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Study of the Relationship Between Evaporation, Soil Water Deficit, and Air Temperature in Arid Regions (Case of the Touggourt Zone)

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ABSTRACT

The primary objective of this study is to evaluate soil evaporation in arid regions using a minimal set of readily accessible parameters, which are represented through a nomogram. This work explores the relationships between soil evaporation, soil water deficit, and air temperature. Evaporation is a critical factor influencing the soil water regime. Irrigation artificially adjusts soil moisture to maintain it within optimal limits for vegetation. This regulation can only be effectively managed if the principles of soil-water balance are thoroughly understood. In arid and semi-arid regions, where water quality is often poor (high salinity), prolonged excessive irrigation can lead to soil salinization, thereby reducing agricultural productivity. In this study, ten lysimeters were used to measure soil evaporation at different levels of soil water saturation. The highest evaporation rate was recorded in fully saturated soil, peaking at 548 mm. This rate decreased as the soil water saturation decreased. Therefore, a good knowledge of the evaporation value is necessary to establish appropriate irrigation and soil leaching rates and consequently, an adequate water balance.

Keywords: Arid regions, evaporation, Lysimeter, meteorological elements, nomogram, soil saturation degree.

INTRODUCTION

The Touggourt region, located in southeastern Algeria (Oued Rhig Valley), is characterized by a hot and dry climate with low rainfall. This region has experienced remarkable agricultural development in the last ten years due to the availability of large groundwater reserves (the terminal complex and continental intercalaire aquifers) (Moulla and Guendouz 2003, Salah 2017). Poor water resource management has led to serious environmental problems, such as rising groundwater levels, soil salinization, and the degradation of groundwater quality, in addition to declining agricultural production in this region (Bouchahm et al., 2013, Bekkari et al., 2017).

Evaporation is an important and complex natural phenomenon studied by many researchers. It is a crucial process in the water cycle and has significant implications for many environmental processes (Merta et al., 2006, Teng et al., 2014, Chen et al., 2018). Estimating the evaporation rate is a crucial factor in many fields, particularly agriculture (Allen 1990, Merta et al., 2006, Abdullahi et al., 2013). Several scientific theories have explained the dependency of the evaporation rate on various climatic and physical factors. The literature presents, several formulas and approaches developed to estimate soil evaporation (Chen et al., 2018, Gong et al., 2020). On the other hand, in arid and semi-arid regions where climate conditions are harsh with extremely high temperatures, the evaporation phenomenon is affected by these conditions (King et al., 2015, Shirmohammadi-Aliakbarkhani and Saberali, 2020).

Although there are many studies on estimating evaporation in arid and semi-arid regions (Boutoutaou 1995, Remini 2005, Meziani et al., 2020), there are still uncertainties due to the complexity and the lack of understanding of this phenomenon (Aydin et al., 2005). Among the most significant studies conducted in this field, Lemon's 1956 study stands out for its rigorous approach to analyzing the bare soil evaporation process. This study contributed significantly to the scientific understanding of this phenomenon by describing the mechanisms involved in the three distinct stages of evaporation (Lemon 1956).

In the initial phase, the potential evaporation rate is determined exclusively by the meteorological conditions in the vicinity of the soil and is not influenced by the moisture content of the soil. During the second stage, the natural properties of the soil restrict the movement of water within the soil profile, causing the rate of evaporation to decrease in direct proportion to the decrease in the overall moisture content of the soil. In the last stage, the evaporation variation in response to the decline in soil moisture becomes minimal and loses its linearity. This stage is characterized by a slow transport of water toward the surface due to the low hydraulic conductivity of the soil (Flumignan et al., 2012).

The Ritchie (1972) approach, commonly employed for estimating water evaporation from uncovered soil, acknowledges evaporation as a process in two phases (Allen, 1990). The initial phase, (also known as stage 1 evaporation), is constrained by the quantity of energy accessible at the soil's surface. Meanwhile, the second phase (Stage 2 evaporation), is regulated by the soil hydraulic parameters. This technique demonstrated its ability to produce precise estimations of the total amount of water evaporated from the soil over considerable periods that are important for hydrology (Ritchie, 1972, Suleiman and Ritchie, 2003, Aydin et al., 2005).

Lemon 1956 and Ritchie 1972 highlighted the significant influence of the amount of water contained in the soil during the different phases of the water evaporation process from the soil. As soil moisture decreases, the amount of water available for evaporation also decreases, which leads to a reduction in the evaporation rate. However, the effect of soil moisture on evaporation can vary depending on environmental conditions (Teng et al., 2014). Nevertheless, the existing empirical formulas and methodologies proposed for soil evaporation assessment in the literature require many parameters and data that are difficult to obtain, especially in arid regions.

This study introduces a simplified and rapid methodology, using a nomogram, for estimating daily or monthly soil evaporation using only two easily measurable parameters. We employed field lysimetric measurements in the arid region of Touggourt to examine the impact of soil moisture on the evaporation rate under varying weather conditions. This approach allowed us to investigate the relationships between soil evaporation, soil water deficit, and air temperature. Ultimately, this study offers a practical tool (nomogram) for agricultural and environmental management in arid regions, contributing to addressing critical challenges such as rising water tables, increased soil salinity, and groundwater depletion. By enabling more precise irrigation practices, this study can help optimize water use and mitigate these issues, promoting sustainable land and water resource management in the Touggourt region.

MATERIALS AND METHODS

Materials

The study was conducted at the experimental station of the National Institute of Agronomic Research of Algeria – INRAA (Sidi Mahdi Station), which is located at Latitudes: 33°.04.293' and Longitudes 06°.05.788' E, 7 km southeast of Touggourt on the eastern plateau of Oued-Righ. The region shown in Figure 1 is characterized by a Saharan climate with high temperatures reaching 50 °C during the summer.

The experimental work is based on determining the actual evaporation of bare soil using the lysimeter weighing method, which is often used in evaporation studies (Boast and Robertson, 1982, Flumignan et al., 2012, Facchi et al., 2016). Many studies have confirmed that lysimeters effectively estimate evaporation with an acceptable degree of accuracy. Therefore, these parameters were used in this study to investigate soil evaporation (Allen 1990, Daamen et al., 1993, Liu et al., 2002, Ruth et al., 2018).

