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A qualitative description of shallow groundwater effect on surface soil temperature

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Abstract



Whether or not shallow groundwater affects skin temperature is important to detect depth and extent of shallow groundwater by dint of remote sensing and important for land surface modelling studies. Although few studies have been conducted to investigate that effect, they have yielded contradicting conclusions and they stopped in 1982. To determine that shallow groundwater affects skin temperature, we measured soil temperature at two different depths (5 and 10 cm) in seven places with variable water table depths every ten minutes and for six days. After that, we correlated the minimum, maximum and average daily temperatures to average groundwater depth. We also built a simple numerical model using a differential equations solver, Flex PDE, to simulate heat transfer into soil profile and used it to simulate groundwater effect on skin temperature. We found quite high negative correlation between the maximum and average daily soil temperature and groundwater depth. Contrarily, we could hardly find any correlation between the daily minimum temperature and groundwater depth. Numerical simulations, though simple, were useful in showing that groundwater shifted skin temperature curve up in the winter and down in the summer without affecting the shape of the curve. We conclude that shallow groundwater affects skin temperature directly by its distinctive thermal properties in the soil profile and indirectly by affecting soil moisture which in turn has many different and contradictory effects on skin temperature. This study recommends building comprehensive numerical model that simulate the effect of shallow groundwater on skin temperature and on the different energy fluxes at land surface.

1 Introduction

Whether or not shallow groundwater affects skin temperature is important in many aspects. Skin temperature is a key factor in solving surface energy balance and affects all its components (i.e. latent, sensible and ground heat fluxes). Besides, skin tempera-

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ture is the only means through which thermal remote sensing can detect the existence, depth and extent of groundwater perching at shallow depths.

In spite of the numerous studies which have dealt with heat transfer and temperature distribution within the soil profile and at land surface, a few have investigated the effect of shallow groundwater on the behaviour of surface soil temperature.

Although Kappelmeyer (1957) could successfully use temperature measurements conducted at shallow (1.5 m) depth to locate fissures carrying hot water from deep groundwater, pioneering studies to locate shallow aquifers by geothermal measurements were initiated by Cartwright, (1968) who correlated soil temperature at 0.5 m depth to the groundwater depths. A year later, Birman, (1969) found that shallow earth temperatures could be related to the occurrence of groundwater.

Extending his method of Cartwright (1968), Cartwright (1974) included the detection of both the depth of shallow groundwater and the description of the velocity and direction of its flow. In this new method, deeper (one meter) measurement depth of temperature was used. A few studies of utilizing soil temperature in groundwater survey were mentioned by Furuya et al. (2006); those studies (Takeuchi, 1980, 1981, 1996; Yuhara, 1998) developed the study of Cartwright (1974) into a practical method using soil temperature measured at one meter depth.

In 1972 the first attempt to map shallow groundwater was made using the brightness temperature retrieved from airborne radiometers of land surface by Myers and Moore (1972). They found that the correlation between land surface temperature and depths to groundwater was significant in a predawn imagery of 26 August 1971 taken under favourable weather and water table conditions (groundwater depth was between 1.5 and 4.5 m). Where, Quiel (1975) restricted the groundwater depth to 20 cm to be detected by land surface temperature.

Huntley, (1978) presented a critical and detailed study of the potential to detect groundwater from surface temperature measurements. He developed a mathematical model to describe the heat flux and temperature distribution in the soil column and concluded that this detection was not promising with the technology presented at that

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time. He explained that the minimum detectable temperature contrast using a thermal infrared scanner was of the order of 0.5°C , while the minimum detectable change of groundwater depth under the best conditions according to his model was of the same order of magnitude.

The most recent study investigating the effect of groundwater on skin temperature that could be found in the literature was Heilman and Moore's (1982 – four years after Huntley's). They showed again that radiometric temperature measurements could be correlated to depth to shallow groundwater if appropriate considerations were given to the effect of vegetation on the surface thermal regime. They also recommended that techniques for distinguishing water table influences from those of soil moisture should be developed to make the temperature method works for groundwater studies.

The concern of many of the surveyed studies was the depth in the soil column (0.5–1.5 m) to investigate the effect of shallow groundwater on soil temperature. Other studies which focused on the effect of shallow groundwater on skin temperature were few and yielded contradicting results. And most importantly, they have ceased since 1982.

The objective of this paper is to show the effect of shallow groundwater on skin temperature by field measurements and to examine the reason behind this effect with a simple numerical model. A detailed numerical model, that can simulate the energy balance components and solve this balance for skin temperature and soil moisture, needs a very complex numerical modelling effort, and is beyond the scope of this paper.

In this study the relation between soil temperature close to the surface (5 and 10 cm) and water table depth was investigated by correlating the daily minimum, maximum and average soil temperature readings to water table depth. To simulate the effect of shallow groundwater on skin temperature, a one dimension transient heat transport model was built using FIDEL, a scripted finite element model builder and numerical solver. This model has been useful for explaining and justifying the reason behind the effect of shallow groundwater on land surface temperature.

