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Soil surface-atmosphere interaction in a monitored embankment constructed with two compacted lime-treated soils

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Article

Keywords
Field monitoring
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Abstract

This study was carried out in an instrumented and monitored embankment divided into two symetrical sections and constructed with compacted treated soils (i.e., a silty soil and a clayey soil) exposed to the same atmospheric conditions in a continental climate, with oceanic influences. It aimed to investigate changes of bare soil surface moisture (w) and corresponding suction (s) as result of soil water evaporation processes on a monthly time scale. Seasonal variations in the w (and s) measurement in both soil surfaces show overall consistency with the meteorological measurement within the study area. The paper also examines the ability of four air temperature-based potential evaporation (*PET*) formulations to capture the process of evaporation at the site. Results indicated that soil water evaporation is controlled by both atmospheric and soil conditions. And, during the most significant drying time period, the measured s consistently increased and the corresponding w decreased suggesting a relatively significant water evaporation effect. However, the monthly predicted *PET* data varied from a maximum of over 120 mm/month to less than 50 mm/month during the drying time, depending on the used method. The continuously monitored soil surface suctions are used for discussing the variations of evaporation according to the predicted *PET* method and time period at the site.

1. Introduction

Geotechnical engineering works are subjected to soil moisture and corresponding soil suctions variations at both weather and climate timescales. Periodical drying-wetting cycles can alter soil seepage and stability analysis in earth works (Toll et al., 2011; Azizi et al., 2023). And, the knowledge of the effects of soil surface-atmosphere interaction (SAI) in earth engineering works can reduce faulty or very conservative engineering designs and deficient long-term performance of geo-structures (Bordoni et al., 2021). The SAI can be reflected by heat and water transfer in soil-plant-atmosphere continuum and described by the variations of soil surface boundary conditions (Blight, 1997; Elia et al., 2017; Sedighi et al., 2018; Toll et al., 2019).

In order to understand the dynamics and the variability of soil moisture in geotechnical engineering, it is crucial to well evaluate the main mechanisms related to water balances for the soil systems (Blight, 2003; Cui & Zornberg, 2008). Previous studies have shown that using only precipitation data for soil stability analysis provides insufficient information for assessment of landslide processes especially for clayey shallow soil (Toll et al., 2011; Bittelli et al., 2012; Bicalho et al., 2018; Fusco et al., 2022; Cui, 2022). Soil surface suctions (and moistures) respond directly to wetting by infiltration of rainfall or drying as a result of evapotranspiration. These changes in suction/moisture can take place independently of the main ground water table.

The amount of rainfall infiltration into the soil mass depends on external factors as well as intrinsic soil parameters, and the effect of rainfall infiltration on soil instabilities has been studied by many researchers (Wolle & Hachich, 1989; Springman et al., 2003; Rahardjo et al., 2005; Huang et al., 2009). Though forming a fundamental component on studies of soil water balance and applications, soil water evaporation is challenging to quantify in practice occurring in the form of combined liquid and vapor transport both at the depth and ground surface. Potential evaporation (*PET*), which represents the upper reference limit to the regional evaporative capacity in a given surface under given meteorological conditions (Lhomme, 1997; Zhou et al., 2020), is often estimated using

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climate models at multiple scales. Yet, soil water evaporation is controlled by atmospheric, vegetation and soil conditions (Wilson, 1990; Tran et al., 2016) with significant spatial variability (Niranjan & Nandagiri, 2023), and the suitability and accuracy of the *PET* empirical methods can be questioned.

Relative evaporation (i.e. the ratio of actual to maximum or potential evaporation, ET_a / *PET*) varies in time and space depending on soil-moisture conditions (Wilson, 1990), conceptual *PET* model, and measured data. The difference between the actual ET_a and the *PET* is considered negligible in humid regions or under wet conditions (e.g. precipitation greater than potention evaporation) but becomes increasingly large as the surface moisture availability decreases (Fetter, 1994). The local evaluation of the *PET* values is important for understanding soil atmosphere fluxes in the soil work performance over time and estimating the spatial and temporal change in the actual evaporation. *PET* values may vary significantly in both, time, and space, and exist different ways and definitions in use for identifying the model and parameter to estimate potential evaporation (Kay & Davies, 2008; Kalma et al., 2008; Hu et al., 2021). The selection of appropriate *PET* method for analysis of the data depends on input data availability, and the required accuracy of the estimated *PET* values in the investigated site and period.

