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Thermo-Hydro-Mechanical analysis of unsaturated soil considering climate change

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ABSTRACT

The accelerating pace of development throughout the world and the increasing decline of groundwater table underscore the importance of understanding the unsaturated soil behaviour. In particular, realistic estimation of evaporation is necessary in many geotechnical problems, which requires considering the soil stress-strain behaviour. This necessitates soil-atmosphere coupling and performing a thermo-hydro-mechanical (THM) analysis. The 2D finite element program EVAP1, which numerically estimates evaporation from unsaturated soil using THM analysis and atmospheric coupling was used to investigate the sensitivity of evaporation to the change of environmental parameters due to the climate change. The effect of the increase in temperature on evaporation was investigated in 2 regions with average temperatures of 20 and 38 degrees. Based on recent studies on the effects of climate change, a 1º increase in temperature and a ±10% change in wind speed were assumed and modelled. It was found that the increases in evaporation and settlement amounts due to temperature increase are slightly lower when the wind speed decreases compared to when wind speed increases. Meanwhile, the changes in temperature and radiation have greater influence on evaporation change than the wind speed. The amount of increase in evaporation depends on the average temperature in the region. The increase in evaporation due to the same amount of temperature increase is higher in colder areas. Finally, the change in evaporation was found to be strongly affected by the residual amount of the soil moisture.

Keywords: groundwater, unsaturated soil, THM, evaporation, soil cover, finite element

1 INTRODUCTION

Global warming and climate change have been extensively researched and discussed recently due to their significant impacts on many aspects of human life. They affect environmental parameters including air temperature, net radiation, air humidity, and wind speed, which in turn affect evaporation. According to NASA, the average air temperature in the world increased almost one degree due to climate change (https://earthobservatory.nasa.gov/world-of-change/global-temperatures). Meanwhile, the wind speed has been increased in some parts of the world and decreased in some other parts (Eichelberger et al., 2008; Robbins, 2022). Moreover, the global mean surface radiation increased more than 1-2 Wm−2 per decade due to the climate change (Wild and Liepert, 2010). The process of evaporation needs energy, which is obtained from the surface radiation balance and is known as surface net radiation and is composed of the absorbed solar and thermal radiative exchanges at the Earth's surface. The surface radiation is the principale driver of the global hydrological cycle and balances the ecosystem. Estimating evaporation is one of the important issues for many geotechnical and geo-environmental applications.

To achieve a realistic estimation of evaporation, it is necessary to properly evaluate the coupling effects of moisture, heat, and air as well as the deformation of soil surface. Thermo-hydro-mechanical (THM) analyses are usually performed to properly evaluate those coupling effects. Evaporation also depends on environmental parameters, which include air temperature, net radiation, wind speed, and relative humidity (i.e., actual amount of moisture in the air as a percentage of the maximum amount of moisture that the air can hold). Therefore, it is necessary to consider atmospheric coupling when predicting evaporation. Consequently, solving the coupled nonlinear governing partial differential equations of heat and mass transfer at the soil surface including atmospheric coupling is crucial. Meanwhile, the regions with predominantly unsaturated soil are expanding due to continuous decline of groundwater level because of over-withdrawal of groundwater resources accelerated researches on evaporation from unsaturated soil surface. Therefore, a sound understanding of the mechanical behaviour of unsaturated soil is required.

The 2D finite element program EVAP1 was verified against experimental results (Mousavi et al., 2022) and can be used to evaluate the evaporation from unsaturated soil using THM methodology and accounting for the atmospheric coupling. In this study a parametric study on the effects of climate change and, in turn, environmental parameters on evaporation from unsaturated soil and the resulting soil settlement is performed using program EVAP1. The program's input data include both the environmental parameters and soil thermo-hydro-mechanical characteristics.

2 EVAPORATION

Evaporation is a major component of the hydrologic cycle. From the environmental and geotechnical viewpoints, it is important to estimate evaporation rate from soil surface, waste deposit or soil cover. As an example, the long-term performance of soil covers depends on evaporation from their surfaces. The moisture flow between soil and atmosphere is a complex process governed by a number of factors that interact as a coupled system, not as independent variables. The first factor is the supply of water at soil surface and the demand for water at the soil surface imposed by atmospheric conditions. Another important factor is the soil ability to transmit water, and the associated water regime. The influence of vegetation on the evaporation process is also an important factor (Wilson, 1990; Rao and Rekapalli, 2020).