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Theory

Soil temperature at land surface (i.e. skin temperature) is an outcome of the equilibrium among the different forms of energy transfer and exchange that occur at the very top soil; this equilibrium is usually described by the famous surface energy balance equation:

$$R_n = G + H + LE \quad (1)$$

where G is the ground heat flux, H is the sensible heat flux, LE is the latent heat flux and R_n is the net radiation which is calculated by using Eq. (2):

$$R_n = K_{in} - K_{out} + L_{in} - L_{out} \quad (2)$$

where K_{in} and K_{out} are, respectively, the short incoming and outgoing radiation, and L_{in} and L_{out} are the long incoming and outgoing radiation, respectively.

After subtracting the sensible and the latent heat fluxes from the net radiation the resultant is considered as ground heat flux: the flux that is of prime responsibility of controlling soil temperature in the absence of inner energy sources (i.e. nuclear minerals, magma eruption, hot springs etc.), then we write:

$$G = R_n - H - LE. \quad (3)$$

Daily G can be described analytically under periodic forcing assumption (Horton and Wierenga, 1983; Santanello and Friedl, 2003) as:

$$G_{\text{daily}} = k \cdot A_1 \cdot \sqrt{\frac{2\pi}{\alpha \cdot \rho_1}} \cdot \sin\left(\frac{2\pi \cdot t}{\rho_1} + \frac{\pi}{4}\right) \quad (4)$$

This can be extended to describe the yearly G by:

$$G_{\text{yearly}} = k \cdot \left[A_1 \cdot \sqrt{\frac{2\pi}{\alpha \cdot \rho_1}} \cdot \sin\left(\frac{2\pi \cdot t}{\rho_1} + \frac{\pi}{4}\right) + A_2 \cdot \sqrt{\frac{2\pi}{\alpha \cdot \rho_2}} \cdot \sin\left(\frac{2\pi \cdot t}{\rho_2} + \frac{\pi}{4}\right) \right] \quad (5)$$

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here k and α are the average soil thermal conductivity and thermal diffusivity A_1 and A_2 , respectively, are the daily and yearly temperature amplitudes at land surface, respectively, p_1 is one day and p_2 is one year expressed in the time unit of the equation.

As soon as heat penetrates the soil its transfer is well described by the heat diffusion equation:

$$\frac{\partial(k \cdot \partial T)}{\partial^2 z} = VHC \cdot \frac{\partial T}{\partial t} \quad (6)$$

where k is the thermal conductivity ($\text{J m}^{-1} \text{s}^{-1} \text{°C}^{-1}$), T is temperature ($^{\circ}$), z is depth [m], VHC is the volumetric heat capacity ($\text{J m}^{-3} \text{°C}^{-1}$) and t is time (s).

Values of thermal conductivity and volumetric heat capacity can be calculated by using the method of de Vries (de Vries, 1963; Wierenga and de Wit, 1970). According to this method and depending on the physical properties of the soil components (i.e. air, water, minerals and organic matter) thermal conductivity can be expressed as:

$$k = \frac{\sum_{i=0}^n k_i \cdot X_i \cdot \phi_i}{\sum_{i=0}^n k_i \cdot X_i} \quad (7)$$

and volumetric heat capacity can be described as:

$$VHC = \sum_{i=0}^n VHC_i \cdot X_i \quad (8)$$

where X_i is the volumetric fraction of each soil component, k_i is its thermal conductivity, ϕ_i is its shape factor, VHC_i is its volumetric heat capacity and n is the number of the soil components.

Groundwater existence within the soil profile is expressed by the distinctive values of both thermal conductivity and volumetric heat capacity of the saturated soil. Saturated soils naturally have high values of both.

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2 Methods and materials

2.1 Field measurements

Field measurements were conducted in an agricultural area that lies within Euphrates basin in the north part of Syria (Fig. 1). The boundaries of this area stretch between longitude 38°43' to 39°03' E and latitude 35°55' to 36°13' N. The agricultural fields are equipped with irrigation canals and drainage conduits. Groundwater level has been monitored by means of a dense net of observation piezometers.

Semi arid conditions prevail in the region with an average annual rainfall less than 200 mm and average free water surface evaporation ranging between 1.4 mm/day in January and 14.3 mm/day in July (Alkhaier, 2003).

Pedological data show that silty clay soils cover most of the fields. The poor hydraulic permeability of these soils together with existence of a heavy clay layer at approximately ten meters depth make the groundwater generally perch at shallow depths all year around.

In January 2008 (winter time) seven locations (Fig. 1) with dissimilar water table depths were chosen. In each location, two temperature loggers were deployed in the soil at two different depths (approximately 5 and 10 cm). The loggers recorded temperature every ten minutes for almost six days duration. However, taking into account only the full 24-h days restricted the data to five days.