Changes of the soil surface suction/moisture in an monitored nonvegetated embankment were examinated considering the SAI in two lime treated fine-grained soils exposed to the same meteorological conditions (dry and wet seasons) in the Northeast of France. The field instrumentation included spatial and temporal changes of the soil suction/moisture at a predefined superficial locations within the embankment, as well as measurements of meteorological data, collected between Spring and Fall in 2011 (the first-year-old embankment building). In the cold period of a year, the evaporation estimated by different methods vary considerably due to the specificity of each adopted methodology. The air temperature can have negative values in the cold period in determined regions with very small calculated values of evaporation. The study was carried out using different meteorological data and soil conditions to examine the comparison among field monitoring soil surface suctions at specific location and calculated *PET* values determined using four common empirical expressions obtained from in-situ recorded meteorological observations over dry months.

2. Materials and methods

2.1 Description of the study area and data collection

A monitored full-scale embankment constructed with compacted lime treated soils in the Northeast of France is investigated herein. The site in Hericourt, Haute-Saône, France, is located at Latitude 47º 34' 39" North, Longitude 06º 45' 42" East and average altitude of 413 m. It is exposed to a continental climate, with oceanic influences. The embankment (107m long by about 5m high with side slopes of 1 on 2) was divided into two symmetrical sections, constructed with two natural soils (a silty soil and a clayey soil) treated with cement and/or lime in different dosages (Froumentin, 2012). As the soils were treated with different binders (lime or cement) and with different dosages, for the purpose of comparison, only the points with lime-treated soil have been selected for analysis in this study. According to the unified soil classification system, the two soils were classified as: CL, an inorganic clay with low plasticity, and CH, an inorganic clay with high plasticity. Soil and meteorological conditions on the test plots at the embankment have been monitored since the construction in 2010. A system of runoff measurement was also installed to monitor the runoff from the side slope (An et al., 2017).

The investigations and analysis were divided into two parts. The first part analyzes the potential evaporation calculations in the study site in 2011. A site-specific meteorology station on the top surface was used to record the meteorological data every 30 min, including precipitation, relative humidity, air temperature, net radiation and wind speed. The year of 2011 had a cumulative precipitation (rainfall) at local weather station (773 mm) above average annual precipitation (619 mm) in France. The air temperature and relative humidity were recorded at 0.5 m and 1.5 m above the soil surface in 2011. The second part investigates the monitoring data of matric suction and volumetric water content at predefined locations over time within the embankment. The instrumentation layout was symmetrical for the two sections of the embankment. The embankment consists of 17 layers made of the two fill materials compacted to optimum water contents (Standard Proctor tests). At each layer, the gravimetric water content and soil density were measured at various positions before and after construction, and the measurement variations were quite small. No leachate of lime or cement with rainfall was observed in the monitored area. A layer of the slope, approximately at mid-slope, was selected for the investigations and analyses in this paper. The selected layer, located at about 1.8 m from the embankment base, is instrumented with sensors, for measuring soil suction (s) and volumetric water content (w), located close to allow estimation of the in-situ s - w relationship at the specific position over time.

Time Domain Reflectometry (TDR) method, a measurement technique for electrical properties is used to monitor the volumetric soil water content changes at the investigated embankment. The used sensors are TRIME-PICO 64, of IMKO Micro GmbH, in Germany, which are capable of simultaneously measuring soil temperature and inferring the volumetric water content. The TDR method was used to monitor the soil volumetric water content, together with the soil temperature. The probes installed were linked to a control panel and data acquisition system, which allowed regular measurements. Watermark soil suction sensors connected to a data acquisition system was used to monitor the soil superficial suction changes over time at the embankment. The used sensor is an indirect, calibrated method of measuring soil suction. It is an electrical resistance type sensor. These "Granular Matrix Sensors" electronically read the amount of moisture absorbed through a special "granular matrix", or mix of precisely composed materials. This special mix buffers the sensor against the effects of different salinities and ensures a lifetime much longer than the traditional "gypsum blocks". The readings were calibrated to reflect the same values that would be generated by a Tensiometer.

2.2 Description of the adopted potential evaporation (*PET*) calculation methods

Evapotranspiration represents the combined evaporation from the soil surface and transpiration from plants. Actual evaporation (ET_a) indicates the amount of water evaporated through the bare soil surface while conceptually potential evaporation (*PET*) represents the maximum possible evaporation rate and is the rate that would occur under given meteorological conditions from a continuously saturated surface (Donohue et al., 2010). The regional evaluation of the maximum or potential evaporation is important for understanding soil atmosphere fluxes in the embankment system performance over time and estimating the spatial and temporal change in the actual evaporation ($ET_a < PET$).

Many methods have been proposed to evaluate *PET* calculations based on standard meteorological observations (Xu & Singh, 1998, 2001; Donohue et al., 2010; Tu & Yang, 2022). *PET* methods should be used for open water or fully water saturated soil surfaces. A large variability can be observed on the *PET* methods based on meteorological local date considering different assumptions, input data, and specific climatic regions (Lemaitre-Basset et al., 2022). Actual rates of evaporation from unsaturated soil surfaces are generally greatly reduced relative to the potential rate of evaporation.

