

Methods for calculating phreatic evaporation on bare grounds on rainy and dry days

Zhenlong Wang, Yingying Xu, Guoqiang Dong, Haishen Lv, Yue Fan and Yining Wang

ABSTRACT

In order to depict the impact of rainfall on phreatic evaporation, this study analyzes phreatic evaporation and the phreatic evaporation coefficient between surface evaporation and soil depth in Shajiang black soil and Fluyo-aquic soil. We have improved the existing commonly used mathematical framework, established two rainless day phreatic evaporation calculation models, and then calculated the calculation model of the phreatic evaporation reduction on rainy days. Finally, rainy day evaporation calculation models on two soils were proposed. The results show that the evaporation coefficient is affected by both depth and the evaporation ability of the surface water. The evaporation reduction of Shajiang black soil increased with depth and the increasing trend gradually slowed down until it approached zero. The evaporation reduction of the Fluyo-aquic soil phreatic decreased first and then increased with depth, reaching a minimum at 0.4 m. The reduction of phreatic evaporation in both soils decreased with the increase in rainfall level and decreased with the increase in rainfall duration showing 'inverted S-type'. In summary, the phreatic evaporation composite calculation models on rainy days and rainless days have good fitting and prediction results, which can improve the accuracy of phreatic evaporation calculations.

Key words | calculation of phreatic evaporation, rainless day, rainy day

HIGHLIGHTS

- How the water table depth and surface evaporation influence phreatic evaporation was determined.
- The exponential calculation models of phreatic evaporation under rainless conditions were established.
- The decrease in phreatic evaporation when the level of rainfall and rainfall duration increased.
- The model of phreatic evaporation under rainfall conditions was established.

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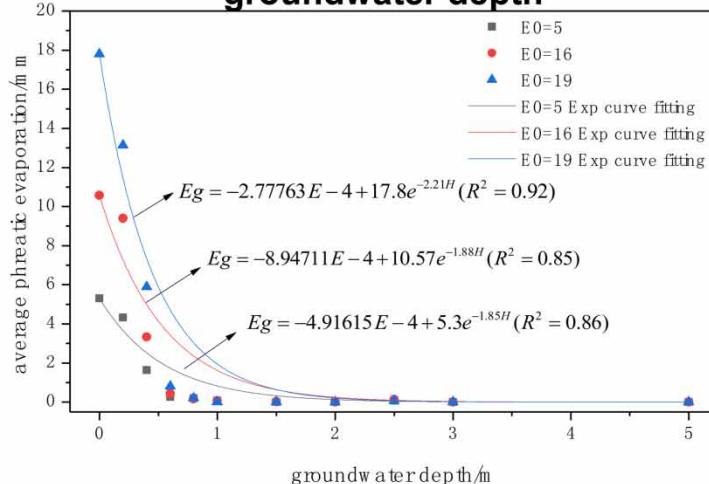
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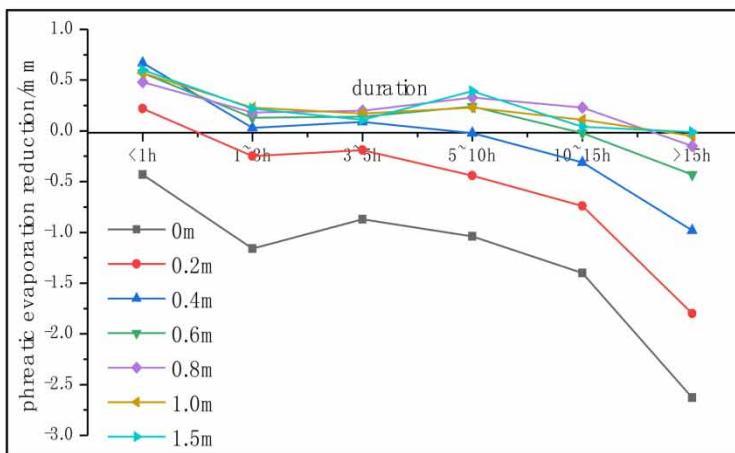
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GRAPHICAL ABSTRACT

Relationship between phreatic evaporation and groundwater depth



Relationship between phreatic evaporation reduction and rainfall duration



INTRODUCTION

Phreatic evapotranspiration refers to the process of groundwater transfer to unsaturated soil layers and through the soil and vegetation into the atmosphere (Liu et al. 2005). Evapotranspiration and phreatic evaporation are intimately linked as one leads to and limits the other. Research and analysis of the principles and calculation methods for phreatic evaporation are of great significance in water resource assessment, prevention and control of soil salinization, and calculation of ecological water demand.

Currently, many studies on the phreatic evaporation principles and calculation have been carried out internationally. Philip's (1957) research on bare soil surface evaporation found that the free water surface evaporation occurs from lakes and the phreatic evaporation takes place from the shallow water table of salt flats as a function of the water table depth. Based on numerical models, Muñoz-Pardo et al. (2004) developed a direct relationship between the water table depth and recharge and evaporation and investigated how this relationship could contribute to keeping the water table stable. Marazuela et al. (2019) used the Salar de Atacama as the experimental area to study the coupled natural and anthropogenic processes and found that in the natural regime, the water table exhibited a gradual drawdown because the evaporation was greater than the recharge most of the time, but the brine pumping causes a fall in the water table, which results in a decrease of the evaporation rate. Marazuela et al. (2020) measured the water table and evaporation rate, obtained an evaporation curve relating phreatic evaporation to water table depth, and then conducted spatiotemporal analysis and the application of the results to a numerical model to improve the brine exploitation design. Tyler et al. (2006) analyzed the hydraulic and solute processes of groundwater in Playa Lake and Sabkhat and built a model based on soil physics to predict the water table response to either upstream recharge changes or changes in potential evaporation. Johnson et al. (2009) studied the evaporation rates from shallow groundwater using the chamber approach in six closed basins in the Altiplano of northern Chile and considered that it is strongly related to groundwater depth and soil texture and obtained evaporation curves by fitting exponential and power relationships as a function of groundwater depth. Liu et al. (2011) analyzed the effects of meteorology, crops, soil,

groundwater depth, and rainfall on phreatic evaporation. Their analysis led to the establishment of a model for phreatic evaporation in different time periods. Zhang et al. (2009) analyzed the control conditions of the phreatic evaporation calculation model and established a new quantitative model for phreatic evaporation which avoids the problem of overestimating the phreatic evaporation when the atmospheric evaporation capacity is large.