Upon loggers' deployment, water table depths were measured, soil samples were taken to the laboratory for texture analysis and soil moisture determination.

To omit the effect of soil moisture difference on soil temperature among the measurement locations, soils at the loggers' locations were watered until saturated immediately before the last day of the experiment. The temperature of the used water was just above the freezing point, as it was taken from the nearby irrigation canals where water froze at the surface of these canals.

To explore the relation between groundwater depth and temperature oscillations of soil at land surface, correlation coefficients were calculated between on the one hand,

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the maximum, minimum and average daily temperatures at depths (5 cm and 10 cm) and the average water table depths for a year before (i.e. 2007) on the other. In addition, the maximum, minimum and average daily temperatures in the different sites of measurement for two days (day 3 and day 5) were plotted against the average water table depths. Also, soil moisture values of the different locations were plotted against average water table depths.

2.2 Numerical simulations

Flex PDE, a scripted finite element model builder and partial differential equations numerical solver, has been utilized to simulate heat transfer in one dimension soil profile. Supposing that groundwater existence within the soil profile does not affect the energy balance at land surface, the same G (Eq. 5) was applied as an upper boundary condition at the top of two different profiles:

- The first has no groundwater. So, it has a single value of thermal conductivity and another single value for volumetric heat capacity (please note that we simplify the simulation by assuming that the soil profile is homogenous with invariant soil thermal properties).
- But, the second profile has shallow groundwater perching at different depths (one, two, three, four and five meters), respectively from land surface downwards. Therefore, it has two different sections with different values of both thermal conductivity and volumetric heat capacity. Values of thermal conductivity and volumetric heat capacity of the unsaturated part of the second profile were given exactly the same values of the first (dry) profile.

The lower boundary condition at ten meters depth (approximately the yearly penetration depth of heat) was set as a fixed temperature (22°C) which is the annual deep soil temperature of the region.

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The two profiles simulations were run for one year  after one year of pre-simulation to reach the actual initial boundary condition. The resultant skin temperature of the two profiles was then compared to each other.


3 Data and results

3.1 Field measurements

Table 1 contains the correlation coefficients between, on one hand, the maximum, minimum and average daily temperatures at the two depths (5 cm and 10 cm) and the average water table depths for a year before, on the other.

We can see that the correlation coefficients values of the minimum temperatures are very low and have contradicting signs (negative and positive) between 5 cm and 10 cm, while those for maximum and average temperatures are high and have negative sign. Another remark can be elicited here that the values of the correlation coefficients did not change significantly in the last day when the soils were saturated.

To inspect the relation between soil temperature oscillations and water table depth schematically, the maximum, minimum and average daily temperatures plotted against the average water table depths at the different measurement sites for the third day (chosen arbitrarily) are shown in Fig. 2a and b, and for the last day (saturated soil) in Fig. 3a and b. Depending on these figures, one can recognise that the deeper the water table is the lower maximum and average values of soil temperature oscillations reach. Whereas, the relation between the minimum temperatures and the water table depth might hardly exist.

For both figures, it is clear  the maximum temperature has the highest coefficient of determination (R -squared) followed by the average temperature, while the minimum temperature has very low coefficient of determination (R -squared). Moreover, there is no drastic change in the coefficients of determination (R -squared) before and after wetting the soils.

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Figure 4 shows the relation between volumetric soil moisture measured at the seven different locations and the average water table depth. It can be seen that soil moisture decreases when the depth to groundwater increases.

3.2 Numerical simulations

5 Values of thermal conductivity ($\text{J m}^{-1} \text{s}^{-1} \text{°C}^{-1}$) and volumetric heat capacity ($\text{J m}^{-3} \text{°C}^{-1}$) of the dry and saturated sections of the simulated profiles, calculated using Eqs. (7) and (8) are shown in Table 2.

Figure 5 shows skin temperature oscillations of the dry profile for the simulated year which begins in October. The lowest temperatures are in February and the highest are in August.

The difference between the simulated values of both profiles (skin temperature of the profile with groundwater perching at one meter, minus the skin temperature of the dry profile) is shown in Fig. 6.

15 Several remarks can be elicited from this graph, firstly, there is no oscillation in the values of difference, meaning that the skin temperatures of the two simulations are shifting up or down without changing their daily amplitudes. Secondly, the difference is positive in months from January to May, and reaches its maximum value of 3°C in March. Thirdly, the difference is negative in months from July to November and reaches its minimum value of -3°C in September, and finally there are two months (namely December and June) when the difference is at lower values.

20 Values of maximum differences between the dry profile and the simulated profiles with different water tables are 1.5°C for 2 m depth, 0.8°C for 3 m depth, 0.4°C for 4 m depth and 0.2°C for 5 m depth. Naturally, this water table depth includes the capillary rise value.

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4 Discussion and conclusions

In this study, we show that shallow groundwater affects skin temperature. This is evidenced firstly, by the high correlation between daily maximum and average soil temperatures and water table depth, and secondly, by the difference in simulated skin temperatures caused by groundwater perching within the relevant soil profile.