Solar radiation, air temperature, air relativity humidity and wind speed are climatological input data to consider when assessing the evaporation process. In this study, the *PET* was estimated using four formulations applied in the year 2011 when the weather data were directly measured in the study area. The four *PET* methods (Thornthwaite, 1948; Blaney & Criddle, 1950; Kharrufa, 1985; Romanenko, 1961) are briefly summarized here (Table 1) and the cited references are suggested for a detailed discussion. The mean monthly net radiation and wind speed measured values in the region remained essentially unchanged during the evaluation period; therefore, it may be reasonable to make the assumption of no influence of the net radiation and wind speed on the evaporation considered by the used methods for the region in 2011.

Thornthwaite (1948) formulation is highly used, even though the empirical method is not recommended for areas that are not climatically similar to the developed area, in the eastern region of USA, where sufficient moisture water

Table 1. Equations for estimating potential evaporation (*PET*) according to air temperature-based methods (Thornthwaite, 1948; Blaney & Criddle, 1950; Kharrufa, 1985), and a combination of air temperature and air relative humidity-based method (Romanenko, 1961).

Method	Required inputs	Equation (*PET*)	Variable definition
Thornthwaite (1948)	average air temperature, and latitude	$16\left(10\frac{T}{I}\right)^{a}$	$i=\sum_{1}^{12}\left(\frac{T}{5}\right)^{1.514}$
			$a = 6.75x10^{-7} I^3 \ -7.71x10^{-5} I^2 + 1.7912x10^{-2} I \ +0.4939$
		$0 \le T \le 26°C$	$I =$ annual heat index, given by the sum of the 12 monthly values of i, monthly heat index
			$T =$ average air temperature
Blaney & Criddle (1950)	average air temperature, latitude, coefficient dependent on the vegetation type, location, and season	$k\,p\left(0.46T+8.13\right)$	$k =$ crop coefficient (plantation). It is obtained from curves based on field measurements. In Blaney & Criddle (1962) an extensive table is presented with the values of k for several states of the Western USA.
			$p =$ monthly average percentage of light hours.
			$T =$ average air temperature
Kharrufa (1985)	average air temperature, and latitude	$0.34\,pT^{1.3}$	$p =$ monthly average percentage of light hours.
			$T =$ average air temperature
Romanenko (1961)	average air temperature, and average relative humidity of air	$0.0018\left(25+T\right)^2 A$	$R_h =$ air relative humidity
			$T =$ average air temperature
			$A = \left(100 - R_h\right)$

was available to maintain active transpiration. The original equation is misused in arid and semi-arid irrigated areas (Xu & Singh, 2001). Moreover, one should be aware that the soil temperature fluctuates daily and yearly mainly by changes in air temperature and solar radiation. Often, one chooses a model to estimate *PET* based on the available data to calculate the model. Generally, more sophisticated models require larger input files, and obtaining the necessary input data can be time consuming and difficult. The air temperature-based equations are evaluated in this paper due to the advantage that the methods allow calculating *PET* by using only the monthly average air temperature and the locations of the geographic coordinates.

Atmosphere water balance refers to the balance of the inflow and outflow of atmosphere moisture. An atmosphere water balance (*B*) is tied to an overall balance through the processes of precipitation (*P*), and evaporation (*ET*) at a given local and time scale (Blight, 1997, 2003). The actual evaporation (ET_a) differs from the potencial evaporation (*PET*) under most circumstances. For assessing four common air temperature-based *PET* methods, a dependency between ET_a and *PET* values is assumed in this study. And, *B* values are estimated using *PET* instead of ET_a:

$$B = P - PET \tag{1}$$

During the period of excess water (*B* positive), there is moisture available for ground-water recharge and runoff. The runoff were monitored for the investigated embankment. And, the runoff remained quite low (<0.1 mm/h) when the precipitation was lower than about 11 mm/h, and became significant beyond 11 mm/h precipitation (Cui, 2022).

Net water fluxes are a function of the infiltration entering the soil cover due to precipitation and exfiltration leaving the soil cover due to atmospheric evaporation. The uncertainties regard to the potential evaporation value, which depends on the model structure and input data, might result in different *B* values. The results of Equation (1) were estimated using four air temperature-based equations (Thornthwaite, 1948; Blaney & Criddle, 1950; Kharrufa, 1985; Romanenko, 1961) of *PET* values (see Table 1). Romanenko (1961) method is based on a combination of air temperature and air relative humidity data. Table 1 presents a summary of the required inputs, equation and variable definition used for determining *PET* values at site specific meteorology station on the top surface of the monitored embankment.