The evaporation process from soil surface occurs in two distinct stages: constant rate stage (or stage I); and falling rate stage. The falling rate stage itself consists of two parts: a significant part (stage II), and almost insignificant part (stage III). Figure 1 presents a representation of evaporation processes from porous media.

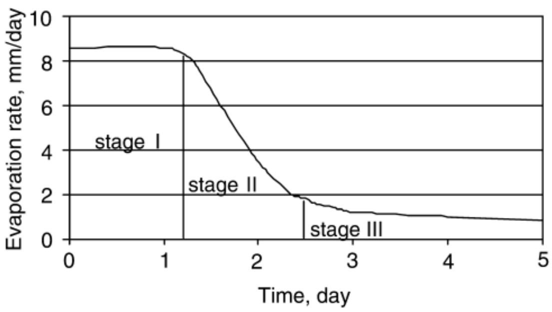

Figure 1. *Schematics of the three stages of evaporation from soil (Yanful & Mousavi, 2003)*

2.1 Evaporation from unsaturated soil surface and soil surface settlement

The accelerating pace of development all over the world combined with over-withdrawal of groundwater from the aquifers causes the drop of groundwater level, which increases the importance of unsaturated soil. The unsaturated soil zone affects the movement of water, nutrients, chemicals, pathogens, and contaminants to groundwater table. Unsaturated or vadose-zone affect movement of contaminants that have been released to the unsaturated zone, or contaminants that will be disposed in special geotechnical structures built in vadose zone such as landfills (Li et al., 2017; Dahan, 2020). A considerable number of engineering problems are associated with unsaturated soils. Therefore, a deep understanding of the mechanical behaviour of unsaturated soil is required to enable devising cost-effective and safe solutions to these problems (Likos et al., 2019; Lu, 2020).

Compaction of soil is an important aspect that affects the performance of compacted clay barriers, and its possible differential settlement, which can induce bending strains and damage in the clay barrier (Scalia et al., 2017; Aman et al., 2021). Localized failure in unsaturated soil was studied by Menon and Song (2020). Strain localization in partially saturated soil with inhomogeneous degree of saturation is another concern worthy of consideration (Song and Menon, 2018; Phan, 2021). Song et al. (2012) investigated this concern and demonstrated that a non-uniform degree of saturation could serve as an imperfection to trigger strain localization. They concluded that a fully coupled hydro-mechanical model is required to capture the relevant multiphase processes. THM is a more complete method of analysis that considers heat transfer too.

The study of soil covers for waste disposal sites involves the interaction of soils with the atmosphere (Lozano-Parra et al., 2018; Vardon P. J., 2019; Chen et al., 2021). In engineered soil covers used for environmental protection, evaporation and evapotranspiration rates can impose significant influence on suction, hydraulic conductivity of unsaturated soil, and the water flux (Yang and Yanful, 2002; Vriens et al., 2020; Alam et al., 2021). The assessment of evaporation from soil surface is thus very important for designing soil covers for hazardous waste sites (Gorakhki and Bareither, 2017; Li et al., 2020) and for predicting their long-term performances (Wilson, 1994; Yanful and Mousavi, 2003; Basche et al., 2016; Maurais et al., 2021).

Climate change and global warming influence the environmental parameters, which in turn vary the potential and actual evaporation magnitudes. A brief description of the effects of climate change on environmental parameters is provided in the next section, including the considerable heterogeneity of climate change in different parts of the world. In some parts the wet areas become wetter, and dry and arid areas become drier and more arid (Rahmat et al., 2019). This heterogeneity and its effect on environmental parameters including temperature, net radiation and wind speed are considered in the analyses performed within this study.