The lysimeters used are self-made. They consist of two loosely inserted PVC cylinders,

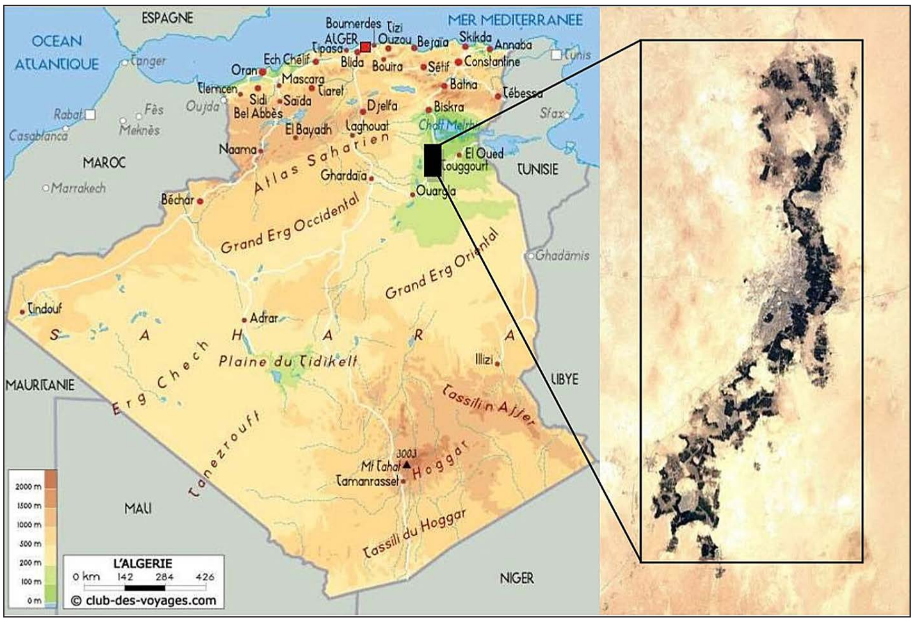

Figure 1. Geographic location of the study area

one inside the other Figure 2. A soil monolith is placed in the inner cylinder (lysimeter) with a height of 50 cm, a wall thickness of 6 mm, and a cross-sectional area of 452.2 cm^2. Starting from the bottom, this cylinder is closed by a perforated concave plug under which is placed the collection container (15 cm deep) to drain water from the soil monolith and rain. The upper part, which has two hooks for the lifting of the cylinder with the soil monolith for weighing, is kept open to allow soil evaporation. The outer cylinder (the protecting cylinder) serves as a protection for the inner cylinder (lysimeter). It has a diameter of 30 cm with a wall thickness of 7.5 mm. It is closed at the bottom to ensure the tightness of the bottom. The sand used is from the region of the INRAA experimental station. It is a fine sand. Figure 3 shows the formation and homogeneous nature of the soil from the first layer to a depth of 80 cm, end the particle size distribution curve of the sand used for the evaporation study.

The depth of the groundwater table in the agricultural fields of the INRAA experimental station fluctuates between 1.5 and 3 m below the soil surface. It is monitored by the piezometers at this station. The groundwater table is therefore far from the bottom of the lysimeter and does not create a problem of water intrusion from this

Figure 2. Lysimeter: 1 – inner cylinder (evaporator cylinder), 2 – outer cylinder, 3 – infiltration water collection container

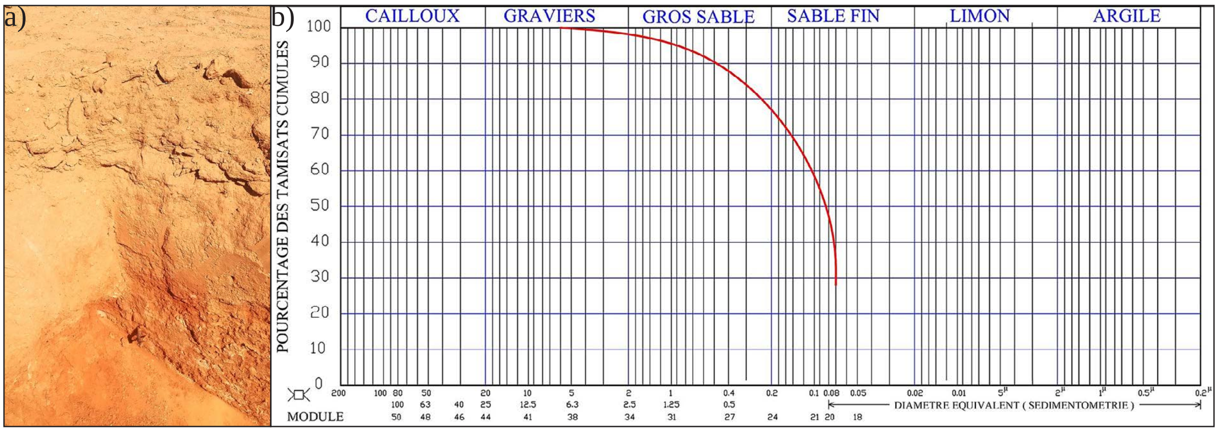

Figure 3. The soil of INRAA experimental station: (a) cross-section of soil layers in the first 80 cm, (b) particle size distribution curve of the sandv

table into the lysimeters. As a safety measure, we nevertheless ensured a watertight seal by hermetically sealing the bottom of the guard cylinder.

To avoid measurement errors and obtain actual soil evaporation data, the measurements were repeated twice using two lysimeters under identical states of water saturation; that is, the experiment was conducted twice. For five states of saturation, 10 lysimeters were prepared and installed in the agricultural field of the INRAA experimental station, Figure 4 shows the installation of lysimeters in the study area.

The meteorological parameters that play an important role in the soil evaporation process were measured at the INRAA weather station, which is located next to the experimental site (Figure 5). This station has a weather shelter equipped with thermometers for measuring air temperature, a psychrometer to measure air humidity, and a Piche evaporimeter for measuring potential evaporation. This measuring device is distinguished by its ease of use and its effectiveness in estimating the evaporation rate. However, it is important to note that the measurements provided by this device can

Figure 4. Installation of lysimeters in the INRAA agricultural field

sometimes be overestimated due to the significant impact of wind speed and solar radiation (Jacobs and Arriëns-Bekker, 1983). However, other studies confirmed its long-term effectiveness (Papaioannou et al., 1996, Marenholtz et al., 2010).

The station is also equipped with a class «A» evaporation pan, which allows for the measurement of evaporation from the surface of the water. It is necessary to take into account the technical conditions of use to avoid possible errors in the measurement of water body evaporation, given that these devices are sensitive to weather conditions, especially temperature, which affects the edges of the tank and the height of the water inside the tank, being maintained between 16 and 20 cm to avoid the aerodynamic effect of the wind (Jacobs et al., 1998, Chu et al., 2010). The wind speed is measured by two anemometers located 2 and 10 m above the ground surface.