It is difficult and expensive to measure skin temperature in situ for different locations simultaneously. However, the recorded measurements can be extrapolated to land surface and show that skin temperature oscillations behave similarly.

Although both field measurements and numerical simulations show that shallow groundwater affects the temperature oscillation at land surface, their results are not exactly the same. While the simulated skin temperature difference shows no oscillation i.e. groundwater shifts the daily temperature curve up (in winter) or down (in summer) without affecting the shape of the curve itself, field measurements show that the shape of temperature curves are affected by shallow groundwater. That is clear from the different values of correlation coefficients of the minimum, maximum, average daily temperature with water table depth.

The dissimilarity between the two results is because, as we assumed in the numerical model, that ground heat flux has the same values in both cases (with and without groundwater) which is not strictly true. In fact, when shallow groundwater affects skin temperature it affects all the components of the energy balance including ground heat flux thereby. Another point, which has not been considered in the model, is the soil moisture effect. Not only does shallow groundwater affect skin temperature directly by influencing heat flow within soil due to its distinctive thermal properties, but also it affects skin temperature indirectly by increasing soil moisture due to capillary rise and vapour transport within soil pores. This is clear in Fig. 4, where soil moisture values increase with decreasing water table depth.

Soil moisture affects soil temperature in different and contradicting aspects. These effects fall into five categories: soil surface albedo, soil emissivity, evaporation, soil

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thermal conductivity and volumetric heat capacity. Firstly, increasing soil moisture decreases albedo which in turn increases the absorbed radiation during day time; hence, this increase daytime temperature. Secondly, soil emissivity increases with increasing soil moisture, which in turn increases the upward emission thus decreases surface temperature. Thirdly, the increase of soil moisture increases actual evaporation which accordingly decreases temperature. Fourthly, the increase of soil moisture increases soil thermal conductivity which eases heat transfer down and up within the surface soil and thereby decreases the absolute values of daily maximum and minimum temperatures. Finally, the increase of soil moisture increases soil volumetric heat capacity which increases the energy required for raising or lowering soil temperature, and in a similar manner to that of the third effect, it decreases the absolute values of the daily maximum and minimum temperatures.

On the last day of the experiment all locations were wetted till saturation. Consequently, the difference in soil moisture effects among the different locations was almost vanished. However, the relation between soil temperature and water table depth (Table 1, Figs. 2 and 3) was not affected considerably. This clarifies the direct effect of groundwater on skin temperature.

An unexpected phenomenon is worth mentioning here. Despite the general awareness that in daytime, wet soil must have lower temperature than dry one (due to its higher actual evaporation and higher heat capacity), the correlation between water table depth and maximum temperature was negative (Figs. 2 and 3) and so was it for soil moisture (Fig. 4). That means the observed maximum temperature was higher in wetter soils.

In summery, we conclude that shallow groundwater affects skin temperature on yearly basis. As mentioned in many previous studies it acts like a heat sink in summer and a heat source in winter. However, due to the complex processes that take place at land surface (radiations and fluxes interactions) its effect is not simple to describe. Many studies avoided this complexity by going with their measurements deep into the soil to correlate groundwater existence to soil temperature. And the other studies which

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dealt with skin temperature had different opinions and contradicting results. Through the results of this study, we show that shallow groundwater has a clear impact on skin temperature. This impact will be useful in two fields: first, in utilizing thermal satellite remote sensing in groundwater studies and second, in land surface energy balance studies (land surface models and climate models).

In this study we show qualitatively that shallow groundwater affects skin temperature. Thus, we recommend setting a comprehensive numerical model that takes into account all the different factors which contribute to determining skin temperature and the exact magnitude of that effect.

Finally, we have noticed that the studies which utilized remote sensing for detecting depth to groundwater used a single scene (i.e. one reading). This study proves that a single scene /reading only is not sufficient, and recommends having a high temporal resolution of temperature measurements to detect shallow groundwater depth.

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Table 1. Correlation coefficients between the min, max and average daily temperatures at the two depths (5 cm and 10 cm) and average water table depths.

	Minimum temperature		Maximum temperature		Average temperature	
	5 cm	10 cm	5 cm	10 cm	5 cm	10 cm
day 1	0.03	-0.07	-0.85	-0.78	-0.69	-0.69
day 2	0.06	-0.14	-0.85	-0.77	-0.73	-0.76
day 3	0.08	-0.11	-0.83	-0.75	-0.70	-0.77
day 4	0.04	-0.28	-0.71	-0.67	-0.72	-0.78
day 5	0.22	-0.03	-0.75	-0.66	-0.55	-0.68

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Table 2. Soil thermal properties used in the simulation.