3 THE EFFECT OF CLIMATE CHANGE ON ENVIRONMENTAL PARAMETERS

3.1 Effect of climate change on temperature

According to an analysis led by NASA's Goddard Institute for Space Studies (GISS), the average global temperature in the world has increased by at least 1.1° Celsius (1.9° Fahrenheit) since 1880. The temperatures did not rise by same rate everywhere at every time. It might rise 5 degrees in one region and may drop 2 degrees in another region. For example, extremely cold winters in one part of the world may balance extremely warm winters in another part. In general, warming is more over land than over the seas and oceans because water is slower to absorb and release heat. Generally, an increase of 1 degree Celsius in average temperature in the Earth is accepted by the researchers and therefore is assumed in analyses performed in this study. Because the climate change occurs all over the world, two regions with average temperatures of 20, and 38º Celsius were assumed with 1 degree Celsius increase in temperature due to climate change (https://earthobservatory.nasa.gov/world-of-change/global-temperatures).

3.2 Effect of climate change on wind speed

Different researchers forecasted very different changes in wind speed due to climate change (Eichelberger et al., 2008). Research showed a worldwide stilling of winds from 1978 until 2010, with speeds dropping 2.3 percent per decade. However, other studies released in 2019 indicated that after 2010, global average wind speeds has increased from 7 to 7.4 miles per hour (Robbins, 2022). However, the UN's Intergovernmental Panel on Climate Change predicts slowing winds for the coming decades so that the average annual wind speeds may drop by up to 10 percent by 2100 (Robbins, 2022).

Eichelberger et al. (2008) state that recent global climate model forecasts show stronger magnitude of wind speed across northern and central Europe but weaker magnitude across the rest of the Europe. Considering the abovementioned conflicting predictions of change in wind speed due to climate change in different regions in the world, both an increase and a decrease of 10% in wind speed were assumed in the analyses conducted in this study.

3.3 Effect of climate change on net radiation

Variations in the intensity of the global hydrological cycle can have a considerable effect on living conditions in the globe. While the discussions on climate change often revolve around possible consequences of future changes in temperature, the adaptation to changes that may happen in the hydrological cycle might impose more important challenge to societies and ecosystems. Any change in surface evaporation implies an equivalent change in precipitation, and therefore in the intensity of the global hydrological cycle. Global warming and climate change affect net radiation as well. Wild and Liepert (2010) estimated an increase in global mean surface radiation as more than 1-2 Wm^{-2} per decade due to the climate change. Therefore, in this study a 4 percent increase in radiation was assumed in the studied regions.

3.4 Effect of climate change on humidity

The water vapor and humidity differ due to many factors including geographical, meteorological, social, economic and agricultural factors. Because of the global warming and 1.1º Celsius increase in average temperature in the globe (https://earthobservatory.nasa.gov/world-of-change/global-temperatures), there is about 7% increase in average relative humidity. The reason is that the air can generally hold about 7% more moisture for every 1º Celsius temperature rise. Therefore, the moisture content in the air also needs to increase by 7% (Willett, 2020) for relative humidity to stay the same under 1º Celsius of warming. However, the average relative humidity decreases in the world due to global warming because there are some other factors that cause regional changes in relative humidity.

4 ESTIMATING EVAPORATION FROM SOIL SURFACE

All climatological methods for estimating evaporation provide or rely on the potential rate of evaporation. In general terms it may be considered as an upper limit to evaporation. Calculation of the actual evaporation rate from an unsaturated soil is more difficult than the calculation of potential evaporation. Standardized measurement and estimation of evaporation is challenging. The lack of uniformity in input data collection and quality control is another factor that causes variation in estimates of evaporation (Tezza et al., 2019; Zhao et al., 2019). Estimating evaporation from standard meteorological data has been an active area of research and practical application.

The Penman (1948) approach provides an estimate of potential evaporation for a saturated surface under specific atmospheric and energy supply conditions. Wilson (1990) proposed a relationship to provide more physical relationships to make evaporation calculation determinant. He proposed a modified Penman (1948) approach by combining vapor transfer equation with heat transfer equation to determine actual evaporation from unsaturated soil surface. His method, which is used in program EVAP1 to estimate actual evaporation, requires routine weather parameters, i.e., air temperature, net radiation, relative humidity and wind speed.