Methods

The study of the bare soil evaporation was based on different soil saturation states. To obtain a well-defined degree of saturation of the soil monolith, humidification was performed artificially until the total soil saturation level reached 100%.

To determine the soil field capacity, a progressive irrigation process was performed until saturation. Irrigation was stopped just after the starting drainage. A period of 24 to 48 hours was sufficient for the excess water contained in the monolith to be drained. The weight of the evaporation cylinder filled with saturated soil was 41.15 kg, containing 7.56 liters of water. The weight of the evaporation cylinder after complete drainage was 37.9 kg, corresponding to a useful water reserve (RU) of 6.2 liters. Based on this, the saturation moisture content is Hs = 27.22%, corresponding to a soil saturation degree of Hsr = 100%, and the field capacity is Hcc = 22.06% for a saturation degree of Hsr = 80%.

Thus, the suggested soil saturation degree for each pair of lysimeters is based on the soil›s useful water reserve, wilting point, field capacity moisture point, and saturation point.

Figure 4 shows the plot where the lysimeters were installed was prepared and leveled. Ten excavations were prepared for the installation of the lysimeters, which were spaced two meters apart

To prevent the clogging of the evaporator perforations, a strategy involved placing a 5 cm thick layer of gravel was carefully placed, then covered with a geotextile. The geotextile allows water to pass through while retaining fine soil particles, thus keeping the drains clean and preventing clogging. The lysimeter (evaporation cylinder), filled with agricultural soil, weighed 33.5 kg, while the monolith, weighing 28.1 kg, included an empty lysimeter weighing 5.4 kg.

The soil evaporation rate was measured every two days, Figure 6 shows the using electronic balance, which is characterized by a sensitivity of

Figure 5. The INRAA weather station Touggourt

Figure 6. The lysimeter weight was measured using an electronic balance

± 5 g, equivalent to ± 0.11 mm of evaporation. The experimental period spanned from May 3, 2021, to April 28, 2022. The soil evaporation rate is determined using the following Equation:

$$E_s = (10/S)(M_i - M_f) - D + P \quad (1)$$

where: *Es* – is the soil evaporation between two measurements of the weight of the lysimeter (evaporation cylinder) in mm, *Mi* – is the initial weight (weight of the monolith mentioned in the first reading) in grams, *Mf* – is the final weight (weight of the monolith mentioned in the second reading) in grams, *S:* is the evaporation surface in cm, *P* – is the rainfall entering the monolith in mm, *D* – is the drainage of the monolith in mm (the lysimeter is perforated at the bottom).

Table 1, provides an example of calculating the average daily evaporation values of the lysimeters (ten lysimeters) at different states of soil saturation between May 3 and 4, 2021. All meteorological parameters were also measured in parallel with the evaporation measurements in the lysimeters.

RESULTS AND DISCUSSION

The evaporation measurement results for different soil saturation degrees, and the meteorological parameter measurement results obtained, throughout the experiment, were collected and collated according to the measurement start date. Table 2 shows some results.

Soil evaporation is strongly linked to soil moisture and the surrounding weather conditions (Zhang et al., 2022), Figure 7 shows that at a soil saturation degree of 100% (Hs = 100%), the evaporation rate is maximal and nearly equal to the evaporation rate of a water surface measured using a class "A" pan. If the evaporation of the pan is regarded as a reference, i.e. consider it as potential evapotranspiration. The evaporation measured by the lysimeter at maximum soil saturation levels can be considered as potential evapotranspiration. Figure 7 shows the ratio of fully saturated bare soil evaporation to free

Table 1. An example of calculating the average daily evaporation from May 3 to 4, 2021

Lysimeters saturation rate (%)	Lysimeters weight		Weight difference (Mi-Mf)		Lysimeters drainage		Rainfall on the P (mm)	Evaporation from the lysimeters Es (mm)	Average Evaporation Es (mm)
	Initial weight Mi (kg)	Final weight Mf (kg)	(kg)	(mm)	(litre)	(mm)			
Lysimeter1 100%	41.50	39.610	1.890	41.8	1.650	36.48	0	5.32	5.25
Lysimeter2 100%	41.15	39.455	1.695	37.49	1.460	32.29	0	5.20	
Lysimeter3 80%	40.50	39.440	1.060	23.44	0.810	17.91	0	5.53	5.19
Lysimeter4 80%	39.70	39.480	0.220	4.87	0.000	0	0	4.87	
Lysimeter5 60%	39.00	38.800	0.200	4.42	0.000	0	0	4.42	4.42
Lysimeter6 60%	38.50	38.300	0.200	4.42	0.000	0	0	4.42	
Lysimeter7 40%	37.50	37.330	0.170	3.76	0.000	0	0	3.76	3.65
Lysimeter8 40%	36.50	36.340	0.160	3.54	0.000	0	0	3.54	
Lysimeter9 20%	35.50	35.425	0.075	1.66	0.000	0	0	1.66	1.49
Lysimeter10 20%	34.50	34.440	0.060	1.33	0.000	0	0	1.33	

Table 2. Values of meteorological parameters and evaporation for different soil saturation degrees

Date	Meteorological parameters					Evaporation E.mm		Soil evaporation, Es (mm) Soil saturation degree Hsr (%)				
	Dry and humid air temperature		Air humidity (H%)	Wind speed *V*, (m/s)	Soil temperature *ts* (C°)	Piche	Bac « *A* »	100%	80%	60%	40%	20%
	t_{sec} (C°)	t_h (C°)										
04-05-2021	26.20	20.06	55	7.3	23.5	6.2	9.8	5.25	5.20	4.42	3.65	1.49
08-06-2021	33.4	25.5	40	6.3	29.9	13.1	8.3	10.51	9.45	5.53	6.69	3.48
15-07-2021	39.7	24.0	30	10.3	34.3	28	20.0	16.09	17.20	14.98	14.43	9.51
10-08-2021	40.3	29.5	31	6.8	34.1	20	12.4	14.15	12.72	12.22	12.22	11.00
28-09-2021	32.6	23.9	45	5.8	32.1	12	5.9	6.75	5.58	6.75	5.53	4.59
19-10-2021	25.1	16.1	40	1.7	24.7	6.2	5.6	5.58	4.48	3.37	3.37	2.27
30-11-2021	15.0	11.0	60	4.4	12	2.8	2.8	2.27	2.05	1.11	1.11	1.11
23-12-2021	9.5	7.1	72	4.4	12	1.75	2.4	2.32	1.71	1.71	0.61	0.55
18-01-2022	10.6	8.3	77	4.2	8.6	1.5	3.0	3.0	2.3	1.8	1.7	0.00
17-02-2022	14.47	11.20	70	4.2	13.4	3.5	5	2.21	2.21	1.27	1.22	1.22
08-03-2022	17.00	13.67	69	3.1	13.9	2	2.4	2.32	2.05	1.44	0.61	0.00
05-04-2022	22.33	15.17	46	6.6	23.5	8.2	10	7.13	5.20	4.48	3.48	2.61

water surface evaporation for the fine sand obtained in our study was close to 100%. This ratio is confirmed by the ratios of the evaporation rates of saturated bare soils to those of a free water surface given for different soil types (Schoeller 1962, Réméniéras 1986). These are as follows:

- Fine sand: 100%;
- Marl: 90%;
- Clay: 75 to 85%.