	Thermal Conductivity	Volumetric Heat Capacity
Dry Soil	0.72	1.21E+06
Saturated Soil	1.27	3.10E+06

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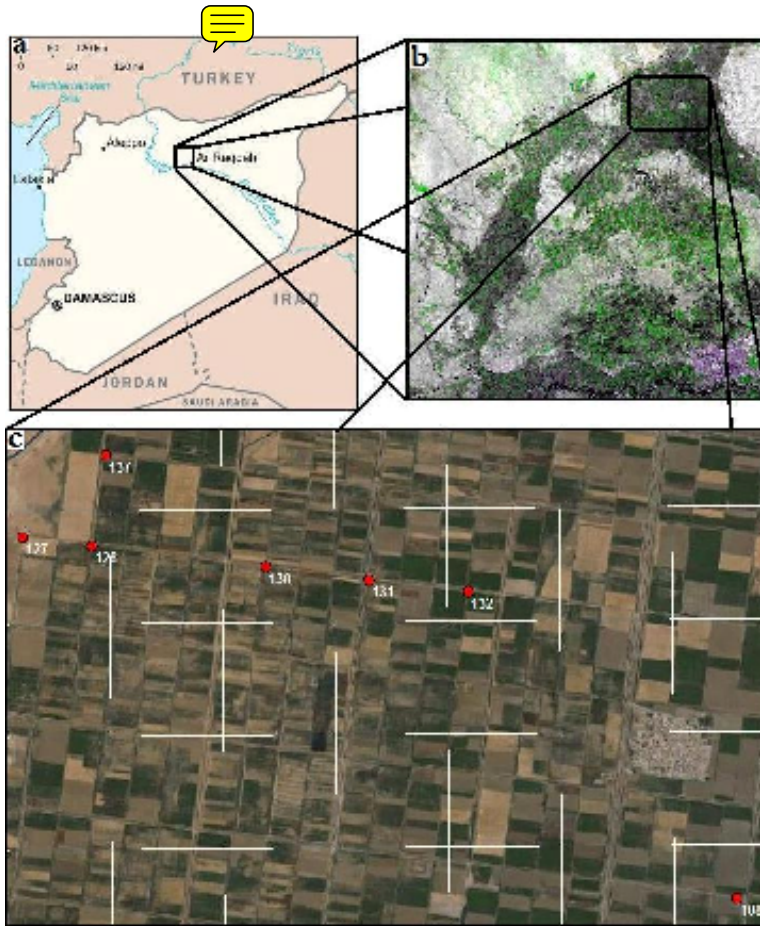


Fig. 1. (a) Map of Syria, (b) Study area: (Google earth image), (c) Observation sites: square=1 km².

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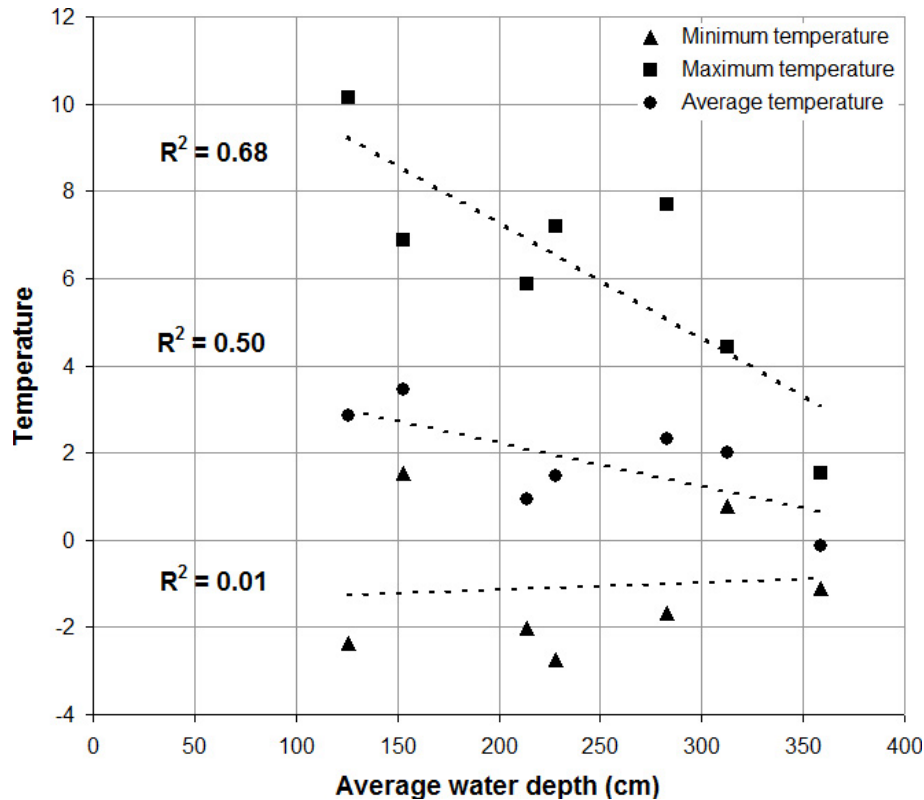


Fig. 2a. Min, max and average temperature vs. water table depth of the third day. Temperature measurements at 5 cm depth.