Thermo-hydro-mechanical (THM) coupled processes in porous media are important in many geotechnical engineering problems such as nuclear waste disposal, oil extraction, geothermal energy, and soil covers (Kumar and Reddy, 2021). Program EVAP1 estimates evaporation from unsaturated soil using THM analysis. The model enables consideration of the effect of the soil settlement on evaporation from unsaturated soil and vice versa (Mousavi et al., 2022).

Due to the soil settlement, void ratio and porosity of the soil decrease. Hydraulic conductivity and gas permeability of soil depends on void ratio (Lloret and Alonso 1980; Thomas and He 1995; Gatmiri 1997; Gatmiri and Delage 1997). The soil settlement decreases both void ratio and soil conductivity and, in turn, decreases evaporation. Therefore, neglecting THM behavior leads to neglecting soil settlement, and consequently neglecting the decrease in void ratio, which for the above-mentioned reason overestimates evaporation from the soil surface (Mousavi et al., 2022).

5 NUMERICAL MODELING THEORY

5.1 Model

There is a full interaction in the system of the soil and the atmosphere. Analysis of this complex system needs a coupled numerical modelling. The calculated values of heat and water transfer depend on the boundary conditions for this numerical model. Because of the coupled nature of the phenomena, these boundary conditions are determined by the soil state and the environmental data. Therefore, the numerical modelling of the problem is performed using the 2D finite element program EVAP1 adopting an incremental scheme in which the boundary conditions of each increment are determined as a function of the actual environmental parameters and the soil state at the end of the previous increment.

In the theoretical framework used in EVAP1 program, two basic theories were modified and combined in order to describe a fully coupled behaviour of unsaturated porous medium. On one hand, the nonlinear theory of isothermal behaviour of unsaturated soil under the coupled effects of net stress and suction was extended to non-isothermal conditions. On the other hand, Philip and de Vries' (1957) theory of heat and moisture transfer was modified in order to take the deformation of the skeleton into account. This fully coupled formulation was presented in a suction-based formulation, which is more suitable for a combination with the deformation theory of unsaturated soils. A description of the theoretical framework is given in Mousavi et al. (2021). The soil-atmosphere interaction model used in EVAP1 is presented in Figure 2 as below:

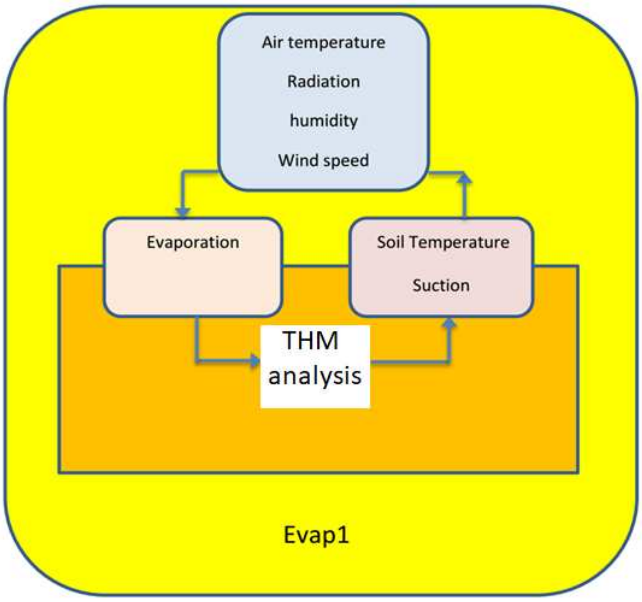

Figure 2. *Schematic soil-atmosphere model used in EVAP1 (Mousavi et al.,2022)*

The soil-atmosphere interaction model was employed in the program to calculate the hydraulic and thermal boundary conditions. The hydraulic boundary condition was defined by the liquid water mass flux. The heat boundary condition was defined by the soil heat flux. The model input data were the meteorological data: air temperature, net radiation, wind speed and relative humidity, accompanied with the soil thermo-hydro-mechanical characteristics. The hydraulic and the thermal boundary conditions are water mass flux, soil heat flux and air flux, which are presented as q_w, q_h, and q_g, respectively. These