3. Results and discussions

The bare soil surface moisture/suction in unsaturated region can be changed under two main mechanisms: infiltration or evaporation. Many factors affect soil evaporation. In this study, the spatial and temporal field measured variations of the soil surface suction/moisture in two lime-treated soils (a silty soil and a clayey soil) due to local environmental conditions are compared to the potential evaporation calculations based upon the assumptions that the *PET* data were dependent only upon meteorological conditions and ignored the effect of soil conditions.

3.1 Prediction of *PET* data from the local recorded meteorological observations

Figure 1a illustrates the mean monthly recorded precipitation, *P*, and the calculated *PET* (mm/month) values according to air temperature-based methods (Thornthwaite, 1948; Blaney & Criddle, 1950; Kharrufa, 1985), and a combination of air temperature and air relative humidity-based method (Romanenko, 1961) from May to October in 2011, at Hericourt, France. The air temperature *T* and relative humidity R_h values were recorded at 0.5 m and 1.5 m above the soil surface at the site. The air temperatures are approximately constant at the measured heights, and a small difference (5-10%) was observed in the R_h values recorded at 0.5 m and 1.5 m above the surface. The air close to the soil surface is warmer than it is higher up from April to August in 2011. The same trend is not observed in the months with lower temperatures (October and November 2011).

Wind speeds between 0 and 5.5 m/s were recorded in 2011 at the site. The mean monthly wind speed was about 1.0 m/s for the monitored period. Wind speed is important because stronger winds cause more evapotranspiration. But rate of transpiration may decrease with increasing wind speeds (Schymanski & Or, 2016). It is also presented in Figure 1a, the *PET* values calculated by using Romanenko (1961) formulation and the mean month R_h values recorded at 0.5 m and 1.5 m above the ground surface, *PET* - R1 and *PET* - R2, respectively, at the site in 2011. The difference of about 5-10% observed in the R_h recorded at the measured heights resulted in calculated *PET* variations over 20 mm / month in June 2021 according to Romanenko (1961) *PET* - R1 and *PET* - R2 results. Fluctuations observed in the estimated *PET* (mm/month) values according to the recorded air temperature-based methods (Thornthwaite, 1948; Blaney & Criddle, 1950; Kharrufa, 1985) in the site in 2011 indicated a wide variation in the calculated *PET* data depending on the used method and considered time period. June (J) and August (A) in 2011 were the hottest investigated months, with the highest values of evaporation estimated by air temperature-based methods in the investigated site. The analysis of *PET* (mm/month) values identified that the highest values of evaporation were estimated by Blaney & Criddle (1950) and Kharrufa (1985) formulations (see Figure 1a). *PET* values by Thornthwaite (1948) were underestimated (over 40 mm/month in June 2021) concerning the Blaney & Criddle (1950) and Kharrufa (1985) formulations. Variation of evaporation depending on the estimation method and the time period of the recorded meteorological data. Higher differences between estimated values using the selected ways were identified in

