, wherefore the continuous increase in population. In this case, geothermal energy is a good option in terms of both energy and clean environment. It is well known that geothermal energy has negligible emissions of CO_2, SO_x, NO_x, and particulates. These features are compatible with sustainable growth of global energy supplies in both developed and developing countries, geothermal energy is an attractive option to replace fossil and fissile fuels [1]. Accordingly, geothermal energy applications have increased day by day [2–31]. Moreover, there are different type of papers about shallow depths geothermal resources [21–36]. Even though soil temperature values could be design, the parameters for both geothermal and solar applications cannot be reached with ease and the approachability to complete measured data is a drawback.

In summary, knowing soil temperatures is an advantage in regards to different disciplines.

Mihalakakou et al. studied the modeling of earth temperatures with multiyear measurements and in the other study Mihalakakou obtained estimated different soil temperature profiles and authors emphasized that the soil temperatures are important for soil and geothermal applications [2,3].

Ogunlela described soil temperature variations as a function of time and depth in order to reach correct soil temperature values [4].

Chandrasekharam et al. studied about low enthalpy geothermal resources for power generation and authors focuses on all aspects of low enthalpy geothermal thermal fluids [5].

Ozgener et al. focused the prediction of soil temperatures via ground heat exchanger applications. He used a number of data that was taken from his experimental earth to air heat exchanger system. According to the experimental study, the authors expressed the connection between soil and air temperatures. Moreover, that study contain the correlation about amplitude soil temperature [6].

Tsilingiridis and K. Papakostas investigated the relationship between air and ground temperature fluctuations in shallow depths.

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Nomenclature

A_0	amplitude of the daily mean air temperatures (°C)	t	time a day in year expressed in hours (h)
A_z	amplitude of the temperature wave at depth z (°C)	t_0	time, zero point (h)
P	period (h)	z	soil depth (cm)
T_m	annual mean air temperature (°C)		
$T_{z,t}$	soil temperature at depth z, at time t (°C)		

Greek letters

γ	inverse of damping depth (cm^{-1})

Tsilingiridis and Papakostas used 10 year records of daily average values of ambient air, bare and grass-covered ground surface, and ground under bare surface temperatures at depths of 0.02, 0.05, 0.10, 0.20, 0.50, 1.00 and 1.50 m in their study [7].

Yener et al. investigated the prediction of soil temperatures theoretically. Authors estimated soil temperatures at different depths in Izmir/Turkey for heat exchanger applications, for example, earth to air heat exchanger and ground source heat exchanger applications. In this study, predicted soil temperature values obtained through ambient air temperature [8].

Zheng et al. reported a daily soil temperature model based on air temperature and precipitation for continental applications. This study shows daily soil temperature at 10 cm depth for various sites and years may be predicted from daily air temperature. Authors handle the subject from the point of biological processes for example soil respiration [9].

Holmes et al. analyzed the estimation of a soil temperature profile. The developed model is about the surface soil temperature profiles from a single observation depth. This approach consists of two parts; modeling an instantaneous ground flux profile based on net radiation and the ground heat flux at 5 cm depth; the use of this ground heat flux profile to extrapolate a single temperature observation to a complete surface temperature profile [10].

Yener D. et al. developed an estimation model for temperatures of bare soil according to Manisa/Turkey. The soil temperature estimation model was mediated by average air temperatures. This study included both theoretical and real soil temperature data at different depths. These values were compared and error rates were obtained [11].

Thorn et al. investigated statistical relationships between daily and monthly air shallow-ground temperatures in Swedish Lapland for the 1995–1996 records [12]. Staniec et al. prepared a model for the prediction of annual soil temperature distribution. This model is based on a transient heat conduction differential equation with the energy balance at the soil surface as a boundary condition [13].

Knowing soil temperatures especially at different depths is really an important advantage in terms of studies and applications. The temperature has a big impact on soil technique applications such as earth to air heat exchanger, ground source heat pump systems, thermal energy storage systems and different study areas. The importance of soil temperature to many ecological processes is huge, particularly for vegetation growth, soil biological activity, the soil carbon cycle and soil carbon sequestration [37]. Decomposition of soil organic matter (SOM) is of importance for CO_2 exchange between soil and atmosphere and soil temperature and moisture are considered as two important factors controlling SOM decomposition [38]. The effects of temperature changes on soil organic carbon (SOC), labile organic carbon fractions (microbial biomass carbon, MBC; dissolved organic carbon, DOC; particulate organic carbon, POC), and enzyme activities under long-term fertilization regimes as well as their relationships at different temperatures [39]. In addition, soil moisture can be determined by assimilating soil temperatures [40]. Dong J. et al. investigated the potential to use particle approaches to estimate soil moisture from temperature observations [41]. Furthermore, soil temperature is a necessary value in good agricultural practices [42–44] and these values could be used in underground food drying systems. Also, vegetation of forests and soil chemical content may be affected by soil temperature variation [45,46]. On the other hand, there are relationships among snow cover, air temperature and soil temperature [47–50].

1.1. Methods of soil temperature predictions

1.1.1. Thermal infrared techniques

Thermal infrared (TIR) techniques to collect thermal imagery have been useful for recording quasi continuous plant surface temperatures. Youngil et al. applied a thermal camera to measure canopy skin temperatures in a mature ponderosa pine forest in central Oregon over one growing season from May to September 2014 [51]. This method was applied in different investigations for the estimation of surface soil temperatures [52,53].

1.1.2. Artificial neural network model

An Artificial Neural Network (ANN) model can be a particularly efficient and accurate tool for determining nonlinear relationships among a number of inputs and one or more outputs, and this approach has been successfully applied for optimizing, predicting, forecasting, and controlling many complex systems [54]. In recent years, there have been several studies on estimating soil temperatures [55–70] artificial neural network models [55–60]. Bilgili et al. studied the prediction of soil temperatures using neighboring station data. According to the mentioned study, the authors used an artificial neural network model based on the stepwise regression analysis and as a result, the correlation coefficient (R) was compared between measured and predicted soil temperatures in Izmir/Turkey via neighboring station data [61].

1.1.3. Philip and De Vries (PDV) model

Early pioneering studies on interactions between liquid water, water vapor, and heat movement were reported by Philip and de Vries (1957), who provided a mathematical description of liquid water and water vapor fluxes in soils driven by both pressure head (isothermal) and soil temperature (thermal) gradients [62]. Jiang et.al investigated estimating the effect of shallow groundwater on diurnal heat transport in a vadose zone. Authors' results showed that both the soil temperature near shallow groundwater and the soil water content were effectively simulated by the PDV model [63]. This model guide different types of study areas [64,65].

1.1.4. Soil heat calculator program

Valipour et al. determined soil heat flux and thermal properties through a software named "Soil Heat Calculator Program", and in this study, the authors showed that the soil heat calculator program (SHCP) was an appropriate tool for calculating soil heat flux [66].

The present study approaches the prediction of soil temperatures based on depth and time via sinusoidal model. This sinusoidal model has extreme importance especially for earth to air heat exchanger, ground source heat pump systems and thermal energy storage applications. The reason for this, soil temperature at different depths is a design parameter for the mentioned systems. Hence this mathematical model was developed in order to help both researchers and engineers to reduce costs, for instance, drilling and measurement setup costs. Also, this engineering model besides being able to decrease risks related with designing parameters, it can also help identify in advance negative situations that might occur. As a result, the main goal included