In summary, a lot of research has been done to improve evaporation models and analysis of phreatic water, but there are few studies on the effects of rainfall on phreatic evaporation and quantitative methods that distinguish between rainy and dry days. Based on phreatic evaporation data and meteorological observations from the Wudaogou Experimental Station from 1993 to 2015, this paper analyzes the influence of evaporation and depth of Shajiang black and Flujo-aquic soil on phreatic evaporation and its coefficient in a bare ground scenario. Based on this law, the empirical formula has been improved to establish a model for phreatic evaporation on rain-free days in two soils and to estimate the effects of rainwater on phreatic evaporation. Comparing the differences between estimations, measurements, and model predictions, this study was able to quantify – in different soils (black and yellow) and under different conditions (rainy and dry) – the effect of rainwater and groundwater depth on evapotranspiration. The calculation model of the rainfall duration. Based on the integrated rain-free day phreatic evaporation calculation model and the rainy day phreatic evaporation reduction calculation model, the rainy day phreatic evaporation calculation model of Shajiang black soil and yellow Flujo-aquic soil was established and verified to provide technical support for exploring the impact of rainfall on phreatic evaporation.

EXPERIMENTS AND METHODS

Overview of the experimental area

This experiment was carried out at the Wudaogou Hydrology and Water Resources Experimental Station in Bengbu City,

Anhui Province. The Wudaogou Experimental Station is in Hubei.

The large-scale comprehensive experimental station in the plain area, located at 33°09' N, 117°21' E, is located in an original seed field in Xinmaqiao, Anhui Province, 28 km north of Bengbu City, Anhui Province, and belongs to the closed plain experimental station. The Huabei Plain has a typical semi-arid and semi-humid monsoon climate with four distinct seasons, simultaneous rain and heat, dry in winter, and hot and rainy in summer, rainfall in the rainy season (June–September) accounts for approximately 60% of the annual precipitation. There are two main types of soil types: Shajiang black soil (54%) and Fluyo-aquic soil (33%). The experimental station has 62 sets of large-scale underground lysimeters which are equipped with undisturbed soil samples of two soils, namely sand ginger black soil and yellow Fluyo-aquic soil. The lysimeter is provided with different groundwater depths. Under the bare ground conditions, the groundwater depth of the Shajiang black soil is: 0.0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0, 5.0 m. The groundwater depth of the yellow Fluyo-aquic soil under bare soil conditions is: 0.0, 0.2, 0.4, 0.6, 1.0, 2.0, 3.0, 4.0 m. Meteorological measurements can gather data on surface temperature, average temperature, water surface evaporation, incident radiation (sunshine), relative humidity, wind speed, saturation difference, absolute humidity, water vapor pressure difference, and rainfall. The groundwater level is shallow with fluctuations between 1.5 and 3.5 m.

Experimental facilities and data selection

This paper relies on the large-scale underground lysimeter at Wudaogou Experimental Station. The area of the bare soil measuring instrument is 0.3 m².

Two main soil types (Shajiang black soil and yellow Fluyo-aquic soil) in the Huabei Plain area were studied. The groundwater depths of the selected Shajiang black soil measuring cylinders were 0.0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.5, 2.0, 2.5, 3.0, 5.0 m. The groundwater depths of the selected yellow Fluyo-aquic soil measuring cylinder are 0.0, 0.2, 0.4, 0.6, 1.0, 2.0, 3.0, 4.0 m. According to the water balance principle, the phreatic evaporation under different groundwater depth conditions is measured by

the lysimeter on a daily basis. Surface water evaporation is measured by the meteorological field E601 evaporating dish. Rainfall is measured with a standard meteorological rain gauge. The rainfall duration is monitored by meteorologists. According to the rain gauge measurement, the phreatic evaporation and meteorological data were fitted by the data series analysis from 1993 to 2015, and data were predicted by 2018 data. The classification of rainfall levels is based on criteria given by China's meteorological agency. The division of rainfall duration is divided into five levels according to quantity. The specific classification criteria are shown in Table 1.

Mathematical modeling

The model construction in this paper is completed according to the basic steps of mathematical modeling (Figure 1).

Model preparation: Understand the actual background of diving evaporation, clarify the practical significance of the calculation model of diving evaporation on rainy and non-rainy days, and collect various necessary information.

Model establishment: Graphs are used to describe the relationship between variables, and MATLAB is used to quantify their specific mathematical relationships to establish corresponding mathematical structures.

Model solution: Use the obtained data to calculate (estimate) all the parameters of the model.

Model verification: Compare the analysis results of the model with the actual situation to verify the accuracy, rationality, and applicability of the model.

Model application: The established model must produce benefits in practical application, and constantly improve and perfect in application.

Table 1 | Classification criteria of rainfall level and rainfall duration

	Rainfall types/mm	Duration/h
1	Light rain (<10)	0–1
2	Moderate rain (10–24.9)	1–3
3	Heavy rain (25–49.9)	3–5
4	Rainstorm (50–99.9)	5–10
5	Extremely rainstorm (100–199.9)	10–15