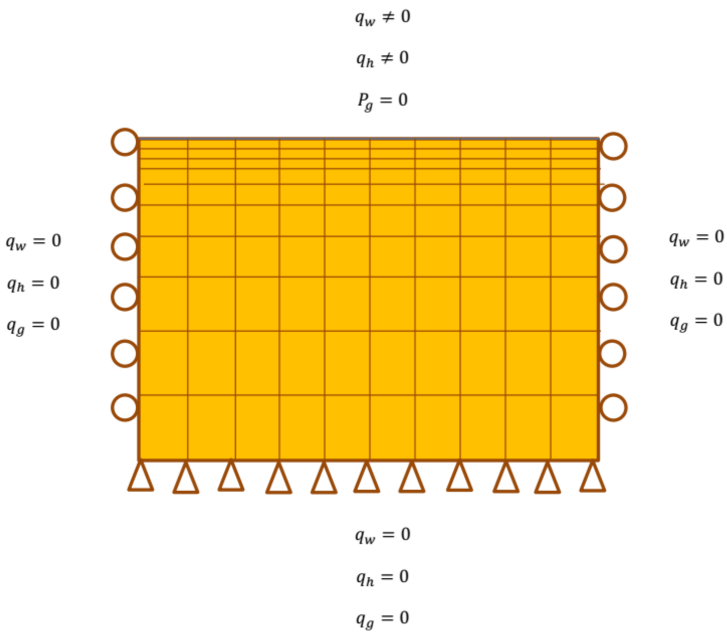

Figure 3. *Boundary conditions of soil-atmosphere model used in EVAP1, q_w=water flux, q_h=heat flux, q_g=gas flux, and P_g=gas pressure (Mousavi et al., 2022)*

boundary conditions are calculated from meteorological data of the actual time step and the soil thermo-hydro-mechanical state corresponding to the previous time step. A schematic of the model and its boundary conditions were presented in Mousavi et al. (2022) and is presented in Figure 3. To verify program EVAP1, the soil column drying test of Wilson (1990), and soil column test of Yang and Yanful (2002) were used (Mousavi et al., 2022).

Wilson (1990) proposed a modified Penman (1948) approach for atmospheric coupling and estimating actual evaporation. He combined vapor transfer equation with heat transfer equation to determine actual evaporation from soil surface. This method needs atmospheric data like air temperature and humidity, net radiation, and wind speed. He presented the “modified Penman equation” as below.

$$E = \frac{\Gamma Q + \nu E_a}{\Gamma + A\nu} \quad \text{Eq. 1}$$

Where,

E: vertical evaporative flux (mm/day)
$E_a = f(u)P_a(B-A)$
P_a: vapor pressure in the air above the evaporating surface
B: inverse of the relative humidity of the air
A: inverse of the relative humidity at the soil surface = 1/h
Wilson (1990) approach was used in this study for estimating actual evaporation.

5.2 Set of data used in the analyses

The data set used for unsaturated soils including the mechanical and model parameters for unsaturated soils, thermal parameters and hydraulic parameters for unsaturated clay and sand, are presented in Mousavi et al. (2022). EVAP1 program’s input data are both environmental parameters and the soil thermo-hydro-mechanical characteristics.

6 EFFECT OF CLIMATE CHANGE ON EVAPORATION FROM UNSATURATED SOIL AND SOIL SETTLEMENT

Almost a 1ºC increase in average temperature has occurred in the globe due to climate change as was mentioned before. In this study the effect of the increase in temperature on evaporation was investigated in 2 regions with average temperatures of 20 and 38 degrees. Regarding the effect of climate change on radiation, a 4% increase in net radiation assumed as well (Wild and Liepert, 2010; Willett, 2020). Because of ± 10% change in wind speed in different parts of the world due to climate change (Robbins, 2022), a ±10% change in wind speed was assumed and modelled. Figure 4 presents the change in actual and potential evaporations in a region with average temperature of 20 degree Celsius.