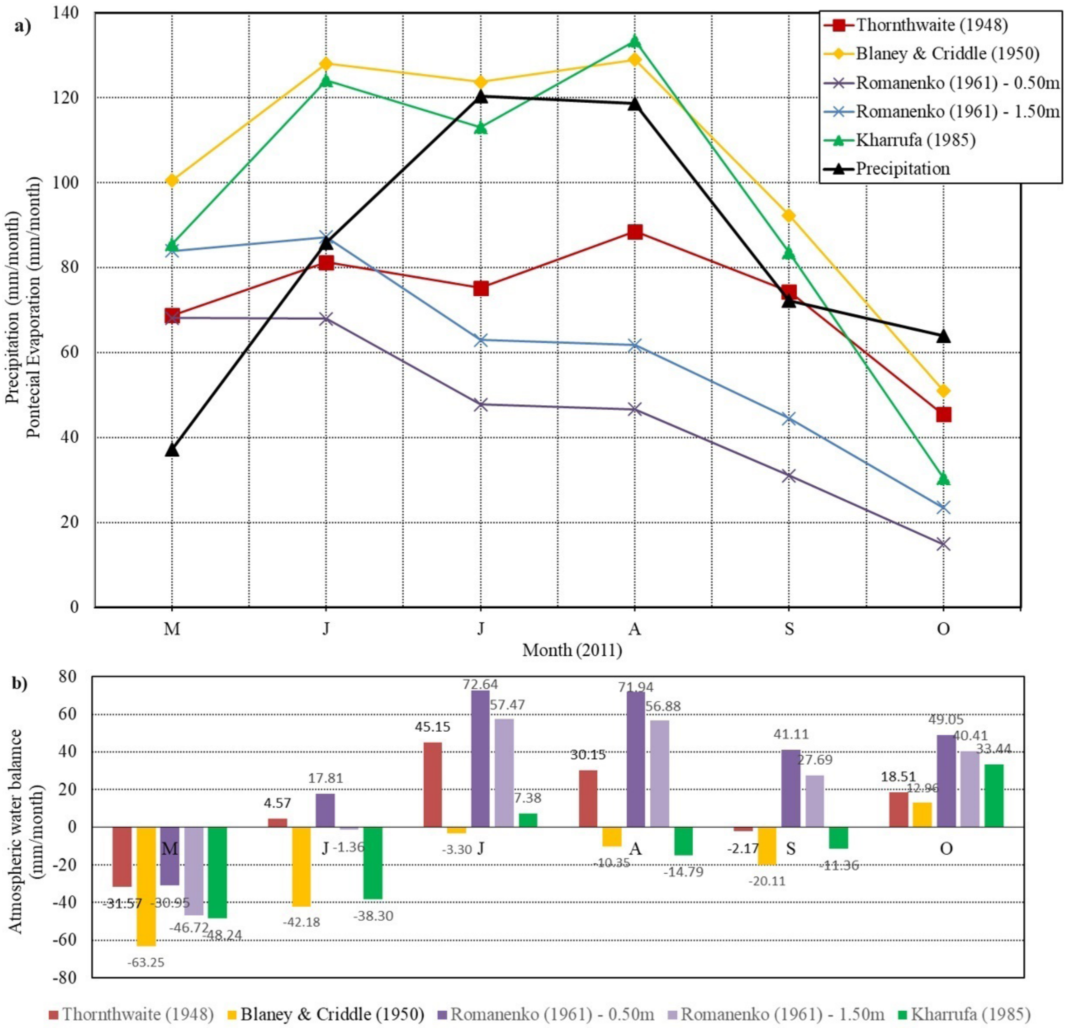

Figure 1. Variation of the measured (a) monthly precipitation and the calculated *PET* (mm/month) values (Thornthwaite, 1948; Romanenko, 1961; Blaney & Criddle, 1950; Kharrufa, 1985), and (b) calculated *B* values from May (M) to October (O) in 2011 in the investigated site.

the hottest months (i.e., July and August 2011) and lower in the coldest month (i.e., October 2011) of the evaluated period at the site.

Potential evaporation is an important component in the atmospheric water balance equation (*B*). It can be seen from Figure 1b, the comparison between the four methods clearly highlights the influence of the considered *PET* formulation on the predicted *B* values (Equation 1). The results show that May 2011 is a month of water deficit (*B* negative), and from June to September 2011, *B* values may be negative or positive depend on the adopted *PET* formulation. In October 2011, *B* is positive (water surplus) according to the four adopted *PET* methods. In June 2011, *B* varies from approximately –40 mm/month according to Blaney & Criddle (1950) and Kharrufa (1985) to approximately +20 mm/month by using Romanenko (1961) - R1. The difference observed in the formulations can be attributed to variations of the conceptual *PET* model, and measured input data (i.e., air relative humidity). The consideration of the runoff term in Equation 1 may prevent large positive anomalies of soil wetness (Delworth & Manabe, 1988). But there were no particularly intense rainfall events (>11 mm/h) during the significant water deficit period characterized by increasing soil surface suctions in the late spring (May and June in 2011) suggesting a relatively small amounts of runoff for the time period and site.

Thornthwaite (1948) considered only the mean monthly air temperature and sunlight as input data while Romanenko (1961) used the air temperature and relative humidity as input data. The mean monthly measured solar radiation and wind speed in the region remained essentially unchanged in 2011; therefore, it may be reasonable to assume no influence of the solar radiation and wind speed on the evaporation considered herein. Thornthwaite (1948) equation may underestimates the measured evapotranspiration (Blight, 1997) or overestimates *PET* where climate is relatively humid, while for arid and semiarid parts of China it produces an underestimation (Chen et al., 2005). The Blaney & Criddle (1950) method for estimating *PET* values is well known in the western USA and has been widely used elsewhere also (Xu & Singh, 2001).

3.2 Comparison between field measured soil surface suction/moisture and predicted potential evaporation data

Both infiltration and evaporation processes can have impacts on changing soil moisture and suction distribution in unsaturated soil surfaces. Changes of soil water evaporation are relatively expressive during significant periods of water deficit (*B* negative) at a site. Even though the relative contribution of soil evaporation to the amount of soil suction is not well defined. To investigate the effects of soil surface suction/moisture observations on predicted soil water evaporation, the measured in-situ soil surface suctions in the two bare treated fine-grained soils exposed at the same atmospheric conditions over dry months are compared to the simulated *PET* values (Thornthwaite, 1948; Blaney & Criddle, 1950; Kharrufa, 1985; Romanenko, 1961) determined from recorded meteorological observations at the investigated time period and site. *PET* - R1 and *PET* - R2 are the *PET* values calculated by using Romanenko (1961) formulation and the R_h recorded at 0.5 m and 1.5 m above the ground surface, respectively.