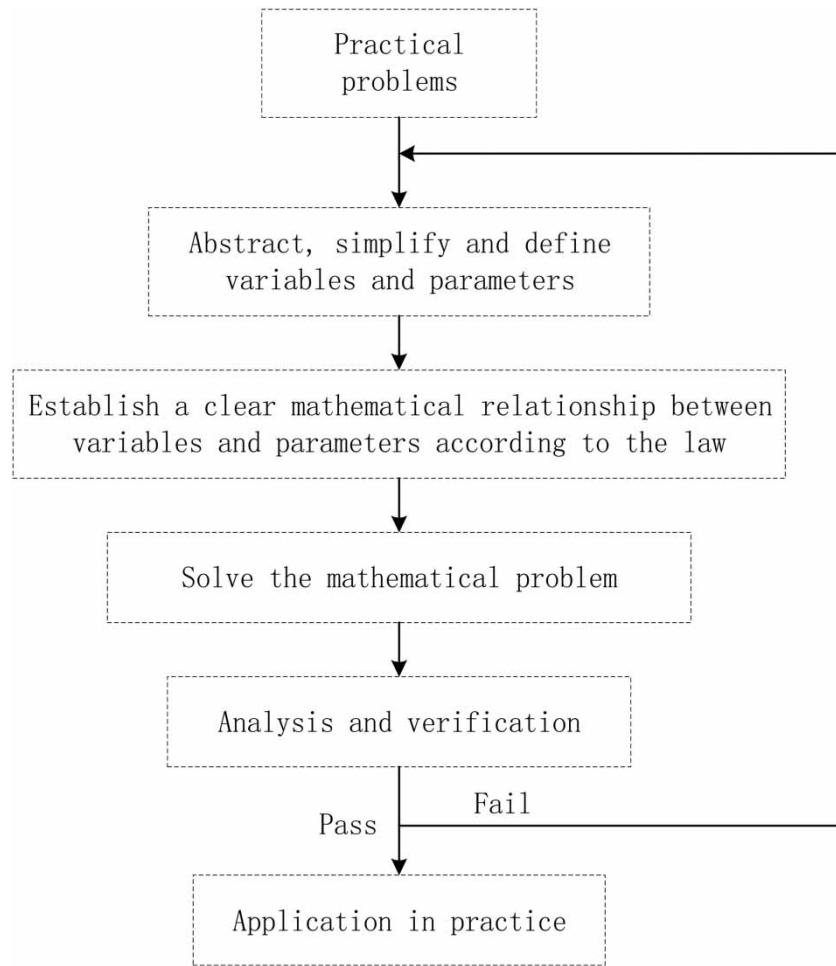


Figure 1 | Mathematical modeling process.

Phreatic evaporation curve fitting

In scientific and engineering problems, several discrete data can usually be obtained by methods such as sampling or experiments. Based on these data, a continuous function (curve) or a more dense discrete equation is obtained that matches the known data. This process is called curve fitting. In this paper, the following steps are used to establish a fitting curve for phreatic evaporation.

Step 1: Obtain the corresponding data of independent variables and dependent variables through observation experiments. Observe phreatic evaporation, water table depth and surface evaporation data on rainy days; observe phreatic evaporation, water table depth, water evaporation, rainfall and rainfall duration on rainy days data.

Step 2: Observe and analyze the distribution of the data points, the specific relationship between the independent variable and the dependent variable and determine the function of the fitted curve.

Step 3: According to the principle of generalized least squares, use known data sets combined with computer software to estimate the parameter values in the curve fitting function.

Step 4: Bring the parameter estimates to the fitting function and establish the calculation model of the final rainy day and no rainy day phreatic evaporation.

Least-squares estimation

When the model is determined based on the relationship between the variables, the method of determining the

parameters in the model according to the principle of minimum squared deviation is called least-squares estimation.

Given a set of data (X, Y) and know the fitting function $\varphi(X)$, which contains parameters $a_k (k = 1, \dots, s)$

$$X = (X_1, X_2, \dots, X_n) = \begin{bmatrix} X_{11} & X_{21} & \dots & X_{n1} \\ X_{12} & X_{22} & \dots & X_{n2} \\ \vdots & \vdots & \dots & \vdots \\ X_{1m} & X_{2m} & \dots & X_{nm} \end{bmatrix} \quad (1)$$

$$Y = (Y_1, Y_2, \dots, Y_m)^T \quad (2)$$

where n is the number of observation variables and m is the number of observation samples. To estimate the parameter values in the model, the sum of the square of deviations between Y and $\varphi(X)$ should be minimized,

$$\sum |\varphi(X) - Y|^2 = L_{\min} \quad (3)$$

According to the necessary conditions of the extremum of the multivariate:

$$\frac{\partial L}{\partial a_k} = 0 (k = 1, \dots, s) \quad (4)$$

Solve equations to get parameter estimates and the parameter estimates are substituted into the model to establish the specific functional formula of the model.

Model evaluation index

This paper uses mean absolute error (MAE), square root error (RMSE), and coefficient of determination (R^2). These statistical indicators evaluate the accuracy of the model; the formulas for each statistical indicator are as follows:

$$MAE = \frac{1}{m} \sum_{i=1}^m |\hat{y}_i - y_i| \quad (5)$$

$$RMSE = \sqrt{\frac{1}{m} \sum_{i=1}^m (\hat{y}_i - y_i)^2} \quad (6)$$

$$R^2 = \frac{SSR}{SST} = 1 - \frac{SSE}{SST} \quad (7)$$

$$SSR = \sum_{i=1}^m (\hat{y}_i - \bar{y})^2 \quad (8)$$

$$SSE = \sum_{i=1}^m (y_i - \hat{y}_i)^2 \quad (9)$$

$$SST = \sum_{i=1}^m (y_i - \bar{y})^2 \quad (10)$$

where \hat{y}_i is the calculated value of the phreatic evaporation, y_i is the measured value of the phreatic evaporation, and \bar{y} is the mean of the measured value of the phreatic evaporation. m is the number of samples, $i = 1, \dots, m$ is the sample number. The more the R^2 metric independent variable interprets the dependent variable, the closer the value is to 1. The higher the degree of interpretation of the dependent variable, the higher the accuracy of the model. The value of MAE, RMSE is more, the smaller the accuracy of the small model.

RESULTS AND DISCUSSION

Model preparation

Relationship between phreatic evaporation and surface evaporation

The evaporation of phreatic water is affected by the atmospheric evaporation capacity, including meteorological elements, such as surface temperature, average temperature, water surface evaporation, incident radiation (sunshine), relative humidity, wind speed, and rainfall. Relevant research (Yu et al. 2011) shows that evaporation can be used instead of atmospheric evaporation ability to study the evaporation of phreatic water. In order to avoid the impact of crops on phreatic evaporation, bare land conditions were tested to establish the relationship between phreatic evaporation and surface evaporation. Figure 2 shows the relationship between the average phreatic evaporation and the average surface evaporation of Shajiang black soil and yellow tidal soil under different groundwater depth (H) conditions from 1993 to 2015.

It can be seen from Figure 2 that for both soils under the same conditions (i.e. groundwater depth), the

evaporation of the phreatic water and the evaporation of the surface water have a power function relationship, functional relationship is significant, that is, the evaporation of the phreatic water increases with surface water evaporation. When increased to a certain extent, the evaporation of the diving is, generally, constrained to a certain limit. The reason for this phenomenon is that the evaporation of the phreatic water is affected by both the atmospheric evaporation capacity and the soil water transport capacity. When the atmospheric evaporation capacity is less than the soil water capacity, phreatic evaporation is mainly limited by meteorological elements and the surface water evaporation increases. When the atmospheric evaporation capacity is greater than the soil water transport capacity, phreatic evaporation is mainly limited by the soil water transport capacity, slowly increasing and trending around the maximum limit (Yu et al. 2011). Therefore, when the surface evaporation level is high, the correlation between phreatic evaporation and surface evaporation weakens, which is manifested by the large degree of dispersion of observation point near the fitted curve, and the fitting is worse.