Notably, soil evaporation decreases as the soil dries out. It is minimal if the saturation degree is low and logically tends to zero for wilting point moisture. Figure 8 illustrates the relationship between the evaporation of the class "A" pan and the evaporation of the lysimeter with a low soil saturation degree. In this case. The evaporation of the water surface is higher than the evaporation of the soil when the latter is depleted of its moisture.Soil

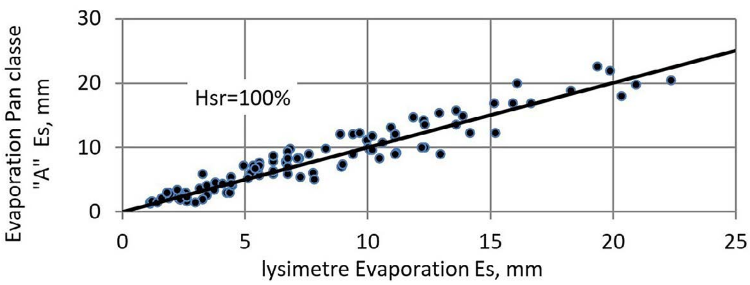

Figure 7. The relationship between the daily evaporation of a fully saturated soil (Hsr = 100%) and the evaporation of a free water surface (class "*A*" pan)

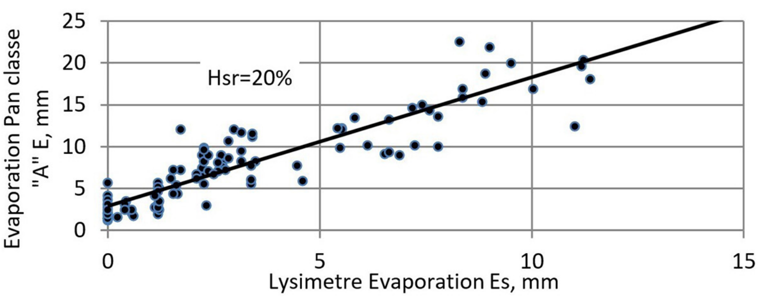

Figure 8. Relationship between daily evaporation of the lysimeter with a low saturated soil (Hs = 20%) and evaporation of the water surface (class "*A*" pan)

evaporation is not constant throughout the year. It varies depending on the evolution of meteorological parameters and soil moisture. For the same degree of soil saturation, evaporation is very low (Table 3) during the winter period. It decreases to zero for low temperatures and high air humidity.

The increase in air temperature and the decrease in the air humidity during the summer period, cause an increase in the air saturation deficit and consequently an increase in soil evaporation. Table 4 shows some values of soil evaporation measured in the different lysimeters during the summer period

Table 3 indicates a decrease to almost zero (0–1 mm/day) in soil moisture from a saturation degree of around 40%. However, during the summer period, for the same degree of soil saturation evaporation is significant, constituting 8–3 mm/day (Table 4). This means that even for a saturation below 20%, evaporation is still active when there is moisture in the soil and tends towards zero when the soil is dry. Therefore, the limiting factor of evaporation in winter is the atmosphere's evaporative power (potential evapotranspiration). In summer. The limiting factor of evaporation is the availability of water in the soil.

To determine the degree of influence of the meteorological parameters on the bare soil evaporation in the arid region. The correlation coefficient between evaporation and these parameters was calculated and is presented in Table 5.

As shown in Table 5, soil evaporation is strongly correlated with the rest of the meteorological parameters. except for wind speed.

To reduce the number of parameters influencing soil evaporation, a calculation model for soil evaporation must be established. This study relied solely on two important standard parameters that are always available and easily accessible: air temperature and soil saturation degree. which are strongly correlated with soil evaporation, Figure 9 shows the relationship between evaporation. air temperature. and soil moisture.

The analysis of the correlation between evaporation. air temperature. and the soil saturation degree led to the definition of three general rules of bare soil evaporation. which can be expressed as follows:

1. For the same soil saturation degree, the evaporation rate decreases with a reduction in the air temperature.
2. At a constant air temperature, the evaporation will be more intense the higher the soil moisture degree. For total saturation (Hsr = 100%), soil evaporation tends towards a limit corresponding to potential evaporation.

Table 3. Lysimeter evaporation values for different degrees of saturation in the winter period

Date	Air temperature *t* (°C)	Air humidity *H* (%)	Wind speed *V* (m/s)	Evaporation Es. mm				
				Lys.1 (100%)	Lys.2 (80%)	Lys.3 (60%)	Lys.4 (40%)	Lys.5 (20%)
23/12/2021	9.5	72	4.38	2.32	1.71	1.71	0.61	0.00
18/01/2022	10.6	77	4.21	2.99	2.32	1.77	1.66	1.00
27/01/2022	9.0	70	7.12	2.21	2.10	0.61	0.00	0.00

Table 4. Lysimeter evaporation values for different degrees of saturation in the summer period

Date	Air temperature *t* (°C)	Air humidity *H* (%)	Wind speed *V* (m/s)	Evaporation Es. mm				
				Lys.1 (100%)	Lys.2 (80%)	Lys.3 (60%)	Lys.4 (40%)	Lys.5 (20%)
08/07/2021	41.06	29	15.0	20.95	18.74	15.15	13.21	11.17
01/07/2021	42.35	31	11.0	16.64	14.93	13.49	11.06	10.01
05/08/2021	40.10	31	5.8	11.89	9.45	8.96	7.69	7.18

Table 5. The correlation coefficient values between the soil evaporation and the meteorological parameters

Characteristic	Soil evaporation Es (mm)	Air temperature (C°)		Air humidity H (%)	Wind speed V(m/s)	Soil temperature Ts (°C)
		Sec	Humid			
Soil evaporation Es (mm)	1	0.897	0.845	0.828	0.359	0.842

