Empirical model of a vertisol evaporation as tool for management of soil practicability using portable lysimetric station under arid land context

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Abstract: Soil compaction caused by traffic is commonly considered as one of the major's problems in agriculture. Moisture content has a significant effect on amplifying soil compaction. This study aims to approach evaporation trend of a vertisol (40.47% clay, 39.30% loam and 20.23% sand) having an organic matter content of 1.5% in order to manage timing of its plasticity as a determinant factor inducing compaction created by the traffic of machines. A portable lysimetric measurement system was developed to evaluate soil evaporation trend. An empirical soil evaporation equation was developed using three measurement campaigns according to different temperature and irradiance behaviors. Soil moisture content was evaluated with two sensors using conductivity and matric potential methods. Data were acquired using an Arduino UNO platform. Climatic data obtained from a meteorological station was used for computing evapotranspiration using Penman-Monteith model as reference for evaluation of the evaporation equation output. According to different climatic behaviors, the rate of vertisol evaporation showed a decrease in moisture content in three campaigns that have two repetitions (2 repetitions /3 campaigns). In the first one (C1), the soil moisture content arranged from 46% to 8% and from 43% to 8%. In the C2 the soil moisture varied from 47% to 7% and from 49% to 6%. Similarly, it changed from 47% to 6% and from 46% to 9% in the third campaign (C3). The occurrence of plasticity interval was between the 4th and the 11th day in the first campaign, the 6th and the 15th day in the second campaign and between the 10th and the 22th in the third campaign. Finally, compared with simulated results developed by an equation in Matlab Simulink, an important correlation has been shown. As a conclusion, we can predict plasticity limits by using soil water content measurements and climatic data (Temperature and Irradiance).

Keywords: compaction, lysimeter, plasticity state, moisture content, sensor and modelisation.

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1 Introduction

Soil water evaporation (SWE) is a dynamic process that can be divided into three phases: the constant-rate phase, the falling-rate phase, and the low-rate phase (Amano and Salvucci, 1999), which have been experimentally observed. The first phase presents the potential of evaporation rate which is dependent on atmospheric condition near the soil surface and on moisture state of the soil profile under assumption of no restriction for upward water flow. This phase ends when the water flows toward the soil surface and the potential of evaporation rate decreases with time.

The falling-rate phase (second phase), soil condition

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can limit the passage of water in the profile. Consequently, the evaporation rate decreases (Suleiman and Ritchie, 2003). Lemon (1956) revealed that soil evaporation rate decreases proportionally with decrease of its moisture content. In this phase, atmospheric conditions have no importance on variation of evaporation to decreases soil moisture content to become low and loss of linearity show beginning of the third phase. The low-rate phase is characterized by a slow upward movement of water to the surface due to low hydraulic conductivity. However, the evaporation rate in this stage is less than 10% of that in the constant-rate stage, and the water loss is less than 5% of the total evaporated water (Hillel, 1980; Wallace et al., 1999). The evaporative water can usually occur in the constant-rate and falling-rate stages (Hillel, 1980; Wallace et al., 1999; Aydin et al., 2005). Otherwise, other authors (Bond and Willis, 1970) described that soil evaporation process can happen only in two phases

Measurement of SWE is based on energy balance (micrometeorology) or water balance methods (Hanks and Ashcroft, 1980; Hillel, 1980). SE can be measured using standard lysimeters or micro-lysimeters (MLs) (Walker, 1983; Boast and Robertson, 1982; Allen, 1990; Villalobos and Fereres, 1990; Howell et al., 1991; Daamen et al., 1993; Evett et al., 1995; Todd et al., 2000; Dalmago et al., 2010; Burt et al., 2005). MLs have similar principle of standard lysimeters and can be mounted on plastic or steel cylinders having a diameter of 5 to 10 cm and a height of 10 to 20 cm (Todd et al., 2000). Several authors compared reliability of MLs to standard lysimeters (Evett et al., 1995; Abdullahi et al., 2013; Rowshon et al., 2013). Others technics based on automatic weighing lysimeter (Marek et al., 1988; Tyagi et al., 2000) or portable evaporation chambers (Stannard and Weltz, 2006) or soil water depletion (Böhm et al., 1977; Fan et al., 2015) were used for measuring SWE but none of these three methods can precisely evaluate evaporation rate as a function of time and soil depth, especially at depth near to the profile surface (Xiao et al., 2011).