It can also be seen from Figure 2 that the influence of surface water evaporation on yellow Fluyo-aquic soil is greater than that of Shajiang black soil, which is determined by the texture of the two soil types. Texture is the main factor affecting soil water conductivity and soil water movement parameters. The surface evaporation coefficient decreased with the increase of soil physical clay content; the clay content of Shajiang black soil accounted for 13.1%, powder (49.4%), sand (37.5%). In yellow Fluyo-aquic soil, clay content

accounted for 2.0%, powder (11.5%), and sand (37.5%). The sandy black soil is more viscous than the yellow Fluyo-aquic soil which is less porous and not conducive to water migration – i.e. it has poor water permeability.

Relationship between evaporation and groundwater depth

Figure 3 shows the relationship between the average phreatic evaporation and depth of Shajiang black soil and yellow Fluyo-aquic soil under different water surface evaporation (E_0) conditions from 1993 to 2015. It can be seen from Figure 3 that evaporation is exponentially related to the depth of the two soils. As depth increases, evaporation gradually decreases. Larger levels of evaporation at the surface lead to more severe phreatic evaporation that decreases with depth. As depth increases, phreatic evaporation increases with the evaporation of the water surface, but the increase in phreatic evaporation is reduced by the function of the exponential curve. The effect of atmospheric evaporation capacity on phreatic evaporation decreases with the increase in the buried depth. In shallower depths, the groundwater rises directly through capillaries to the surface and enters the atmosphere. The evaporation is rapid and large. As depth increases, evaporation of the upper soil continuously loses water and expands downward. Slowly hydrating, the water transport distance is increased. The influence of atmospheric evaporation and the ability of the unsaturated zone to transport water by capillary action are weakened; when depth is increased to a certain extent, the groundwater stops evaporating (Zhu et al. 2002).

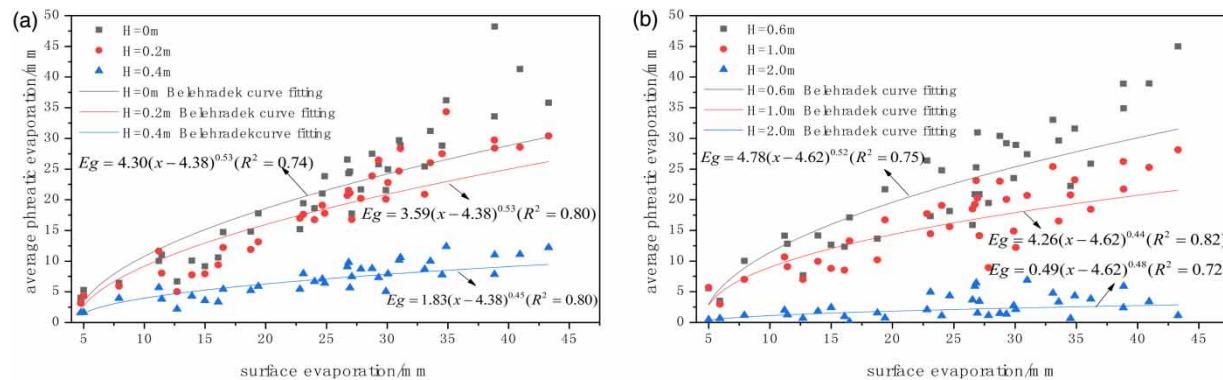


Figure 2 | Relationship between phreatic evaporation and surface evaporation from (a) Shajiang black soil, (b) Yellow Fluyo-aquic soil.

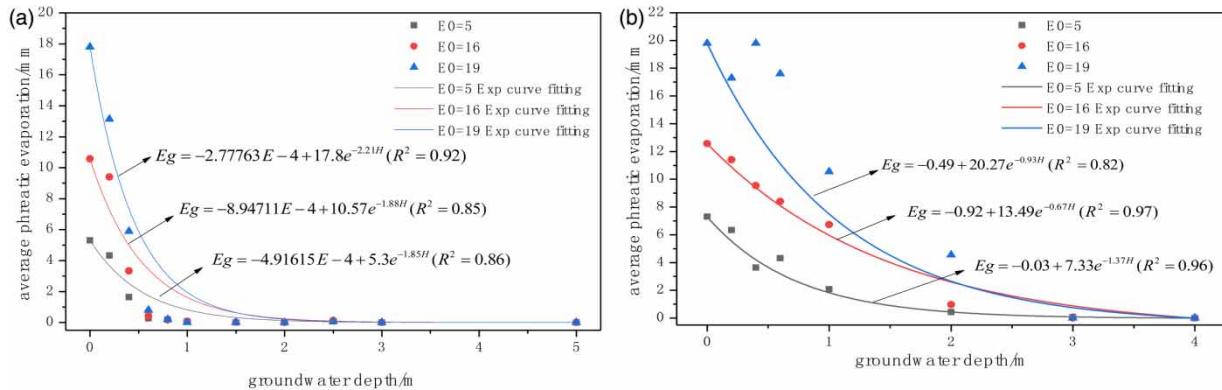


Figure 3 | Relationship between the phreatic evaporation and groundwater depth from (a) Shajiang black soil, (b) Yellow Fluyo-aquic soil.

It can also be seen that under different surface evaporation conditions, phreatic evaporation of Shajiang black soil tends to stop (~0%) at 2 m; that is, the phreatic evaporation limit depth of Shajiang black soil in this area is about 2 m. Marazuela *et al.* (2018) obtained similar values in the Salar de Atacama, the damping capacity ends up when the water table is depleted below 0.5–2 m deep. The phreatic evaporation limit depth of yellow Fluyo-aquic soil is much larger (~150–200%) than Shajiang black soil – up to 3–4 m. The difference is determined by the properties and texture of the soil (i.e. yellow Fluyo-aquic soil is much more porous).

Relationship between evaporation coefficient, surface evaporation, and groundwater depth

The phreatic evaporation coefficient is the ratio of phreatic evaporation to surface evaporation in the same period.

The depth of the groundwater determines water transport distance when the phreatic water evaporates. As depth increases, the water transport distance increases, the influence of atmospheric evaporation decreases, and the ability of the unsaturated zone to transport water by capillary action is weakened. According to the data from 1993 to 2015, the phreatic evaporation coefficient of different evaporation conditions in Shajiang black soil and yellow fluyo-aquic soil was calculated. The relationship with groundwater depth was analyzed. See (Figure 4(a)) Shajiang black soil and (Figure 4(b)) Yellow fluyo-aquic soil.