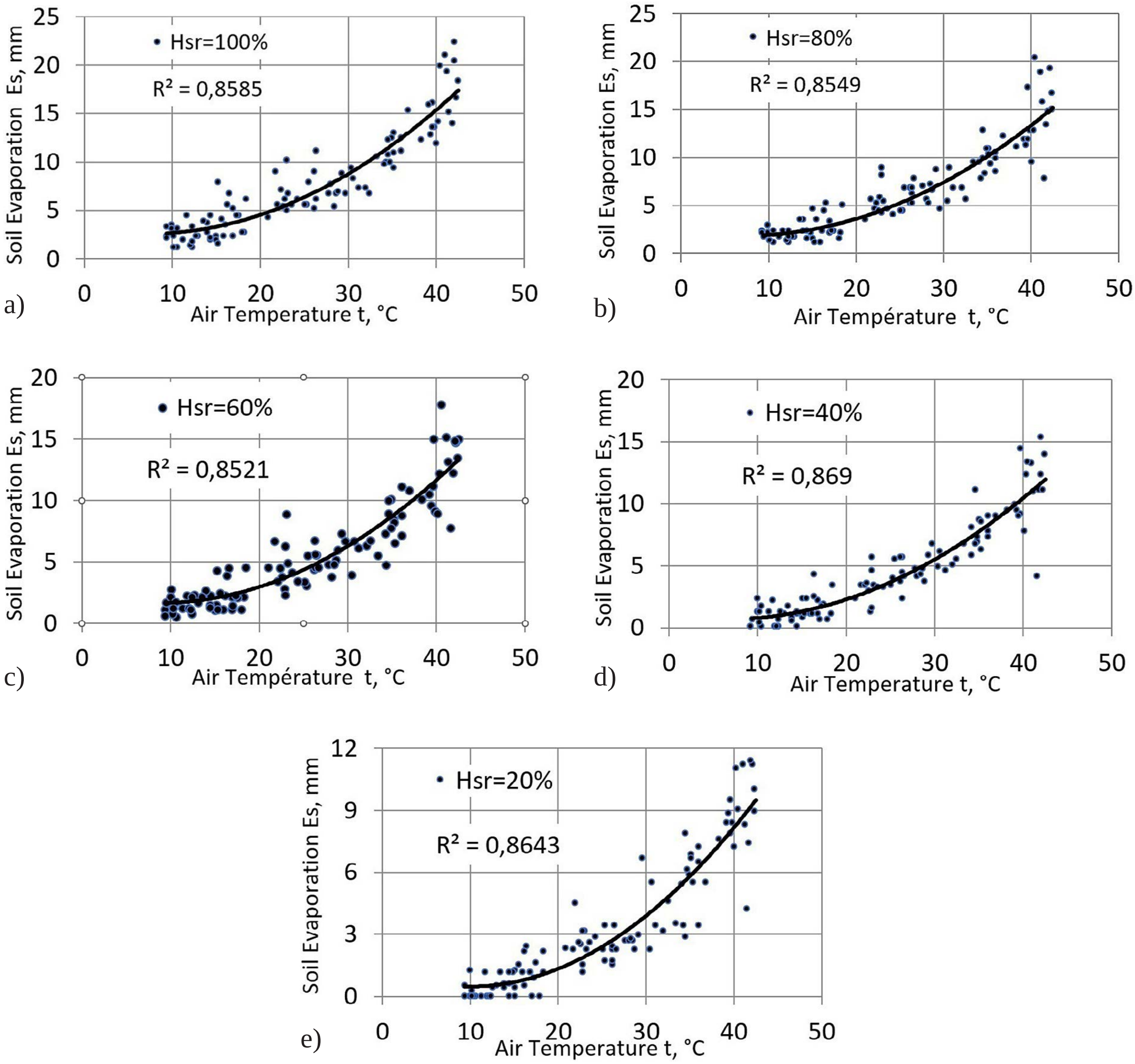

Figure 9. The relationship between soil evaporation (mm), air temperature (°C), and soil saturation degree at: (a) Hs = 100%, (b) Hs = 80%, (c) Hs = 60%, (d) Hs = 40%, (e) Hs = 20%

3. These three rules can be used to suggest a nomogram for calculating the bare soil evaporation (sand) using air temperature (°C) and soil saturation degrees (%) (Figure 10).

The saturation curve Hsr = 10% in the nomogram shown in Figure 10 was obtained by interpolation. The soil evaporation calculation method was validated using the nomogram, with Figure 11 displaying a comparison between the values determined by this method and the measured soil evaporation values. The obtained results are evaluated based on several methods, such as the application of the Nash-Sutcliffe criterion (NSE), the root mean square error (RMSE), the mean bias error (MBE), the coefficient of determination (R^2), and the ratio of sums of ranks (RSR) (Song et al., 2015).

Coefficient of determination

It quantifies the variation in observed values that can be explained by the model and determines the extent to which the predicted values match the measured values. An R^2 value close to 1 indicates a good fit between the predictions and observations, while a value close to 0 indicates a poor fit.

$$R^2 = \frac{\sum_{i=1}^{n}\left(E_i^{measured} - E_{mean}^{measured}\right)\left(E_i^{model} - E_{mean}^{model}\right)}{\sum_{i=1}^{n}\left(E_i^{measured} - E_{mean}^{measured}\right)^2 \sum_{i=1}^{n}\left(E_i^{model} - E_{mean}^{model}\right)^2} \quad (2)$$

Root mean square error

The *RMSE* indicates the overall model error, where a lower value indicates better accuracy.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(E_i^{measured} - E_i^{model}\right)^2}{N}} \quad (3)$$