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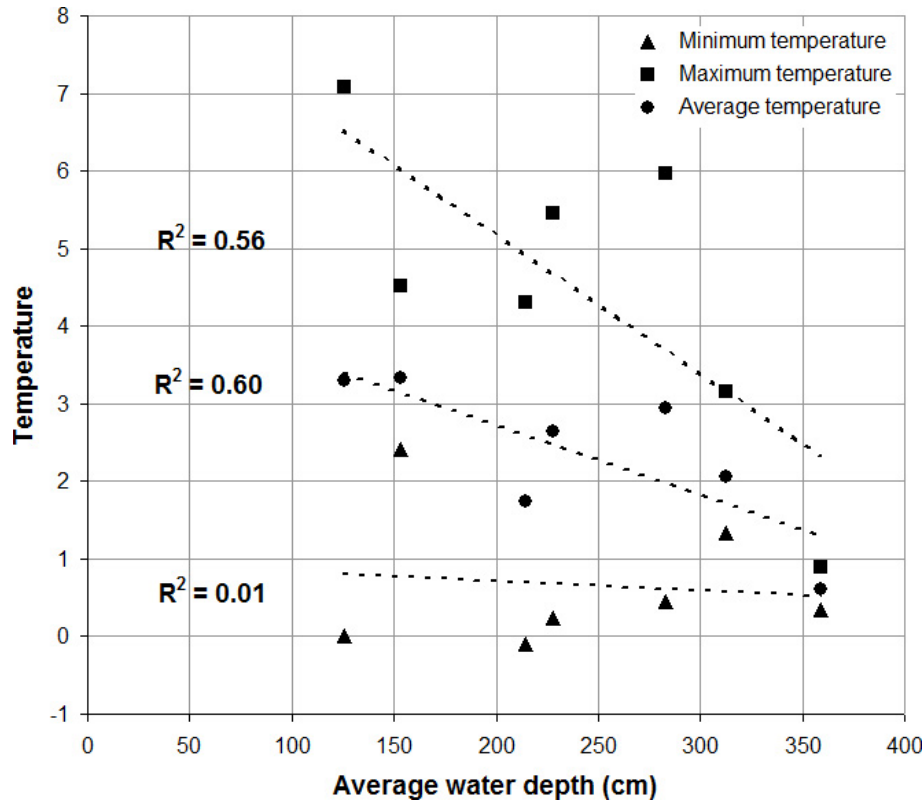


Fig. 2b. Min, max and average temperature vs. water table depth of the third day. Temperature measurements at 10 cm depth.

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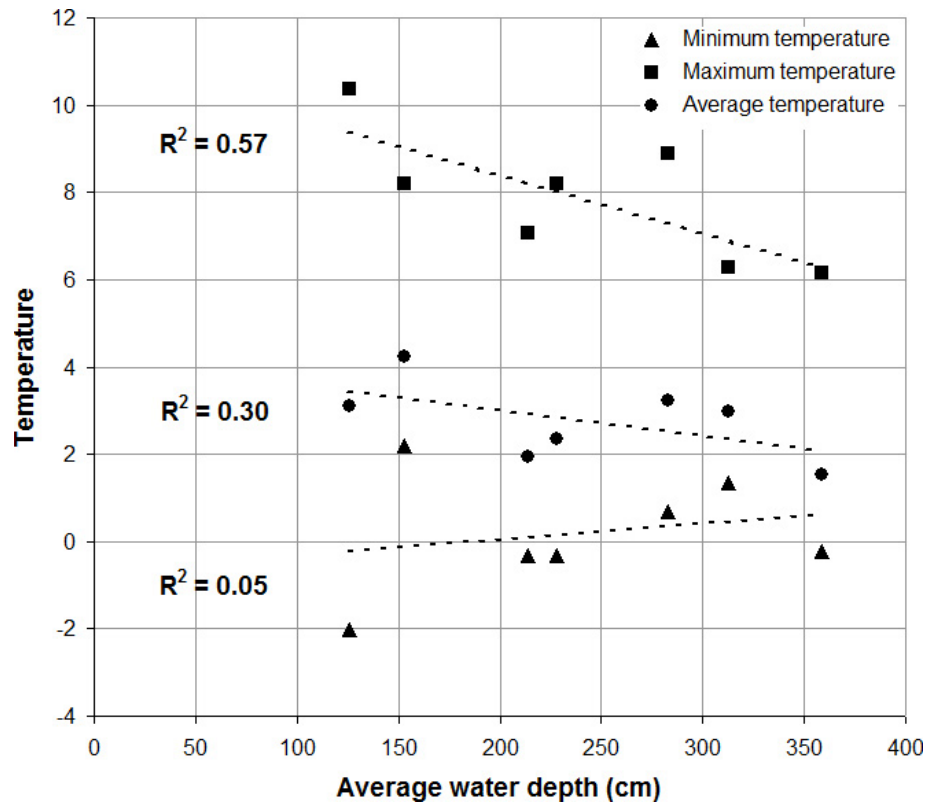


Fig. 3a. Min, max and average temperature vs. water table depth of the last day (wet soil). Temperature measurements at 5 cm depth.