Figure 4 shows that as depth increases, the phreatic evaporation coefficient of the two soils gradually decreases. The relationship between the phreatic evaporation coefficient and depth changes with surface water evaporation has no relationship to depth. It can be seen from Figure 4(a) that under the same depth of Shajiang black soil, the smaller the surface evaporation, the larger the evaporation

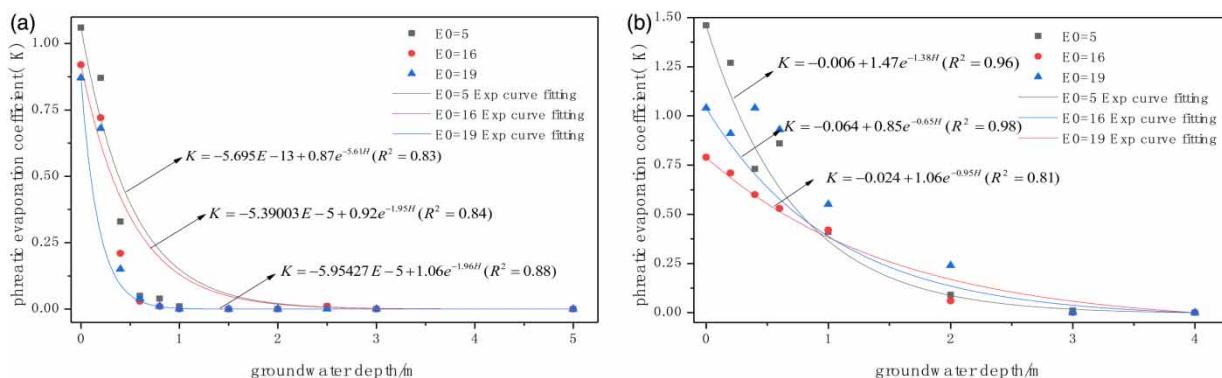


Figure 4 | Relationship between evaporation coefficient, surface evaporation, and depth in (a) Shajiang black soil, (b) Yellow Fluyo-aquic soil.

coefficient of phreatic water. 0 m (b) Yellow fluvo-aquic soil shows the evaporation coefficient of each water surface is close to 1, that is, when depth is 0 m, phreatic evaporation is approximately equal to the evaporation at the surface. It can be seen from Figure 4(b) that when the depth is more than 1 m, the evaporation coefficient of the yellow fluvo-aquic soil is greatly affected by surface evaporation and increases with surface evaporation. Below the buried depth of 1 m, the evaporation coefficient of the evaporation level is similar. Therefore, the same variation characteristics of the two soil types are that the evaporation coefficient of phreatic water decreases with an increase in groundwater depth; the different characteristics are that the two soil types have different slopes in their reductions of the evaporation rate in the shallow buried depth (0–1 m); that is, the ultimate depth is different.

Model establishment

Quantitative model of phreatic evaporation under rainless conditions

The existing empirical formulas for phreatic evaporation are as follows:

The Averyanov's equation (Parabolic Formula) (Aweliyongrufe 1985):

$$Eg = E_0(1 - H/H_{\max})^n \quad (11)$$

The Ye Shui-ting's equation (Exponential Formula) (Ye et al. 1980):

$$Eg = E_0 e^{-\alpha H} \quad (12)$$

The Zhang Chaoxing's equation (Jin & Zhang 1988):

$$Eg = E_0 a/(H + N)^b \quad (13)$$

The Shen Li-chang's equation (Shen 1985):

$$Eg = k u E_0^a / (H + 1)^b \quad (14)$$

The Tsinghua equation (Lei et al. 1988):

$$Eg = E_{\max} (1 - e^{-n E_0 / E_{\max}}) \quad (15)$$

Some researchers believe (Zhang et al. 2009) that an 'extinction depth' or 'cutoff depth' for phreatic evaporation – beyond which phreatic water evaporation ceases – does not actually exist in theory. No matter how deep the phreatic water buried depth is, as long as there is a water potential gradient between any point in the unsaturated zone and the phreatic surface, there will be a transformation from the phreatic zone to the upper unsaturated zone. Other studies (Tang et al. 1989) show that when the buried depth of the phreatic water table (the depth to water table) is zero, the phreatic evaporation coefficient should not be related to water surface evaporation or soil textures, approaching a stable level around one. In addition, the study of phreatic evaporation law above shows that the relationship between the phreatic evaporation coefficient and burial depth is not a single linear relationship but closely related to evaporation capacity. Therefore, a more efficient and practical method to calculate phreatic evaporation is needed. In this paper, a new calculation model for phreatic evaporation under rainless conditions based on the Ye-Shuiting's exponential formula has been introduced and improved.

According to the relationship between the phreatic evaporation coefficient and water surface evaporation discussed above, it can be seen that phreatic evaporation coefficient is not only related to buried depth but also affected by various underlying surfaces. Accordingly, this paper improves the Ye-Shuiting's exponential formula and establishes a new calculation model for phreatic evaporation under rainless conditions, as shown below:

$$Eg = E_0^\lambda e^{-\alpha H} \quad (16)$$

where Eg denotes phreatic evaporation intensity (mm/d); E_0 is the phreatic evaporation intensity (mm/d) when the depth of the water table is zero (a value which generally approximates surface water evaporation); H is the depth of the water table (i.e. phreatic surface depth or depth of phreatic groundwater, m) measured from the surface to the water table; λ and α represent empirical constants.

Calculation model of daily phreatic evaporation under rainy conditions

The phreatic water evaporation is mainly influenced by the atmospheric evaporation intensity, the buried depth of phreatic groundwater and soil texture. Water surface evaporation is the concentrated embodiment of atmospheric evaporation which is affected by some meteorological conditions including solar radiation, temperature, humidity, wind speed, air pressure, etc.

On rainy days, when there is no rainfall, the solar radiation and air temperature decrease and the humidity increases, which results in the decrease in water surface evaporation (i.e. atmospheric evaporation intensity). While during the rainfall period, not only the atmospheric evaporation intensity is reduced, but also the capillary action is weakened due to the supplement of soil water by precipitation (Lei et al. 1988), so the phreatic evaporation is reduced more obviously during the rainfall period. Above all, we can find the degree of reduction of the phreatic evaporation under rainfall conditions of phreatic evaporation is mainly affected by the atmospheric evaporation intensity, the buried depth of phreatic groundwater, rainfall, and rainfall duration. Accordingly, the following calculation model of phreatic evaporation under rainfall conditions can be established.

$$Eg = E_0^2 e^{-aH} + f(H, P, t) \quad (17)$$

where $f(H, P, t)$ represents the decrease of phreatic evaporation caused by precipitation, H is the depth to water table or depth of phreatic surface; P represents the rainfall, t represents the rainfall duration. The other parameters have the same meaning as those mentioned before.