Otherwise, some authors estimated SWE using modeling (Ritchie, 1972; Allen et al., 1998). The Ritchie model was used for quantifying SWE and transpiration separately on cropped surfaces based on evaluating evaporative process of two distinct phases using mathematical approach. After that, Allen et al. (1998) developed another functional modeling approach by referring to the Ritchie model.

SWE Modeling can be used in modern agriculture to manage traffic of heavy agricultural machinery and avoid soil compaction. In fact, vertisol is not be practicable during its plasticity state period due to its high vulnerability to compactness. For avoiding soil compactness, management of soil water statute is important to show its inaptitude for traffic during occurrence of plasticity period and use of lysimetric method can be for monitoring SWE and as a decisional tool for showing its practicability.

SWE of bare soil have been mainly evaluated by direct methods using lysimeters or water content sensors (Gillespie and Kidd, 1978; Chiaradia et al., 2015). However, few works were focused on SWE modeling of a bare soil. The FAO Penman-Monteith (PM) has been considered as a universal model for estimating crops evapotranspiration (Monteith, 1981; ASCE-EWRI, 2005; Jacobs et al., 2002; Moro et al., 2007) and for evaluating evapotranspiration with reference dual effect of covered (crop transpiration) and uncovered (soil evaporation) soil surface. Allen et al. (1998) stated that PM model as a sole method used for determination of evapotranspiration could show errors up to 30% for specific conditions. Otherwise, there is not any research state on feasibility of using PM model for estimating SWE in specific conditions relative to absence of crops covering the soil.

This study aims to implement a sensor-based method for monitoring trends of soil water evaporation (SWE), developing an empirical equation of SWE and comparing its output with the climatic PM model output. In fact, the determination of the SWE trends of a bare vertisol during different measurement periods of varying temperature and irradiance can serve for monitoring occurrence of the soil plasticity limits as a decisional tool for management of the soil vulnerability to compaction by machine traffic.

2 Materials and methods

2.1 Context

The evaporation measurement of vertisol (40.47% clay, 39.30% loam and 20.23% sand) having an organic matter content of 1.5% was undertaken in a field of Regional Center of Agricultural Research at Settat of Morocco (X: -7.6222, Y: 32.9556) (Figure 1).

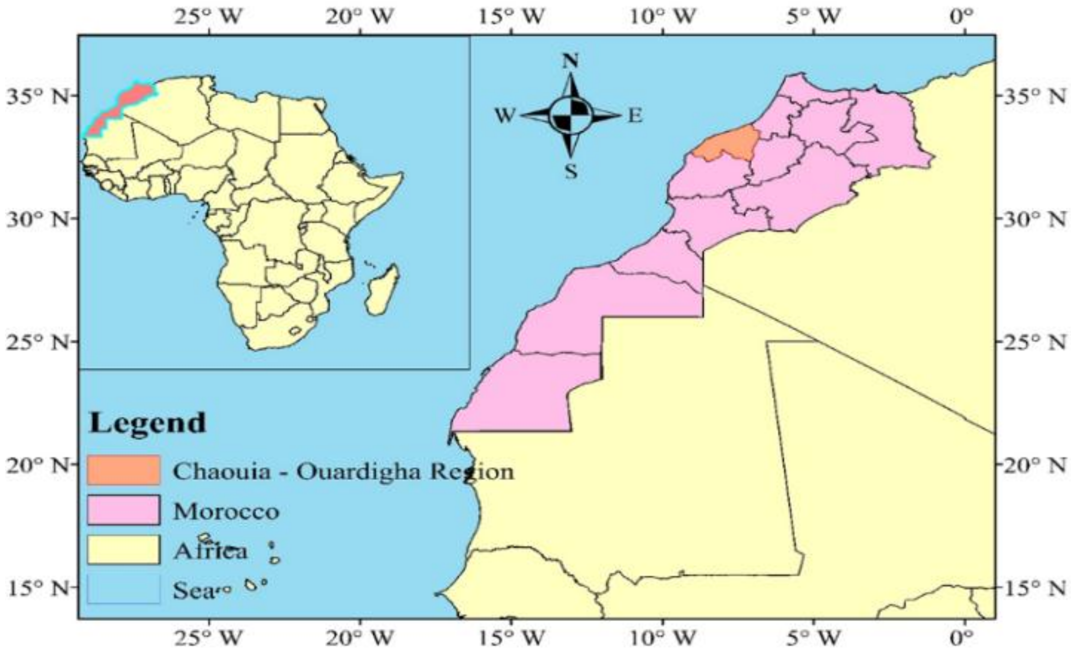

Figure 1 Geographic location of Casablanca-Settat region of Morocco

2.2 Design of lysimeters

Two lysimeters were built in plastic bucket of 21 504.20 cm^3 [internal diameter of 37 cm and height of 20 cm] and filled with bare vertisol. After weighting, the soil was humidified by a tap water volume of 15 L. The lysimetric evaporation (E_L) was obtained from balance weighing [precision of ±15 g] for every 30 minutes.