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F. Alkhaier et al.

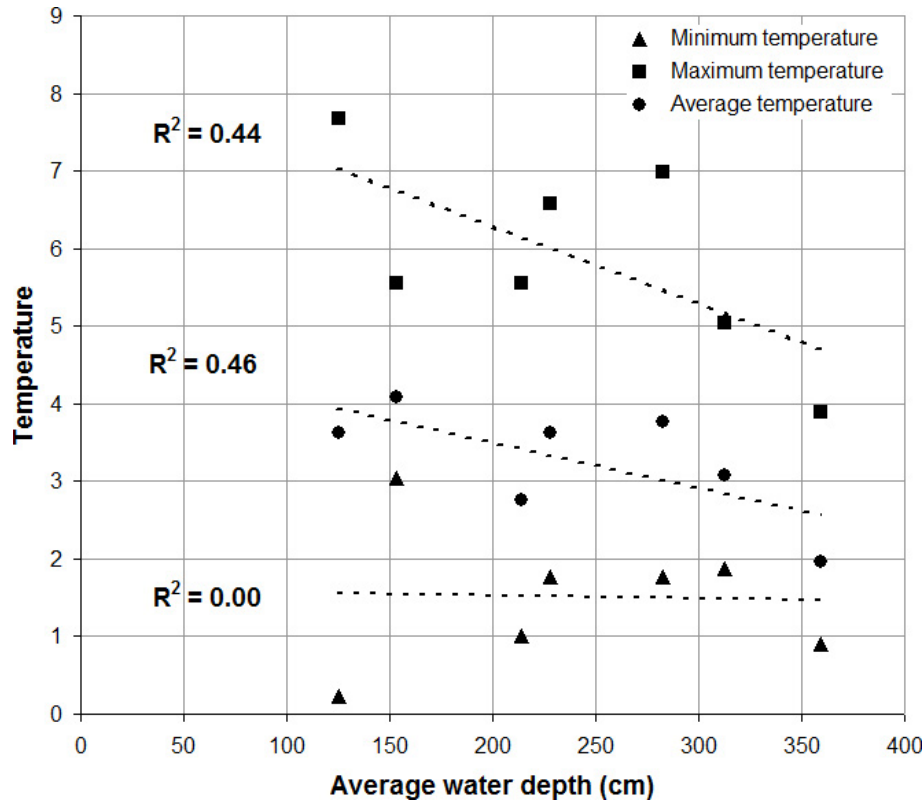


Fig. 3b. Min, max and average temperature vs. water table depth of the last day (wet soil). Temperature measurements at 10 cm depth.

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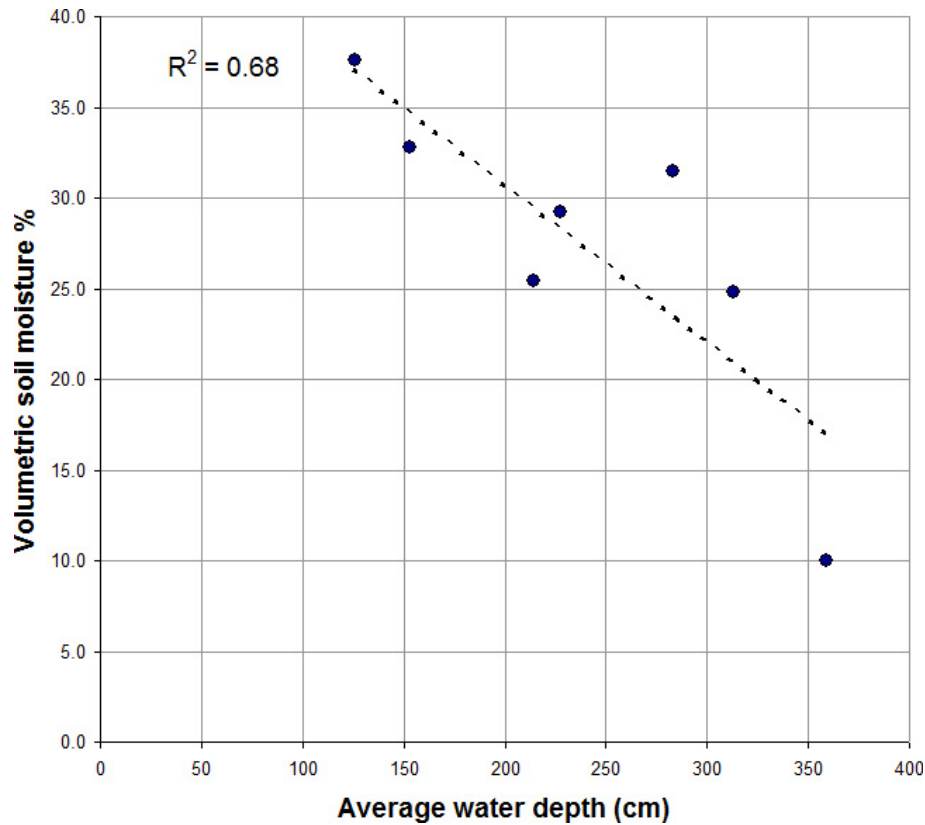


Fig. 4. Soil moisture vs. water table depth.