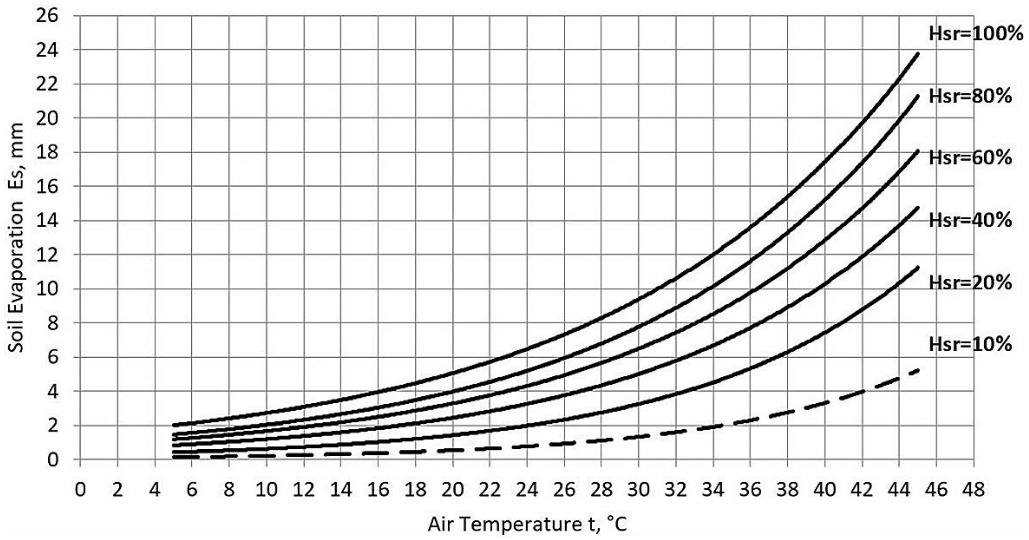

Figure 10. Nomogram for determining the daily soil evaporation based on air temperature (°C) and the degree of soil saturation (%)

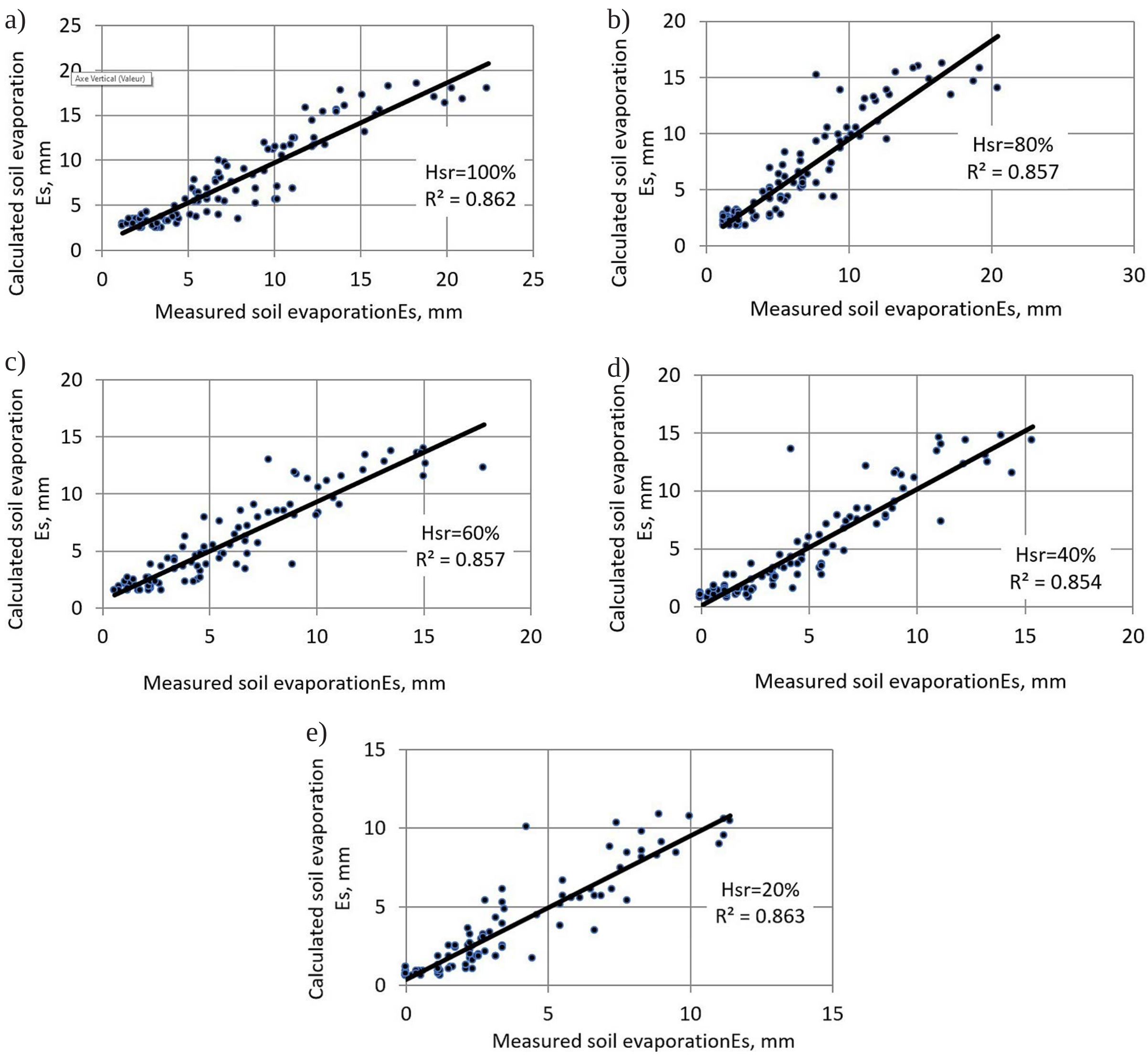

Figure 11. Comparison between calculated and measured evaporation values for different soil saturation degrees at: (a) Hs = 100%, (b) Hs = 80%, (c) Hs = 60%, (d) Hs = 40%, (e) Hs = 20%

Mean bias error

The mean bias error (*MBE*) indicates whether the model tends to underestimate or overestimate the outcome. A zero *MBE* means there is no bias. For example. If *MBE* = -0.5, this means that the model underestimates the outcome by an average of 0.5 units.

$$MBE = \frac{1}{N}\sum_{i=1}^{n}\left(E_i^{measured} - E_i^{model}\right) \quad (4)$$

Nash-sutcliffe efficiency

It evaluates a model's accuracy and efficiency by comparing the deviations between the model's calculated values and the measured values. An NSE close to 1 indicates a good fit between the predictions and observations.

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}\left(E_i^{measured} - E_i^{model}\right)^2}{\sum_{i=1}^{n}\left(E_i^{measured} - E_{mean}^{measured}\right)^2}\right] \quad (5)$$

Ratio of sums of ranks

Compares the ranks of the predicted and measured values. An RSR close to 0 indicates a good fit between predictions and observations.

$$PSR = \sqrt{\frac{\sum_{i=1}^{n}\left(E_i^{measured} - E_i^{model}\right)^2}{\sum_{i=1}^{n}\left(E_i^{measured} - E_{mean}^{measured}\right)^2}} \quad (6)$$

The statistical quantities for comparing the values of evaporation calculated by the Nomogram and observed are shown in Table 6. The coefficient of determination (R^2) values and the Nash-Sutcliffe efficiency index are very close to 1, indicating a good fit between the calculated and measured evaporation values.