In parallel to weighting measurements done by lysimeters, the soil matrix was determined with two sensors of Resistif-Arduino™ and Irrometer™ based on resistive and potentiometric methods, respectively.

Data from both sensors were acquired using an Arduino UNO card. The card was equipped with Bluetooth sensors [HC 06 and DS3231] and a micro SD card for local saving of measurement data (Figure 2). Powers for data acquisition system were supplied by a photovoltaic panel.

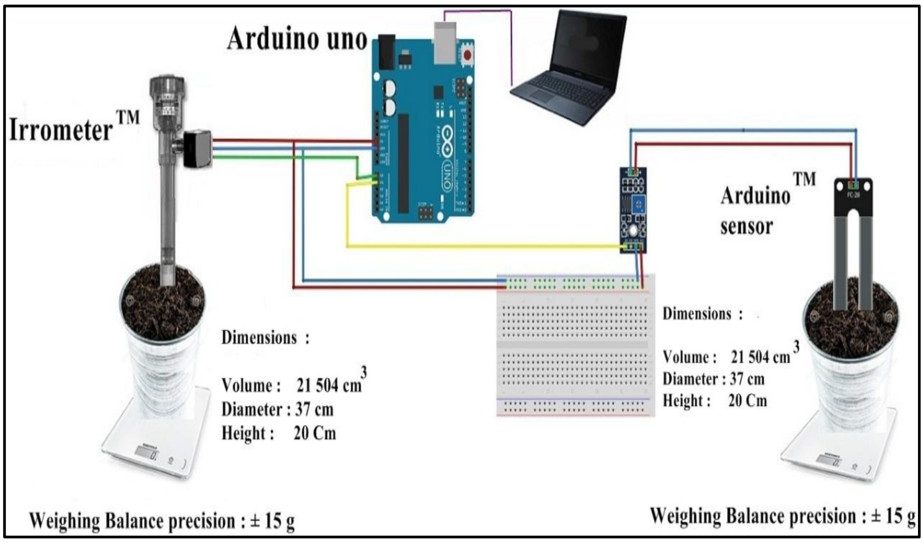

Figure 2 Scheme of the test bench

The sensor calibration was done using a simple setup equipped with a vacuum pump, an Irrometer™ supplied with a manometer, and a H105867 sensor. The vacuum pump leads to an air absorption, which in turn exerts a pressure on the Irrometer™ that can be measured by its manometer. Simultaneously, the sensor gives the pressure in (mV), which allows it to draw a calibration curve (pressure (kPa) vs Voltage (mV)). Figure 3 shows the calibration curve of the potentiometric sensor (H105867).