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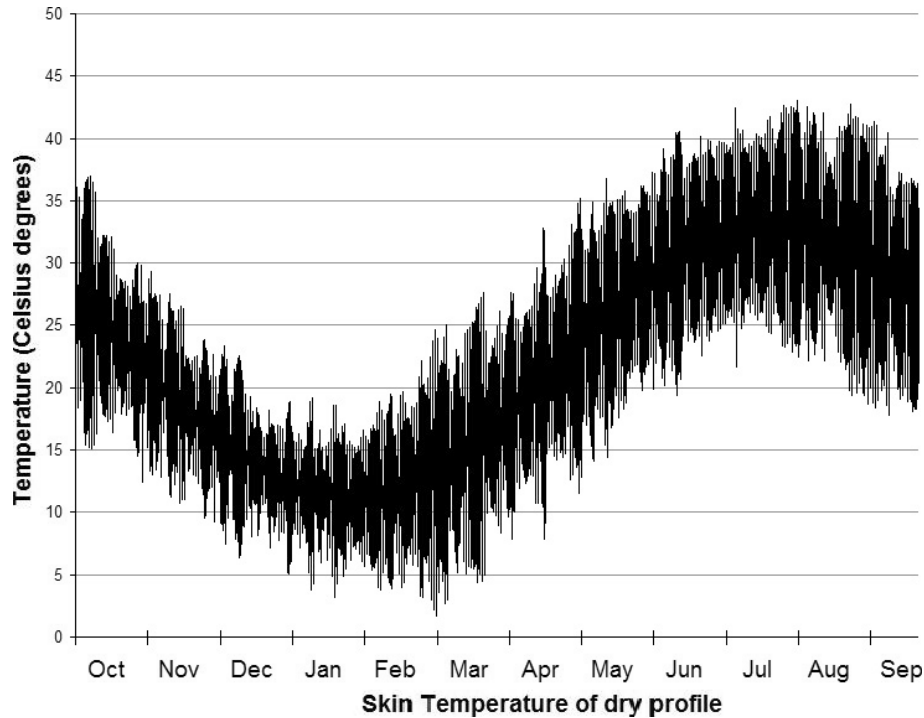


Fig. 5. Skin temperature oscillations of the simulated year.

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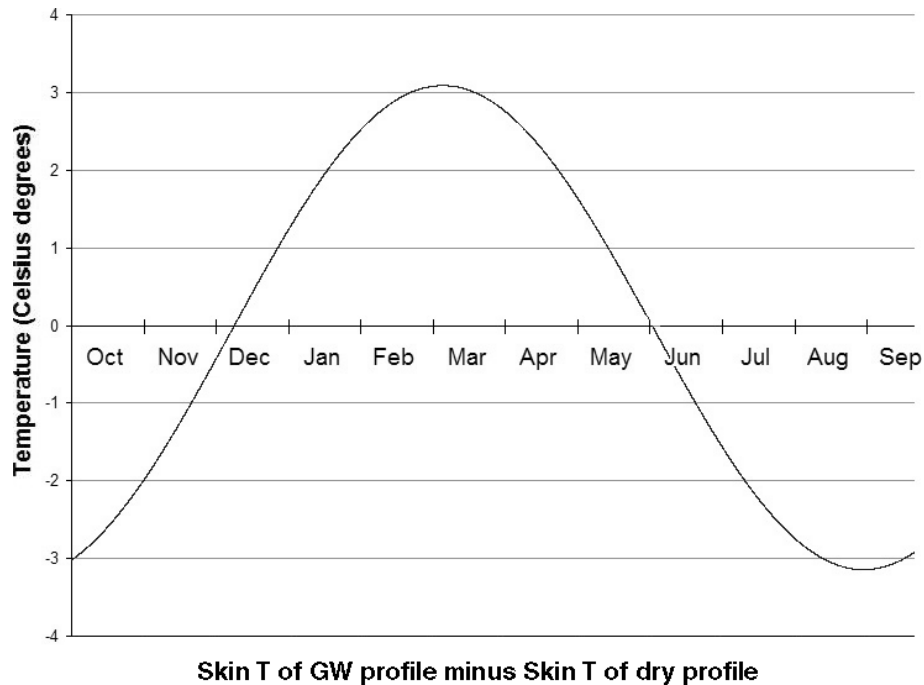


Fig. 6. The difference between skin temperature of the two profiles (with and without groundwater).