The model for phreatic evaporation under rainfall conditions is deduced as follows. Firstly, using the calculation model of phreatic evaporation under rainless conditions to calculate the estimated value of phreatic evaporation under rainfall conditions, and then calculating the difference between the estimated value and the measured value of phreatic evaporation under rainfall conditions. After that, the reduction of phreatic evaporation under rainfall conditions relative to that in rainless is obtained. Secondly,

analyzing the relationship between the reduction of phreatic evaporation and the buried depth of phreatic groundwater, rainfall, and rainfall duration, then establishing corresponding models, that is, $f(H, P, t)$. Finally, combining the quantitative model for phreatic evaporation under rainless conditions and the quantitative model for phreatic evaporation reduction, the integrated quantitative models for phreatic evaporation under rainfall conditions are established.

According to the established calculation formulas of phreatic evaporation under rainless conditions, namely formulas (16), we can calculate the estimated values of phreatic evaporation under rainfall conditions in lime concretion black soil and fluvo-aquic soil separately from 1993 to 2015 and obtain the reduction of phreatic evaporation by calculating the difference between the estimated values and its corresponding measured values. The relationship between the reduction of phreatic evaporation and the buried depth of phreatic groundwater, rainfall level, and rainfall duration in lime concretion black soil is analyzed separately and corresponding results are shown in Figures 5–7. Also, the relationship between the reduction of phreatic evaporation and the buried depth of phreatic groundwater, rainfall level, and rainfall duration in fluvo-aquic soil is analyzed separately and corresponding results are shown in Figures 8–10.

From Figure 5, it can be seen that the reduction of phreatic evaporation in lime concretion black soil increases with depth and the trend slows down until it approaches zero. We can also find that the reduction of phreatic evaporation is basically zero when the depth is 0.8 m.

Figure 6 shows the reduction of phreatic evaporation in lime concretion black soil declines when rainfall increases. When the phreatic water table is shallow, the reduction of phreatic evaporation decreases linearly with increasing rainfall levels. The shallower the buried depth, the more obvious the decreasing trend. When the buried depth reaches a certain deeper depth, the reduction of phreatic evaporation is not affected by rainfall level any more. The explanations for these phenomena above are as follows; it is because when the buried depth of the phreatic water table is shallow, rainfall can directly inhibit phreatic evaporation. With increasing depths, water in the phreatic zone still migrates to the upper soil pores in unsaturated zones

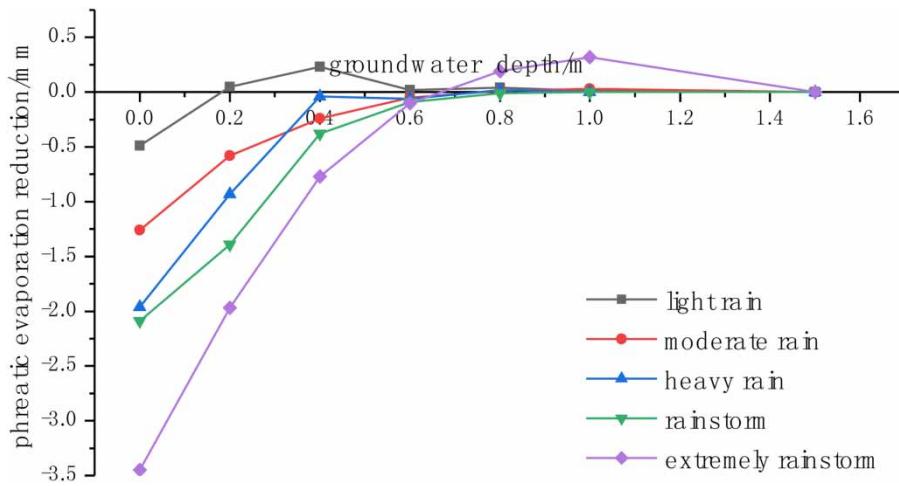


Figure 5 | Relationship between phreatic evaporation reduction and (phreatic) water table depth in black soil.

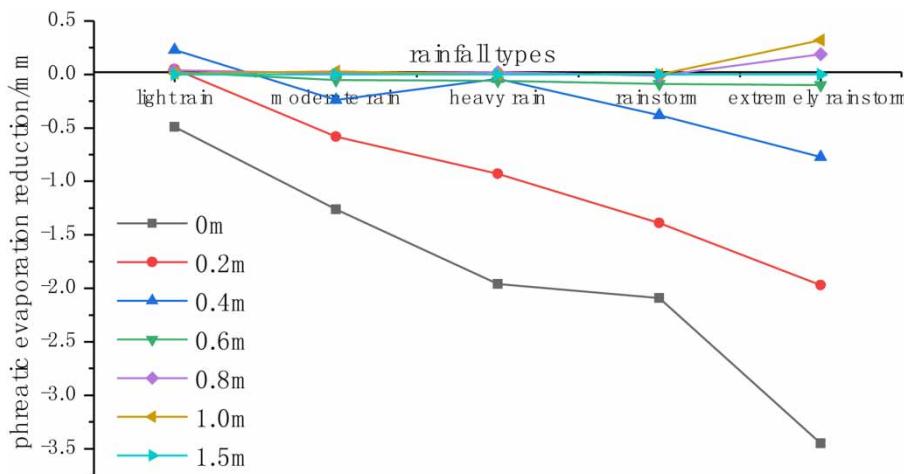


Figure 6 | Relationship between phreatic evaporation reduction and rainfall in black soil.

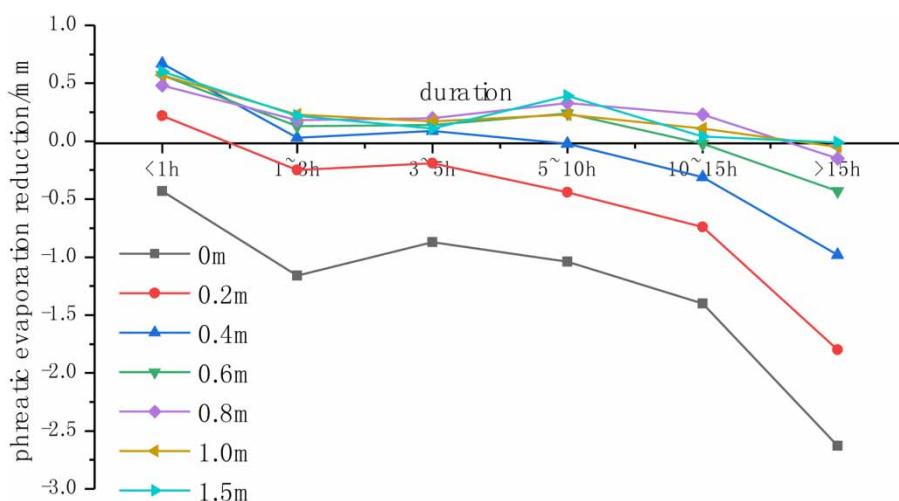


Figure 7 | Relationship between phreatic evaporation reduction and rainfall duration in black soil.