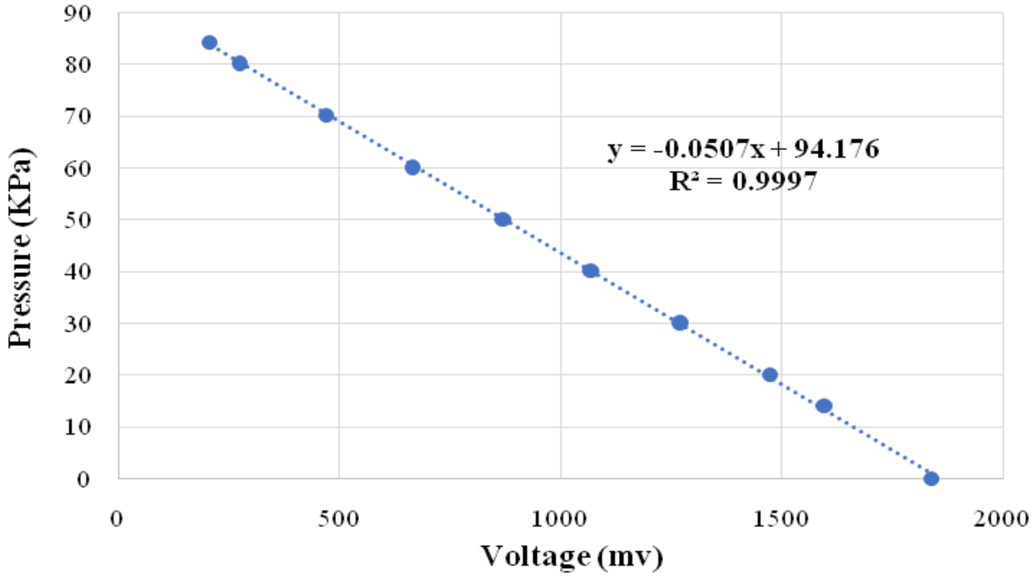

Figure3 Calibration curve of IrrometerTM sensor (Pressure (kPa) vs Voltage (mV))

2.3 Measurements of bare soil evaporation

The monitoring of SWE was done according to three different periods. The first period lasted from 06/26/2018 to 07/18/2018 (17 days), the second period from 17/09/2018 to 15/10/2018 (21 days), and the third (the longest period) from 28/03/2019 to 02/05/2019 (28 days).

In addition, climatic data (temperature/irradiance) were taken from local meteorological station (X: -7.624233, Y: 32.953487), and used for computing evapotranspiration using Penman-Monteith model Equation, 5) as reference for evaluation of the governing equation.

2.4 Empirical equation for governing bare soil evaporation

Development of the empirical equation was carried out for determination of SWE to deduce the vertisol moisture content. This development was based on the elaboration of some mathematical equations.

Variation of the climatic condition (Temperature) according to number of days in each period

$$d = (1119.1)\ exp^{(-0.219*T)} \quad (1)$$

$$D = round\ (d) \quad (2)$$

Where, d = number of days day, and T = Daily mean air temperature (℃).

Evaporated water quantity (EWQ) as a function of temperature and number of days

$$EWQ = (0.0019)\ (D^{2}) - (100.38327\ \ exp^{(-0.219*T)}) + 1.0336 \quad (3)$$

We know that: EWQ = IW – FW (4)

From Equation 3 and 4:

$$FW = IW - EWQ = (0.0019)\ (D^{2}) - (100.38327\ exp^{(-0.219*T)}) + 1.0336 \quad (5)$$

Moisture content (%) according to number of days

$$MC\ (\%) = \frac{WQA \times [1 - \frac{(IW - FW)}{WQA}]}{Lysimeter\ volum} \times 100 \quad (6)$$

Where, d = Number of days, T = Daily mean air temperature (℃), EWQ = Evaporated water quantity (mm day^{-1}), IW: Initial weight (kg), FW: Final weight (kg), MC = Moisture content (%) and WQA: Water quantity added.

2.5 Evaluation of plasticity period occurrence

Based on the daily monitoring of moisture content in the lysimeters, we have found that it is possible to determine the plasticity of vertisol. It can be done through pressing a very small amount of the moist soil in the hands to see if the soil sticks between the fingers. Such a test can help us see whether the soil is nonsticky, slightly sticky, or sticky. This monitoring was done for the seek of evaluating plasticity interval occurrence in order to predict the vertisol agricultural practicability and avoid its compactness.

2.6 Use of Penman Monteith model and soil evaporation

FAO Penman-Monteith equation represents the physical and physiological factors controlling the evapotranspiration process, which is recommended as the one and only method to determine evapotranspiration. This equation provides the best results with minimum errors. Also, many experts have recommended the adoption of the Penman-Monteith combination method as a new standard for reference evapotranspiration.

Besides the SWE, we determined the reference evapotranspiration (ETo) by Penman-Monteith method through using Equation 5, fed with daily data of the local weather station. The daily values of ETo were accumulated for the same periods of analysis of the lysimeters, in order to evaluate the performance of the lysimeters and the adaptation degree of the governing equation output.

$$ET_0 = \frac{0.408\Delta(Rn-G)+\gamma\frac{900}{(T+273)}U2(es-ea)}{\Delta+\gamma(1+0.34U2)} \quad (7)$$

Where ETo = reference evapotranspiration rate (mm d^{-1}), T = mean air temperature (℃), and u2 = wind speed (m s^{-1}) at 2 m above the ground. These values were collected on a daily basis.

2.7 Comparison between experimental and Penman Monteith model outputs

Referring to the evapotranspiration concepts, we can calculate the evapotranspiration under standard conditions using the equation: ET_c = ET0 (reference crop evapotranspiration) × K_c (crop coefficient). Therefore, in our case study, since the cover crop does not surpass 10%, we have found that it is possible to compare the results of the empirical equation with those of Penman equation.