Figure 2 shows the comparisons of the mean monthly measured soil surface suction and corresponding volumetric water content values (about -0.25 m from slope face) in the two lime-treated soil (i.e., CL + 2% CaO and CH + 4% CaO) sections from April to November 2011 (dry and wet seasons). The layer of the slope located at about 1.8 m from the embankment base, approximately at mid-slope, was selected for the investigations and analysis because it is symmetrically instrumented with the sensors for measuring soil suction (*s*) and volumetric water content (*w*) located close to allow the estimation of the in-situ *s-w* relationship at the specific position over time. The data show consistency in the suctions determined by using watermark soil suction sensors and the volumetric water contents (and soil temperatures) determined by using TRIME-PICO 64 sensors, of IMKO

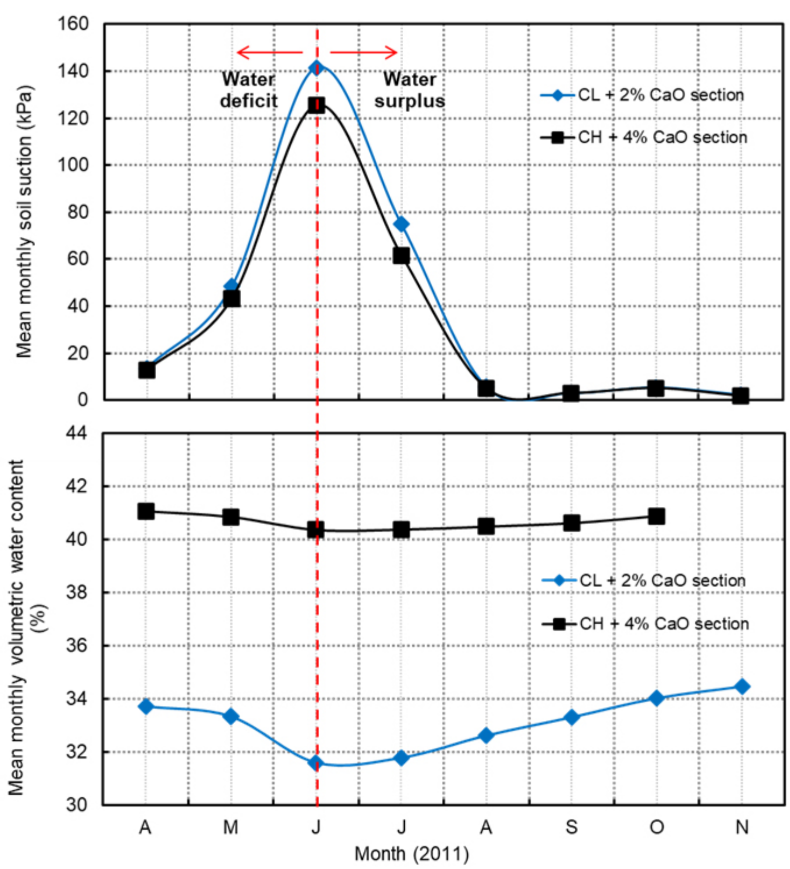

Figure 2. Comparison among mean monthly measured (a) soil suctions, (b) volumetric water contents, at mid-slope in the two treated soil sections from April (A) to November (N) in 2011.

Micro GmbH, variations trend in the two treated soils. Comparison between the lime-treated silty soil and the clayey soil (Figure 2a) showed that the variations of soil surface suction were more expressive in the silty soil in the late spring and summer, between June and August 2021. This confirmed that the hydraulic conductivity is an important factor in the response of soil to atmospheric conditions and the silty soil had a higher hydraulic conductivity, thus its suction changed more under the effects of infiltration / evaporation (Bicalho et al., 2015; Cui, 2022). During the most significant water deficit period in 2011 in the two lime-treated soils (i.e., from April to June), the mean monthly measured soil surface suctions have consistently increased and the corresponding water contents decreased. As can be seen in Figure 2, the responses of soil suction are usually less than 200 kPa (i.e., limit of the working range of each soil suction sensor). The simplified atmospheric water balance based on mean monthly potential evaporation calculated according to the adopted air temperature-based methods Blaney & Criddle (1950) and Kharrufa (1985) formulations, and, presented in Figure 1b (negative *B* values), illustrate well the period of water deficit observed in the responses of the mean monthly soil surface suction/moisture measurements (May and June) at the site. The same trend was not observed by using Thornthwaite (1948) and Romanenko (1961).