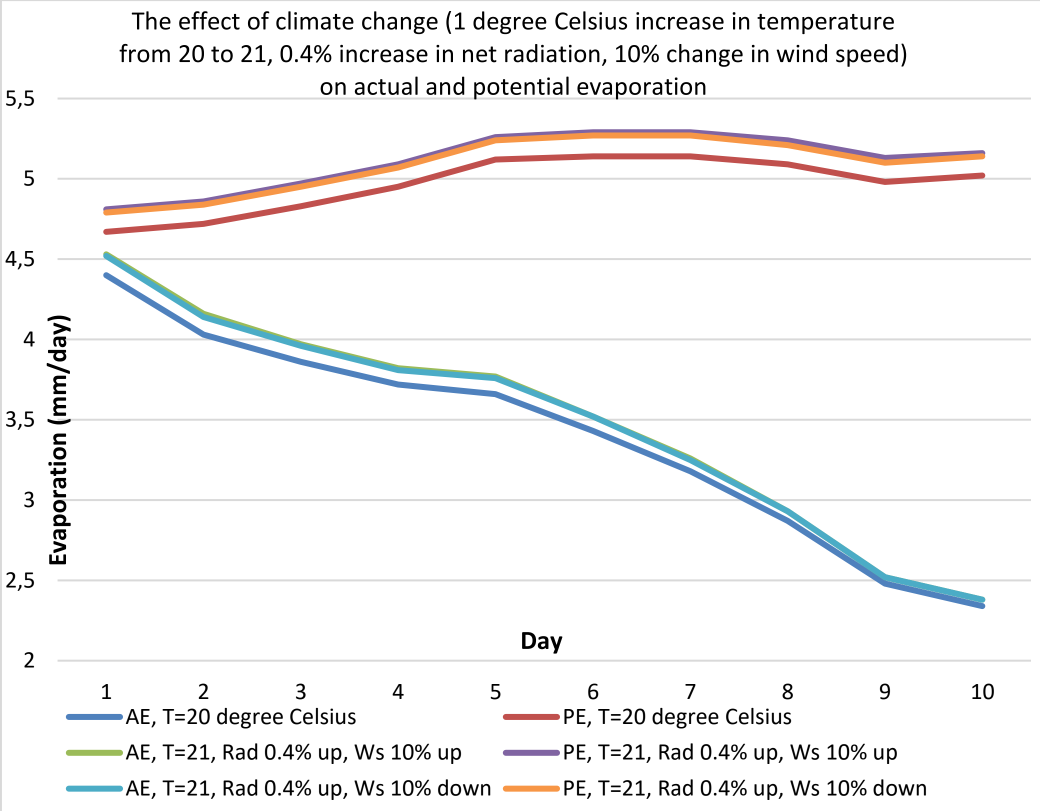

Figure 4. *The effect of climate change on actual and potential evaporation in a region with average temperature of 20 degree Celsius*

Regarding the general mechanism of the evaporation, as Figure 4 shows the potential evaporations does not decrease significantly with time because they depend only on environmental parameters. However, the actual evaporations decrease with time because they depend on specifications and behavior of soil too and follow the three stages, which was mentioned in section 2. In fact, the actual evaporations, which are almost the same amounts of potential evaporations at the beginning, decrease slowly with a mild slope during the first stage followed by a sharp decrease with a higher slope during the second stage. Finally the evaporation is minimized according to the residual amount of the moisture in the soil.

Regarding the effect of the climate change both potential and actual evaporations increase due to the 1 degree increase in temperature and 4 percent increase in net radiation as the figure shows. With 10 percent increase in wind speed the evaporation amount will be more than that with 10 percent decrease in wind speed. However, the increase in temperature and net radiation is much more effective than the increase/decrease in wind speed so that even with a decrease in wind speed the evaporation amount still increases. Same analysis was performed in a region with average temperature as 38 degree Celsius. Figure 5 presents the results.

As Figure 5 shows the amounts of both potential and actual evaporations were increased again due to an increase in temperature and radiation and an increase/decrease in wind speed due to climate change. Obviously, the evaporation increase is slightly lower with the decreasing wind speed than with the increasing wind speed. However, as the figure shows and as it was mentioned before, the governing factor is the change in temperature and radiation. A comparison of figures 4 and 5 show that the amount of the increase in evaporation depends on the average temperature in the region. There is slightly more evaporation increase due to the same amount of temperature increase in colder areas.