Fitting of the governing equation was tested using the root mean square error (RMSE).

$$RMSE = [\frac{\sum_{i=1}^{N}(Ci-Mi)^2}{\sum_{i=1}^{N}(Mi)}]^{0.5} \times 100 \quad (8)$$

Where Mi and Ci are ETo measured and calculated values, respectively and N is the number of measurements.

Correlation coefficient (R^2) was used also to show fitting rate of the linear relationship.

3 Results and discussions

3.1 Measurement of bare soil evaporation

Figures 4, 5 and 6 show trends of SWE (mm day^{-1}) in three distinct measurement periods. Results showed a decreasing evaporation behaviors from 1.91 to 0.01 mm day^{-1} in accordance with a moisture content change within 46% – 8% during the first period, from 1.45 to 0.05 mm day^{-1} in accordance with a moisture content change within 49% – 6% during the second period and from 1.73 mm to 0.01 mm day^{-1} in accordance with a moisture content change within 47% – 6% during the third campaign.

Occurrence of the plasticity intervals were between the 4th to 11th, 6th to 15th and between 10th to 22th for the first, second and third measurement periods, respectively which was determined with daily observations in lysimeters.

In other hand, the results were used for development of an empirical equation in Matlab Simulink. The equation is based also on climatic data obtained from the weather station in order to predict the plasticity state of vertisol from the lysimeters measurements and climatic data.

The equation output was compared to measured values to show the degree of equation fitting. In fact, a significant correlation (Figure 7) was found between the measured and predicted values of daily evaporation trends (mm day^{-1})

[Predicted evaporation= 1.0168 * Measured evaporation + 0.0214; R^2 = 0.9715] (9)

The measured values (mm day^{-1}) are obtained by the lysimeter data, and the predicted values (mm day^{-1}) are obtained by the empirical equation output based on climatic conditions.

This correlation can be of importance to predict soil plasticity state to be used for management of vertisol practicability. In fact, vertisol water content dynamic has an influence on its sensitivity to compaction and the prediction tool can be important to timely manage introduction of agricultural machines and avoid vertisol compaction.

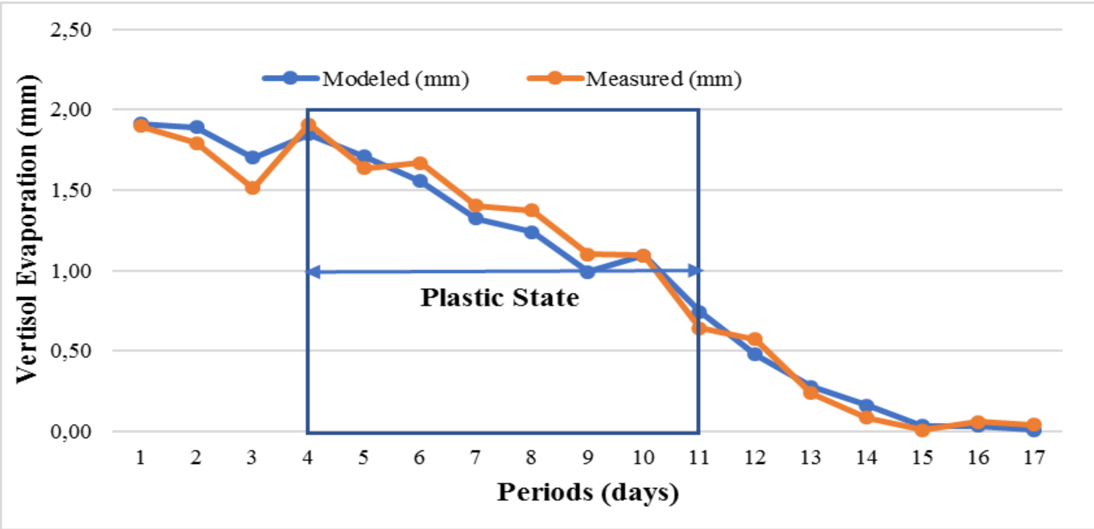

Figure 4 Measured and predicted vertisol evaporation (mm day^{-1}) [1st measurement period]