The mean bias error values have a slight tendency to overestimate the evaporation values. but overall. they are close to unity. The root mean square error values. which indicates the overall error in the evaporation calculation, and shows an acceptable accuracy given that these values are very low. The values of the rank sum ratio (RSR). they are very low and tend towards zero, which also shows a good fit between the calculated and the measured evaporation values. Figure 12 shows the distribution curves of the differences between the calculated and measured values in mm are symmetrical. with no systematic errors (normal distribution).

Given the lack of reliability in measuring daily evaporation values the comparison results can be considered satisfactory. The monthly values of bare soil evaporation for different degrees of saturation were determined from the daily evaporation values. The monthly values of the meteorological parameters were also determined. Table 7 summarizes all the monthly values of bare soil evaporation as a function of the degree of saturation, Piche evaporimeter, evaporation from the water surface of the class ”A” pan, and the air temperature for the entire observation period beginning on May 03, 2021, to April 28, 2022.

A comparison of the monthly bare soil evaporation for different degrees of saturation over the entire observation period shows that Piche evaporation is always the highest throughout this period. The monthly values of evaporation from the class ”A” pan and the lysimeter for total saturation are close to each other Table 7. The distribution of monthly evaporation throughout the year is shown in Figure 13.

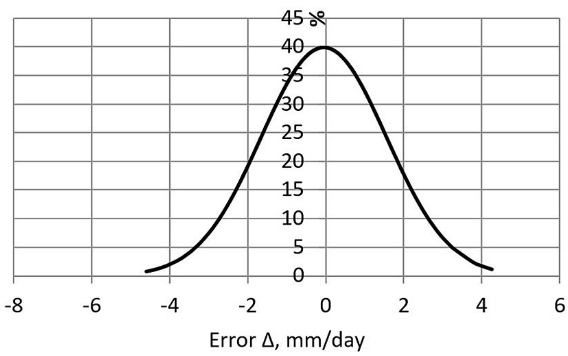

Figure 12. The distribution curve of the errors in the calculation of daily evaporation using nomogram

Table 6. Statistical comparison of calculated and measured evaporation values

Statistical parameter	Statistical values				
Coefficient of determination R^2	0.929	0.966	0.960	0.976	0.965
Nash-sutcliffe efficiency (NSE)	0.86	0.86	0.86	0.83	0.86
Root mean square error (RMSE)	5.57	5.14	4.51	4.69	3.44
Mean bias error (MBE)	1.61	1.48	1.30	1.35	0.99
Ratio of sums of ranks (RSR)	0.37	0.38	0.38	0.41	0.38

Table 7. Monthly values of bare soil evaporation and meteorological parameters

Months	Air temperature	Evaporation (mm)		Soil evaporation. Es (mm) (Soil moisture degree Hsr (%))				
		Bac « A »	Piche	100%	80%	60%	40%	20%
May	28	251	338	198	186	148	131	72
June	36	368	526	379	308	251	234	158
July	41	572	909	548	480	414	366	293
August	38	384	576	364	319	274	258	226
September	34	292	437	290	269	248	214	142
October	24	196	322	192	154	145	118	97
November	18	146	184	150	108	94	74	46
December	11	62	98	75	54	48	27	14
January	11	77	95	81	62	47	18	3
February	15	115	138	89	68	59	43	30
March	18	142	158	114	86	70	44	33
April	24	281	304	270	191	159	117	76

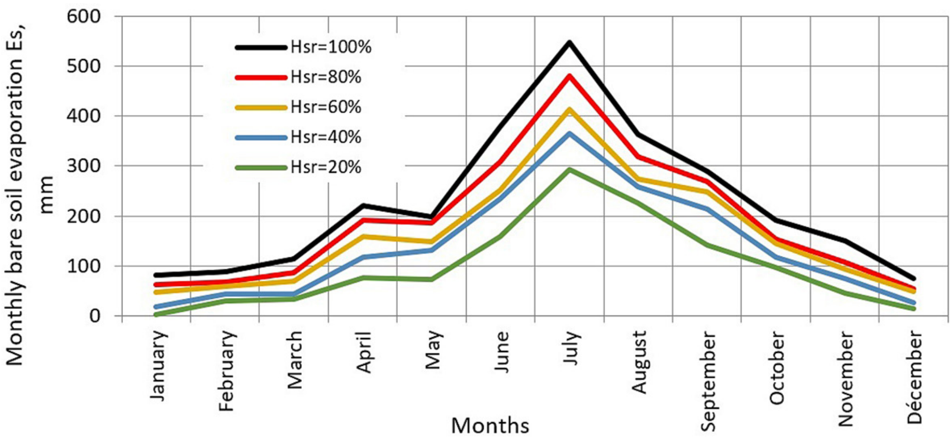

Figure 13. The monthly bare soil evaporation (mm) at different soil saturation degrees (%)

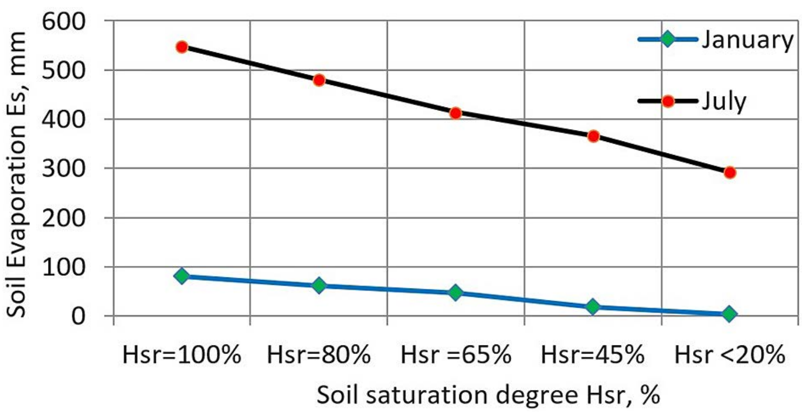

Figure 14. Evolution of monthly soil evaporation as a function of soil saturation degrees in January and July

The lowest monthly soil evaporation values are observed in January. Es = 80 mm for a saturation degree Hsr = 100% and Es ≈ 3 mm for a saturation degree Hsr = 20%. The highest values are observed in July. with Es = 548 mm for Hsr = 100% and Es = 293 mm for Hsr = 20%.

Under the same weather conditions. monthly soil evaporation increases as soil saturation increases. Figure 14 illustrates the evolution of this growth for January and July.