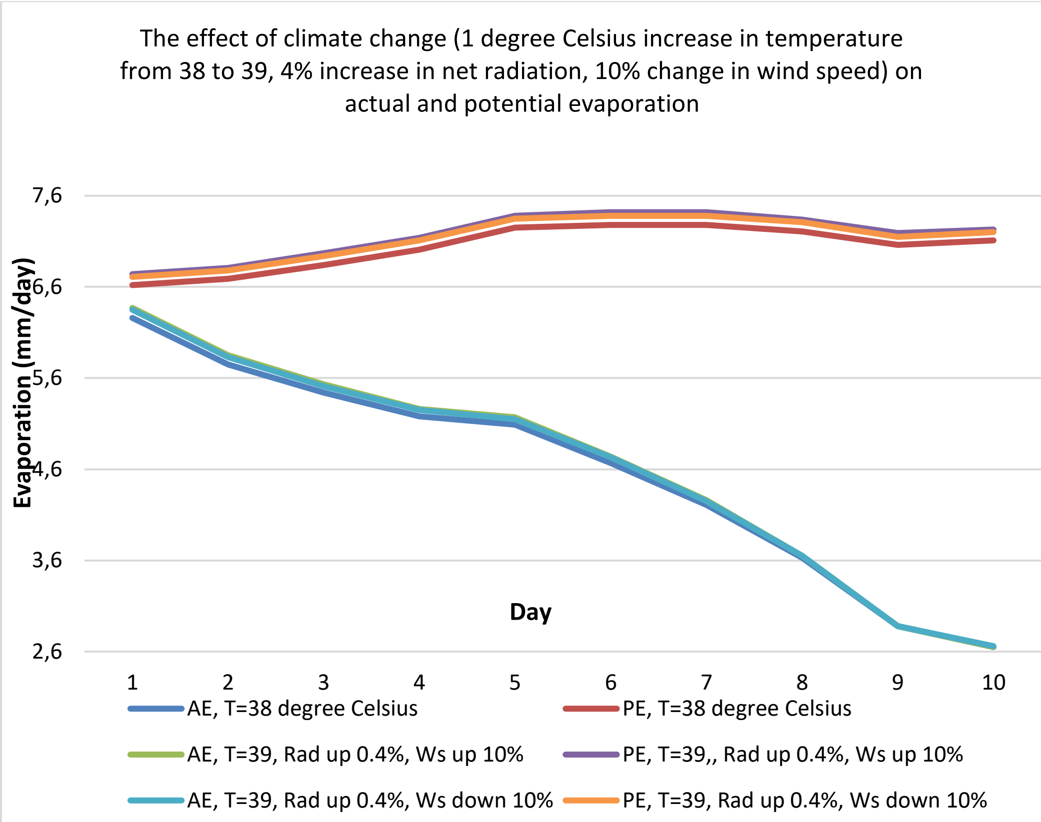

Figure 5. *The effect of climate change on actual and potential evaporation in a region with average temperature of 38 degree Celsius*

Figure 6 presents the change in soil settlement because of one degree increase in temperature, 4% increase in net radiation, and 10% increase/decrease in wind speed due to climate change in the studied areas during the studied time period. The air temperature in the studied region is assumed as 20 degree Celsius. Figure 6 shows the settlement increases with time because of the evaporation. However, there