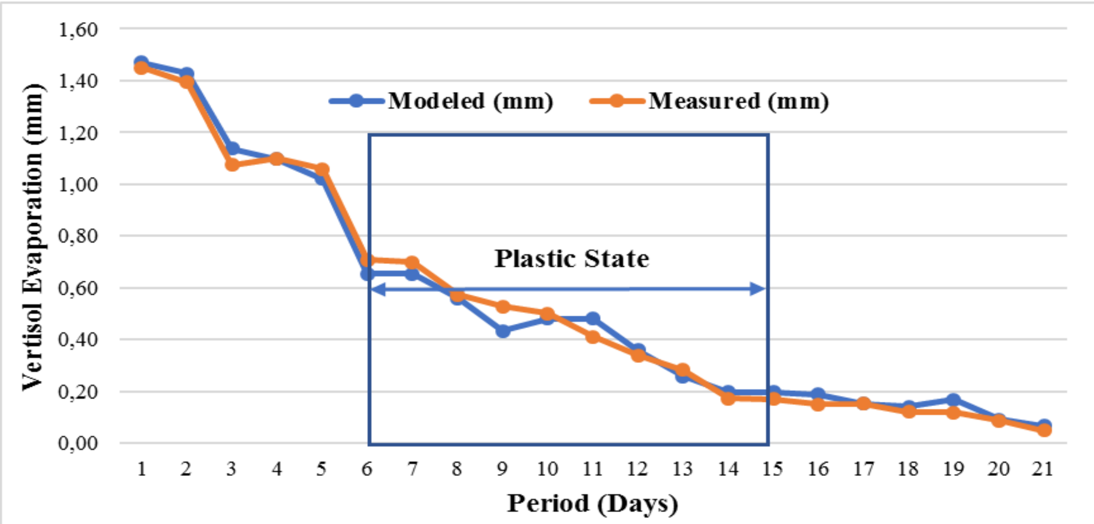

Figure5 Measured and predicted vertisol evaporation (mm day^{-1}) [2nd measurement period]

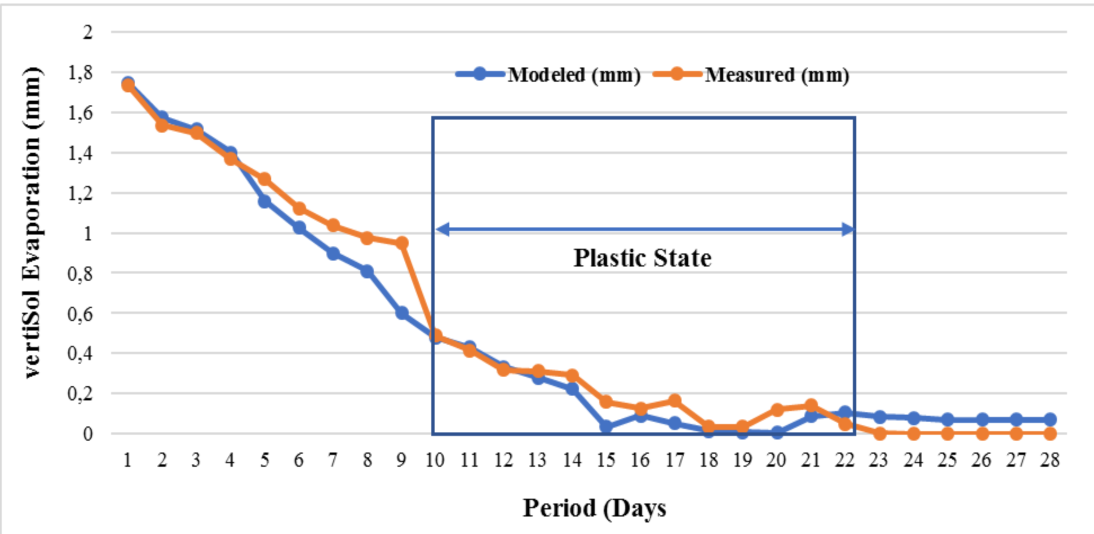

Figure 6 Measured and predicted vertisol evaporation (mm day^{-1}) [3rd measurement period]