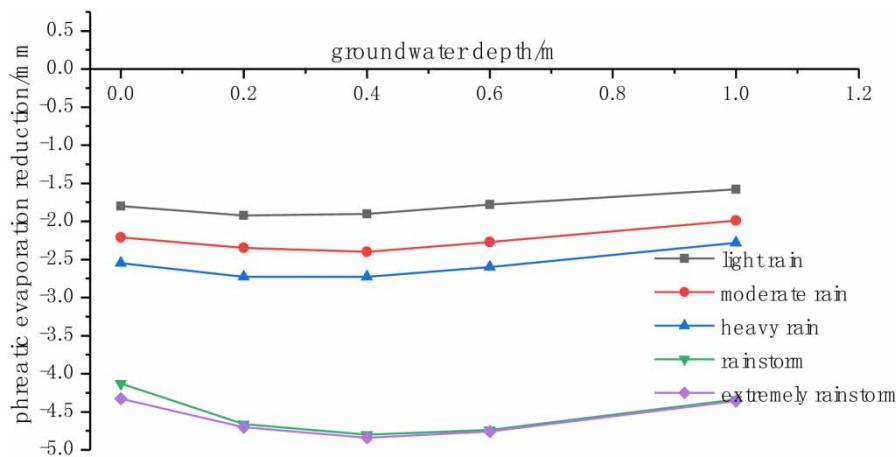


Figure 8 | Relationship between phreatic evaporation reduction and (phreatic) water table depth in fluvo-aquic soil.

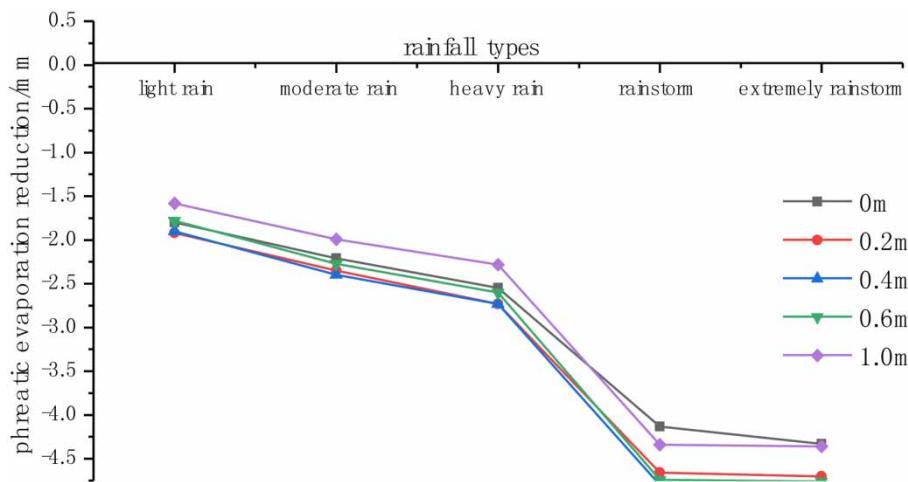


Figure 9 | Relationship between phreatic evaporation reduction and rainfall in fluvo-aquic soil.

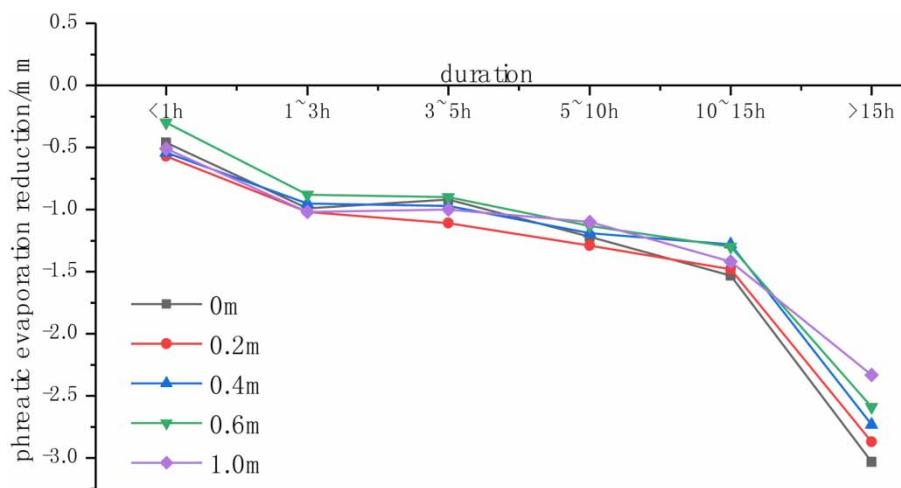


Figure 10 | Relationship between phreatic evaporation reduction and rainfall duration in fluvo-aquic soil.

by capillary action before the rainfall infiltrates into that layer. There is little difference between the phreatic evaporation under rainfall condition or not; that is, rainfall is less inhibiting to phreatic evaporation.

As is shown in Figure 7, the decrease in phreatic evaporation in lime concretion black soil decreases progressively with the increasing rainfall duration in an inverted S-shaped manner. This is because the longer the rainfall lasts, the greater the amount of rainfall infiltrates into the vadose zone and the greater the inhibition effect on phreatic evaporation.

Figure 8 demonstrates that the reduction of the phreatic evaporation in fluvo-aquic soil decreases first and then increases with depth, reaching a minimum when depth is at 0.4 m. We can find that the law of phreatic evaporation varies with the buried depth in fluvo-aquic soil and is not consistent with that in lime concretion black soil. That is because they have different infiltration rates due to their unique soil textures. In comparison with the lime concretion black soil, there exists coarser soil particles and larger soil porosity in the shallow layer of fluvo-aquic soil where rainfall can infiltrate into the vadose zone more quickly at first. But, with increasing depth, soil pores become smaller and rainfall infiltration slows down. At last, the water accumulates at 0.4 m depth, which minimizes phreatic evaporation.