Figure 3 shows a graphical relationship for the mean monthly measured soil surface suction, *s* (kPa) versus the predicted potential evaporation *PET* (mm/month) for the two treated soils from April to June 2011 (i.e., a period of water deficit according to a relatively significant increase in the mean monthly measured soil surface suctions for the two lime-treated soils during the year at the site, Figure 2). *PET* (mm/month) values were calculated for the four methods from local recorded meteorological observations at the investigated site over the dry months in 2011 (i.e., April, May and June). It was joined straight lines through the measured / calculated points. Comparison between the silty soil and the clayey soil (Figure 2a) showed that the variations of suction were more significant for the more permeable soil (i.e., the silty soil). Knowing the responses of soil suction (and corresponding moisture) in association with soil water evaporation is important because soil suction is recognized as an important stress-state variable governing the behavior of unsaturated soils. Soil suction should be viewed as an environmental variable (Gens, 2010). Soil water evaporation is controlled by both atmospheric and soil conditions, and the comparison of the measured soil suction changes versus predicted potential evaporation (*PET*) changes can be used for evaluating the suitability and accuracy of the *PET* formulation. Changes of soil evaporation defined by predicted *PET* methods are related directly to soil suction (s) measurements during the investigated dry period.

The *s* (kPa) - *PET* (mm/month) relationship from April to June 2011 for the predicted air temperature-based *PET* methods proposed by Blaney & Criddle (1950) and Kharrufa (1985) exhibited a more substantial increase evaporation with soil suction increase. And, during the most significant drying time period, between May and June 2011, the measured *s*

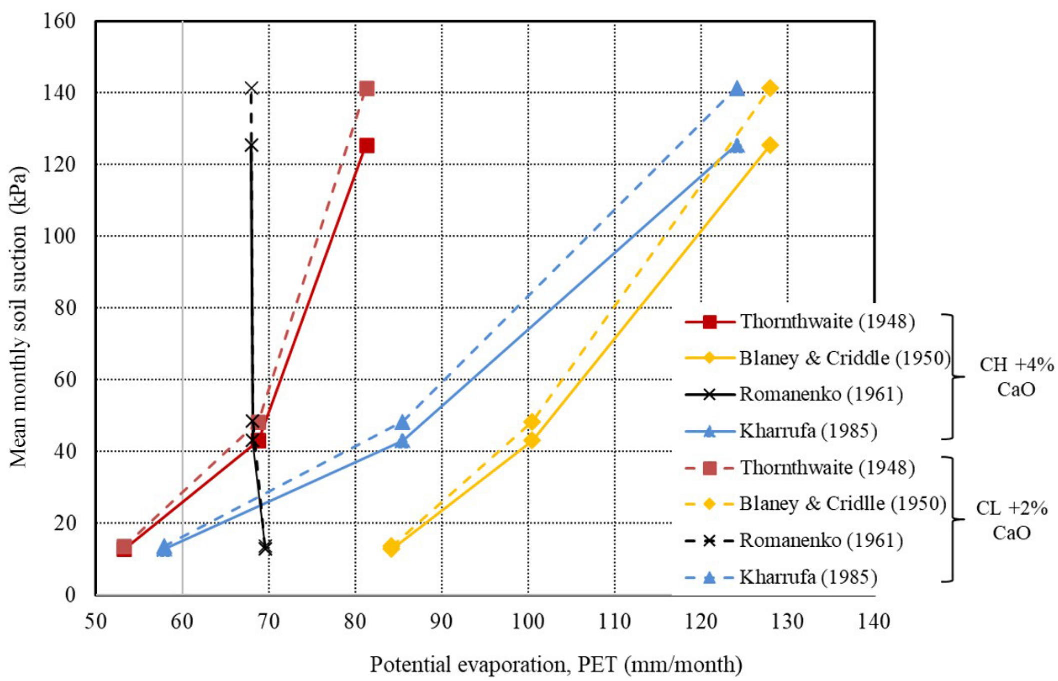

Figure 3. Comparison among mean monthly measured soil suctions at mid-slope in the two treated soil sections and different potential evaporation methods (Thornthwaite, 1948; Blaney & Criddle, 1950; Kharrufa, 1985; Romanenko, 1961) obtained solely by meteorological observations at the investigated site from April (A) to June (J) in 2011.