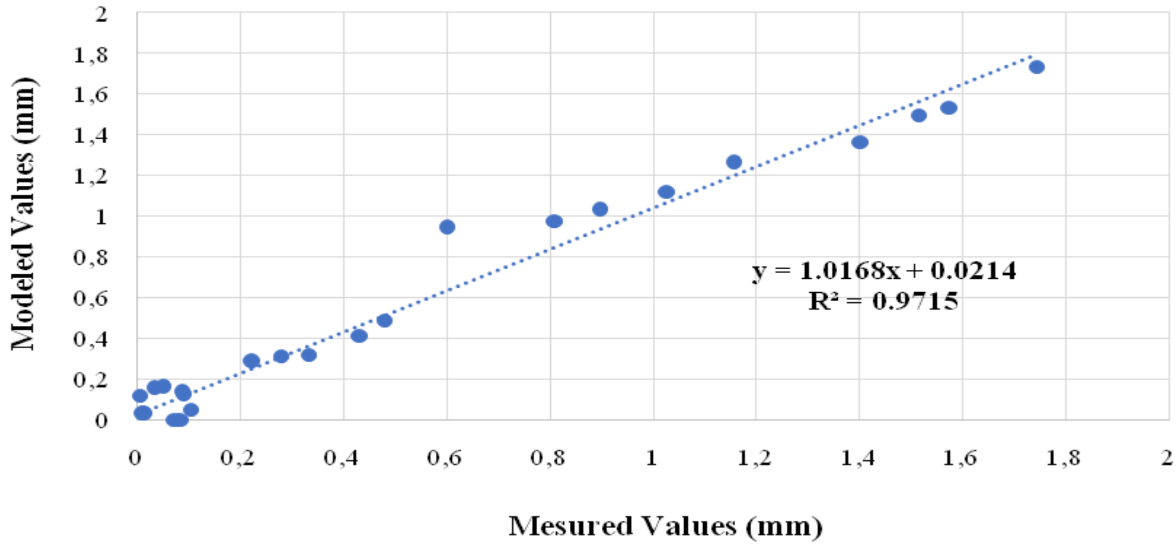

Figure 7 Correlation between the measured and predicted values (mm day^{-1})

3.2 Comparison between experimental and Penman-Monteith model outputs

The equation output was compared also to calculated values using the Penman-Monteith model. In fact, a significant correlation (R^2 = 0.9633) (Figure 8) was found between the equation output and Penman model values of daily evaporation trends (mm day^{-1})

[Equation developed = 5.538 * Penman-Monteith model – 8.337]; R^2 = 0.975 (10)

This correlation can be used to analyze the precision and adaptation degree of the model output in order to manage the vertisol evaporation and practicability to avoid its compaction.

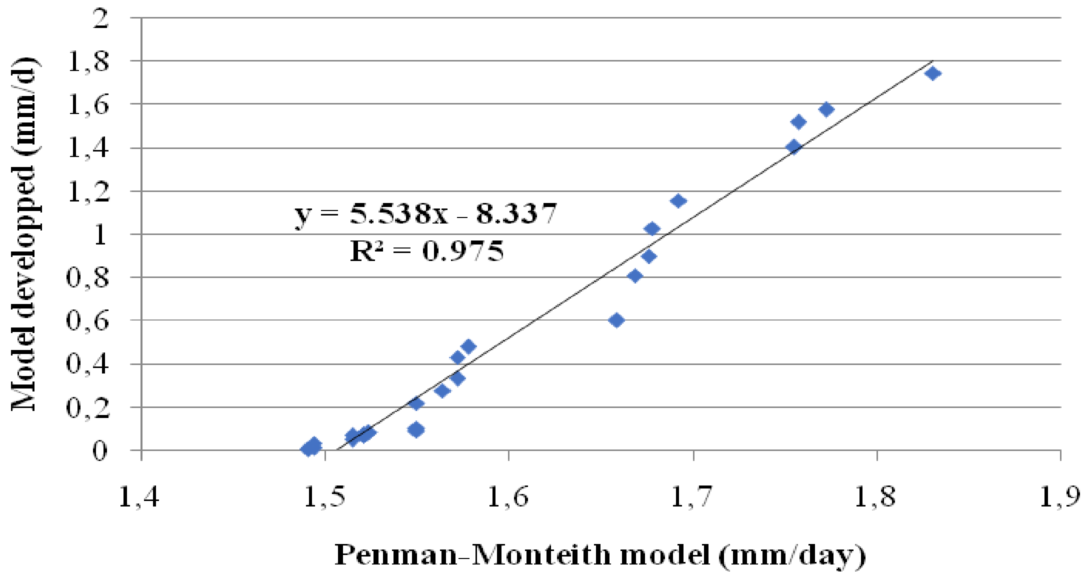

Figure 8 Correlation between the predicted values and penman values (mm day^{-1})

3.3 RMSE result

RMSE was computed to validate the generated equation. The results of error criteria between the vertisol evaporation measured and predicted are summarized in (Table 1). Results showed low spreading of error, which mean that the empirical equation offers a good fitting between measured and predicted values.