The evaporation rates (as a percentage of the annual value) are not constant throughout the year. They vary with the season. Figure 15 shows the distribution of monthly evaporation rates according to the degree of saturation. For a soil saturation degree of *Hsr* = 100%, the evaporated fraction constitutes almost 50% of the annual fraction in the summer and 10% in the winter. For low

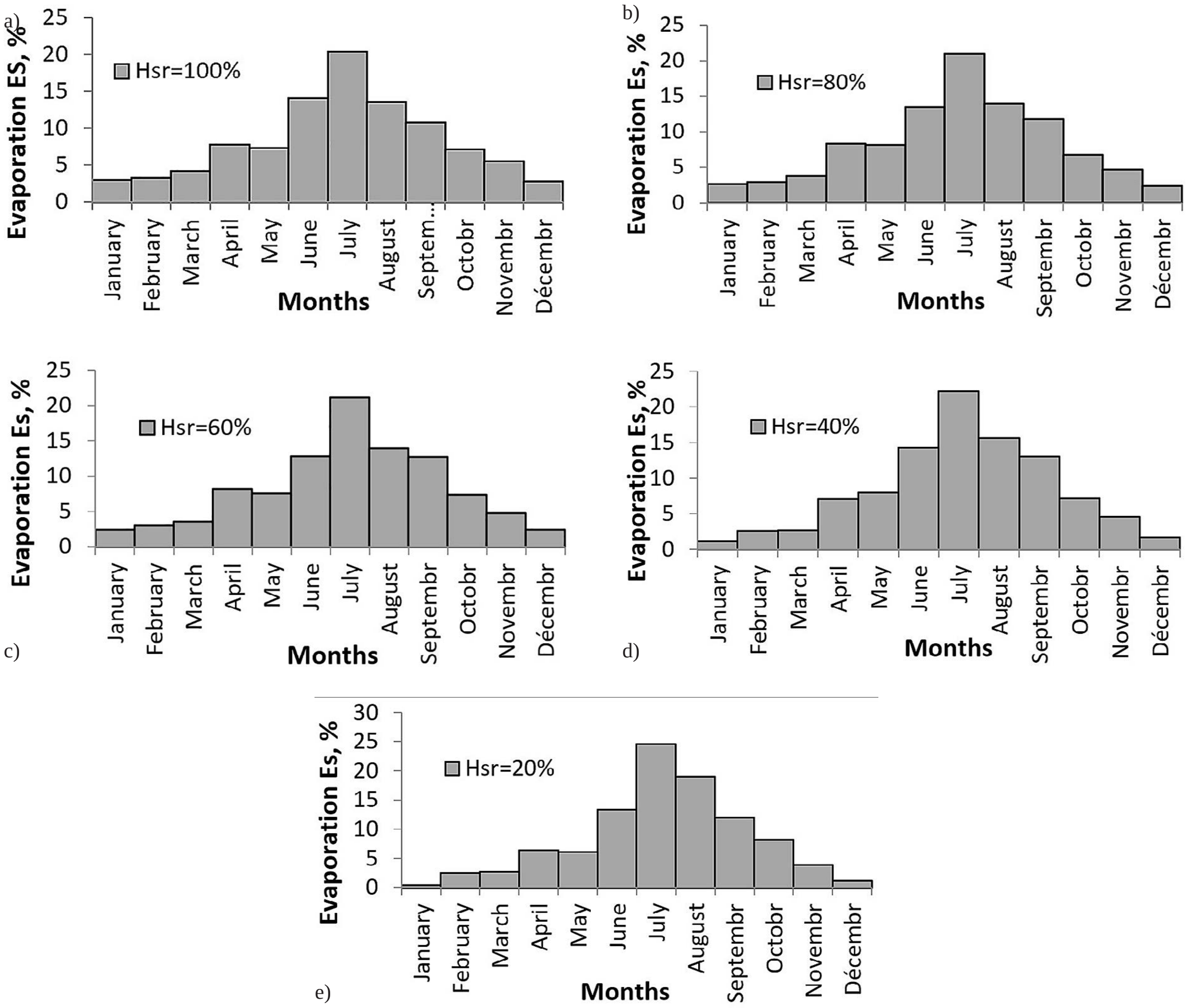

Figure 15. The distribution of the monthly bare soil evaporation (%) for different saturation degrees at: (a) Hs = 100%, (b) Hs = 80%, (c) Hs = 60%, (d) Hs = 40%, (e) Hs = 20%

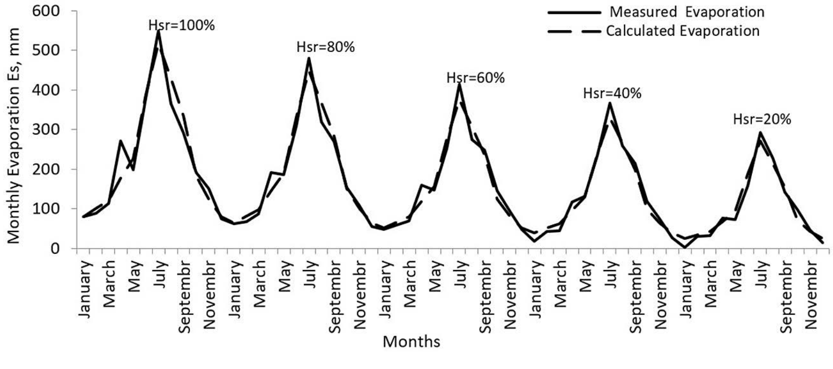

Figure 16. Comparison between calculated and measured monthly evaporation values for different degrees of saturation

saturation degree (*Hsr* = 20%), the evaporated water fraction is 55% in the summer and 5% in the winter. The nomogram established in Figure 11 was also used to determine the monthly soil evaporation. The monthly evaporation values calculated for each degree of saturation are very close to the measured evaporation values Figure 16.

CONCLUSIONS

The value of evaporation is key data for assessing the soil water balances and determining the irrigation doses for agricultural areas. It often remains unknown in many regions, particularly in arid areas, due to a lack of measurement data and/or the absence of a universal calculation methodology. This study of the bare soil evaporation in the Touggourt region clarified the evolution of this important parameter as a function of air temperature and soil moisture content. For the same soil moisture content, the evaporation is lower as the air temperature goes down, At the same air temperature, evaporation will be more intense when the soil moisture content is higher. Finally, for total soil water saturation, the evaporation tends towards a limit corresponding to the potential evaporation. These three defined rules made it possible to suggest a nomogram for calculating the bare soil evaporation (sand) from air temperature and soil saturation degree. It verified a vast very large amount of data, and the nomogram provides satisfactory results and can be considered reliable for agronomic, hydrological, and other studies.

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