consistently increased and the corresponding *w* decreased suggesting a relatively significant water evaporation effect. The monthly predicted *PET* data varied from a maximum of over 120 mm/month (Blaney & Criddle, 1950) to less than 50 mm/month (Romanenko, 1961) depending on the used method during June 2011. The continuously monitored soil surface suctions were used for discussing the variations of evaporation according to the predicted *PET* method and time period at the site. The variations in the measured *s* and predicted *PET* by Blaney & Criddle (1950) and Kharrufa (1985) are more significant between May and June 2011. A similar trend is not observed with predicted *PET* proposed by Romanenko (1961) using mean monthly air temperature and air relative humidity, such that no significant difference in *PET* values were observed from April to June 2011. Moreover, the atmospheric water balances (*B*) calculated from measured precipitation (*P*) and predicted *PET* for the four methods from April to May indicate that May 2011 is a month of water deficit (*B* negative), and in June 2011, *B* values may be negative or positive depend on the adopted *PET* formulation and the position of the recorded input data. Calculated *B* values vary from approximately –40 mm/month (Blaney & Criddle, 1950; Kharrufa,1985) to approximately +20 mm/month (Romanenko, 1961). The difference observed in the formulations can be attributed to variations of the conceptual *PET* model and measured input data. Some previous studies have pointed out a decreasing trend in evaporation despite an increasing trend in air temperature, due to soil moisture limitation (Jung et al., 2010; Lemaitre-Basset et al., 2022). This result demonstrates the importance of previous critical analysis of *PET* formulations based upon the assumption that *PET* was dependent only upon meteorological conditions and empirical basis. Air relative humidity should not be used as input variable because atmosphere moisture is a function of soil moisture (Fetter, 1994). Moisture in the atmosphere is continually changing its physical state and the changes are all related to temperature. Air temperature is considered the most stable input parameter because it is a function of both solar radiation and water availability conditions (Wilson, 1990).

4. Conclusions

This paper examines changes of bare soil surface moistures (*w*) and corresponding suctions (*s*) at mid-slope of an embankment as result of soil water evaporation processes on a monthly time scale during drying period. The study also evaluates four commonly used air temperature-based formulations on predicting potential evaporation (*PET*) data at the site. Analysis of the monitoring data (both soil surface and atmosphere) of the two-lime treated fine-grained soils exposed to continuous soil drying period, in the embankment subjected to a continental climate, with oceanic influences, permit the following main conclusions:

- The measured suctions (*s*) using sensors Watermark and volumetric water contents (*w*) using quasi-TDR based TRIME PICO 64 in the two treated soil surfaces show overall consistency with local seasonal meteorological data variations. The mean month field measured *w* values gradually decreased and the corresponding *s* values increased as the water moved down into the soil or evaporated in the summer time at the investigated site. Mean month soil surface suctions are greater in the lime-treated silty soil at the same atmospheric conditions. This could be explained by the higher hydraulic conductivity of the silty soil;
- Soil water evaporation is controlled by both atmospheric and soil conditions. The continously measured *s* have consistently increased and the corresponding *w* decreased suggesting a relatively significant water evaporation effect during the most significant water deficit period at the site. The results of the predicted *PET* data determined on the basis of climatic conditions varied by about 80 mm/month in the most significant water deficit period depending on the used method. Some predicted *PET* data did not describe adequately the atmosphere water balance during the investigated drying period;
- The *s-PET* relationships for the adopted air temperature-based *PET* methods show a large variability according to the adopted *PET* method, and the differences given by the increased *PET* values during drying period were significant. The predicted monthly *PET* data varied from a maximum of over 120 mm/month to less than 50 mm/month depending on the used method during the hottest month. No significant difference in *PET* values calculated using mean monthly air temperature and air relative humidity, such that no significant difference in *PET* values were observed during the investigated period and site. This result indicates the importance of previous critical analysis of potential evaporation formulations based upon the assumption that *PET* was dependent only upon meteorological conditions and empirical basis;
- While the adopted air temperature-based *PET* methods assumptions are not correct, the methods are still useful for preliminary studies. To propose a calibrate suitable *PET* estimation method based on field measured of soil surface suctions/moistures and local meteorological data for wider applications, more studies within large and representative data for various atmospheric conditions are required. However, the approach of comparions between field measurements of soil surface suctions/moistures during evaporation and simple *PET* methods based on disponible local meteorological data may be used as an indicative of either a gross error in the used *PET* method (input data) or a violation of the assumption of a closed water balance.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Katia Vanessa Bicalho: conceptualization, supervision, review and approval. Thiago Luiz Poleto: discussion, writing, reviewing and editing. Yu-Jun Cui: conceptualization, discussion, reviewing and editing. Yasmina Boussafir: project administration, discussion.

Data availability

All data produced or examined in the course of the current study are included in this article.

List of symbols

a	Index that adjusts to each region (Thornthwaite, 1948)
i	Heat index monthly (Thornthwaite, 1948)
k	Crop coefficient (plantation). It is obtained from curves based on field measurements. In Blaney & Criddle (1962) an extensive table is presented with the values of k for several states of the western USA.
p	Monthly average percentage of light hours
w	Soil surface moisture
s	Soil surface suction
B	Atmosphere water balance
ET	Evaporation
ET_a	Actual evaporation
I	Annual heat index, given by the sum of the 12 monthly values of i
P	Precipitation
PET	Potential evaporation
R_h	Air relative humidity
T	Average air temperature

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