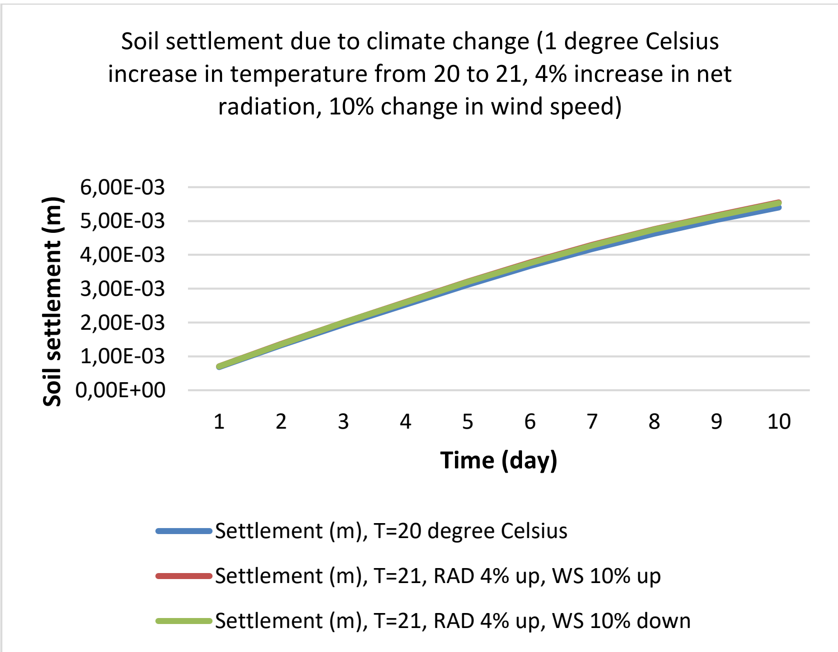

Figure 6*. Soil settlement due to climate change in a region with average temper. of 20 degree Celsius.*

are minor increases in both evaporation and settlement amounts because the increases in temperature and radiation are only one degree and 4 percent, respectively. Meanwhile, settlement increases again in both cases of the increase and decrease in wind speed for the same reason that was mentioned before. However, the settlement is slightly more with the increase in wind speed than with the decrease in that as it was the case with the evaporation amount too.

Figure 7 Presents the results of a similar simulation in a region with an average temperature of 38 degree Celsius.

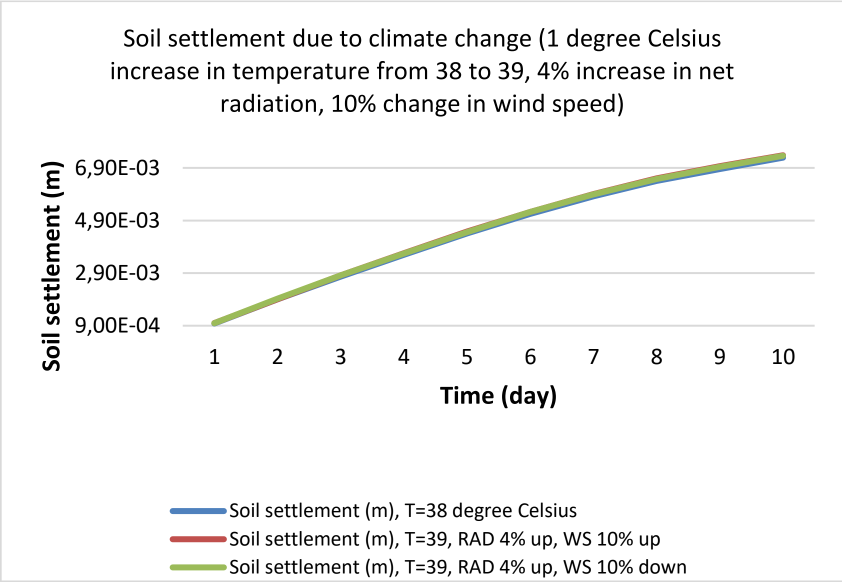

Figure 7. *Soil settlement due to climate change in a region with average temperature of 38 degree Celsius*

8 CONCLUSIONS

THM analysis enables considering the settlement of soil surface as well as temperature and suction in unsaturated soil. Program EVAP1 is used to conduct numerical studies of the coupled thermo-hydro-mechanical (THM) behavior of unsaturated porous media, with particular emphasis on estimating evaporation employing a soil-atmosphere model and using environmental parameters. In this study EVAP1 was used to investigate the effects of climate change on environmental parameters and to study the effects of changes in environmental parameters on evaporation from unsaturated soil and soil settlement. The results showed that potential and actual evaporations increase with the increase in air temperature, net radiation, and wind speed. Moreover, the effect of the increase in temperature and net radiation on the increase in evaporation is more than the effect of the increase in wind speed.

Based on literature survey, the climate change has caused about 1º increase in average temperature in the globe. The wind speed has been increased in some parts of the world and decreased in some other parts. Those changes were modelled in this study and the comparative results were presented. The change in temperature and radiation is more important than the change in wind speed regarding the evaporation change. A temperature increase of 1º slightly increased potential and actual evaporation amounts even in areas that wind speed decreased. The amount of the increase in evaporation depends on the average temperature in the region. There is slightly more evaporation increase due to the same amount of temperature increase in colder areas.

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