3.4 Conductivity and matric potential results

The resistive and potentiometric sensors were used to provide supplementary information on soil moisture content. Both sensors showed adequate responses compared to the lysimetric measurements. Based on the precedent results, the plasticity interval occurred in 8 days (between the 4th and the 11th) during the first period, in 10 days (between the 6th and the 15th) during the second period, and it took 12 days (from the 10th to the 22nd) in the third period. Thus, it can be deduced that the length of the plasticity period depends on the evaporative potential due to climatic conditions of temperature and irradiance.

By referring to lysimetric results it can be predictable to manage time of introducing agricultural tools using the moisture content sensors (Resistive and/or Potentiometric) to avoid the vertisol compaction. In fact, the sensors responses showed that plasticity state occurred in the first period (Table 2) between 400 - 700 mV according to 12.93 - 61.50 kPa, between 350 - 550 mV according to 20.02 - 55.99 kPa in the second period (Table 3) and between 400 - 779 mV according to 22.08 - 61.25 kPa in the third period (Table 4), for the resistive and potentiometric sensor respectively.

Table 1 Root mean square error measurements in three periods in (%)

Periods	Days	Measured (mm)	Predicted (mm)	RMSE (%)
	1	1.90	1.91	
	3	1.51	1.70	
1	6	1.67	1.56	
	9	1.10	0.99	0.6
	12	0.57	0.48	
	15	0.01	0.03	
	1	0.76	0.77	
	3	0.56	0.60	
	6	0.37	0.34	
2	9	0.27	0.22	
	12	0.17	0.18	0.1
	15	0.09	0.10	
	18	0.06	0.07	
	21	0.02	0.03	
	1	1.73	1.74	
	3	1.49	1.51	
	6	1.12	1.02	
	9	0.94	0.60	
	12	0.31	0.33	0.01
3	15	0.15	0.03	
	18	0.03	0.01	
	21	0.14	0.08	
	24	0.01	0.07	
	27	0.01	0.07	

Table 2 Resistive and potentiometric sensors responses [1st measurement period]

Soil State	1st repetition		2nd repetition	
	MC (%)	Arduino TM	MC (%)	Irrometer TM
Liquid state	42 %	279 mV	43 %	7.84 kPa
Plastic state	30 %	400 mV	31 %	12.93 kPa
	7 %	700 mV	7 %	61.50 kPa
Solid state	6 %	893 mV	5 %	69.37 kPa

Table 3 Resistive and potentiometric sensors responses [2nd measurement period]

Soil State	1st repetition		2nd repetition	
	MC (%)	Arduino TM	MC (%)	Irrometer TM
Liquid state	46 %	212 mV	43 %	4.90 kPa
Plastic state	22 %	350 mV	23 %	20.02 kPa
	11 %	550 mV	12 %	55.99 kPa
Solid state	8 %	988 mV	8 %	60.09 kPa

Table 4 Resistive and potentiometric sensors responses [3rd measurement period]

Soil State	1st repetition		2nd repetition	
	MC (%)	Arduino TM	MC (%)	Irrometer TM
Liquid state	49 %	263 mV	47 %	6.40 kPa
Plastic state	23 %	400 mV	23 %	22.08 kPa
	9 %	779 mV	8 %	61.25 kPa
Solid state	6 %	958 mV	7 %	72.55 kPa

4 Conclusion

This study showed that use of lysimeter design is an effective tool for measuring of SWE and predicting plasticity period occurrence. The resistive and potentiometric sensors were used appropriately to measure the vertisol moisture content in order to calibrate the model used to predict the plasticity state for the objective of modeling tools introduction. The governing equation in this study can be a practical method to estimate the evaporation trend in each day (mm day^{-1}) according to climatic data and predict occurrence of soil plasticity state in order to manage soil practicability and avoid its compactness.

5 Future Work

Based on our results we can conclude that the lysimeters developed can be adopted for vertisol evaporation management in bare soil and under vegetation cover. In addition, we can develop advanced sensor that can measure vertisol moisture content in different depths for understanding the dynamic of evaporation process and applied it to different soil types and for different climatic conditions.

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Nomenclature

Symbol	: Meaning
SWE	: Soil water evaporation
ML_S	: Micro-lysimeters
L_S	: Lysimeters
E_L	: Lysimetric evaporation
RMSE	: Root mean square error
EWQ	: Evaporated water quantity
MC	: Moisture content
WQA	: Water quantity added