From Figures 9 and 10, we can find that the law of phreatic evaporation varies with the rainfall level and rainfall duration; still, the trends are consistent in both types of soil.

According to the above analysis, the quantitative models (as shown below) establish the amount by which phreatic evaporation reduction varies with the buried depth of phreatic groundwater, rainfall, and rainfall duration in lime concretion black soil and fluvo-aquic soil, respectively.

For lime concretion black soil:

$$f(H, P, t) = \frac{1}{(H+1)^n} \cdot \frac{aP^b}{c - de^{-\lambda t}} \quad (18)$$

For fluvo-aquic soil:

$$f(H, P, t) = \frac{1}{m(H-l)^2 + k} \cdot \frac{aP^b}{c - de^{-\lambda t}} \quad (19)$$

where $f(H, P, t)$ represents the decrease in phreatic evaporation caused by precipitation, H is the depth of water table

or depth of phreatic surface; P represents the rainfall, t represents the rainfall duration and $a, b, c, d, m, l, n, \lambda$ are empirical constants.

Model solution

According to the daily data on phreatic evaporation under rainless conditions and water surface evaporation in lime concretion black soil and Fluvo-aquic soil from 1993 to 2015, the specific expression of phreatic evaporation under rainless conditions for two typical soils each is as follows. For lime concretion black soil:

$$Eg = E_0^{1.02} e^{-2.69H} \quad (20)$$

For fluvo-aquic soil:

$$Eg = E_0^{1.09} e^{-0.29H} \quad (21)$$

Based on the data of phreatic evaporation reduction, buried depth of phreatic groundwater, rainfall, and rainfall duration from 1993 to 2015, two specific expressions of phreatic evaporation reduction in two kinds of soils are obtained by fitting formulas (18) and (19) with MATLAB, as shown below.

For lime concretion black soil:

$$f(H, P, t) = \frac{1}{(H+1)^{4.93}} \cdot \frac{-0.48P^{0.32}}{0.4 - 1.49e^{-0.04t}} \quad (22)$$

For fluvo-aquic soil:

$$f(H, P, t) = \frac{1}{7.47(H-0.44)^2 + 18.24} \cdot \frac{-3.4P^{0.29}}{0.3 - 2.98e^{-0.06t}} \quad (23)$$

Model verification

Model fitting index

The fitting results of the quantitative model of phreatic evaporation under rainless and rainy conditions are shown in Table 2.

Table 2 | Evaluation results of the model

Situation	Soil type	MAE	RMSE	R ²
Rainless	Lime concretion black soil	0.52	0.51	0.81
	Fluoyo-aquic soil	0.42	0.37	0.89
Rainy	Lime concretion black soil	0.23	0.37	0.82
	Fluoyo-aquic soil	0.27	0.51	0.85

According to the results, the methods discussed above show better fitting results. Combining the quantitative model of phreatic evaporation under rainless conditions and the quantitative model of phreatic evaporation reduction, the integrated quantitative models of phreatic evaporation under rainfall conditions for two kinds of soils (lime concretion black soil and fluvo-aquic soil) are finally established, as shown below.

For lime concretion black soil:

$$Eg = E_0^{1.02} e^{-2.69H} + \frac{1}{(H+1)^{4.93}} \cdot \frac{-0.48P^{0.32}}{0.4 - 1.49e^{-0.04t}} \quad (24)$$

For fluvo-aquic soil:

$$Eg = E_0^{1.09} e^{-0.29H} + \frac{-3.4P^{0.29}}{0.3 - 2.98e^{-0.06t}} \cdot \frac{1}{7.47(H-0.44)^2 + 18.24} \quad (25)$$

Model prediction index

The measured data from 2018 was used to test the predictive effect of the quantitative model of phreatic evaporation under rainfall conditions in lime concretion black soil and fluvo-aquic soil. When the buried depth of the phreatic water table is shallow, phreatic evaporation is more obvious. Therefore, we took the buried depth of 0 m and 0.2 m as an example to compare the predicted and actually measured values of phreatic evaporation under rainfall conditions in lime concretion black soil and fluvo-aquic soil. The comparison results are shown in Figures 11 and 12. From the figure, we can see that there is not much difference between the estimated value and the measured value except for some abnormal points. Evaluation results of phreatic evaporation at different depths in lime concretion black soil and Fluoyo-aquic soil are illustrated in Table 3. This demonstrates that the predictive abilities and results of the modified quantitative model of phreatic evaporation at different depths in two kinds of soils are better.

To sum up, the following formulas can be used to calculate phreatic evaporation on the Huaibei Plain in China. Applications in other areas may require significant alterations of the calculations. Very similar soil types may find this modified quantitative model useful for approximations.

Quantitative model of phreatic evaporation under rainless conditions in lime concretion black soil:

$$Eg = E_0^{1.02} e^{-2.69H} \quad (26)$$

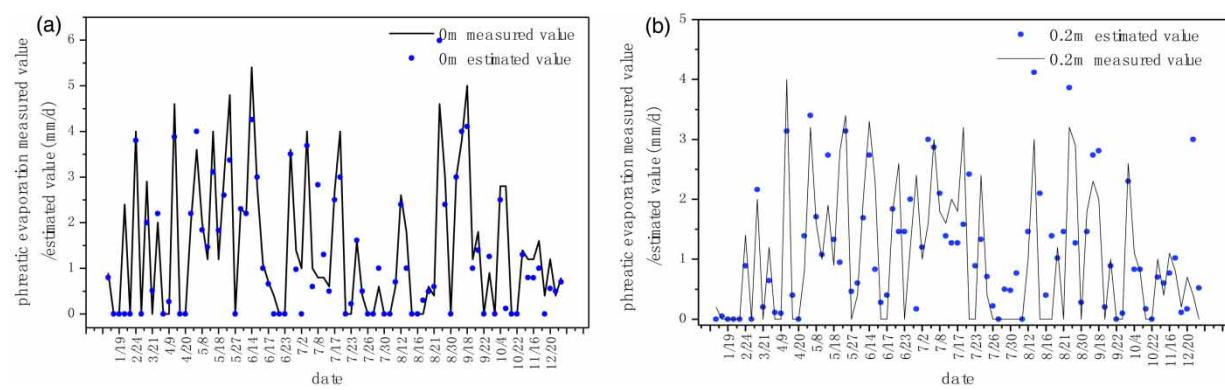


Figure 11 | Comparison of the predicted and measured values of phreatic evaporation under rainfall conditions in lime concretion black soil from (a) depth = 0 m (b) depth = 0.2 m.

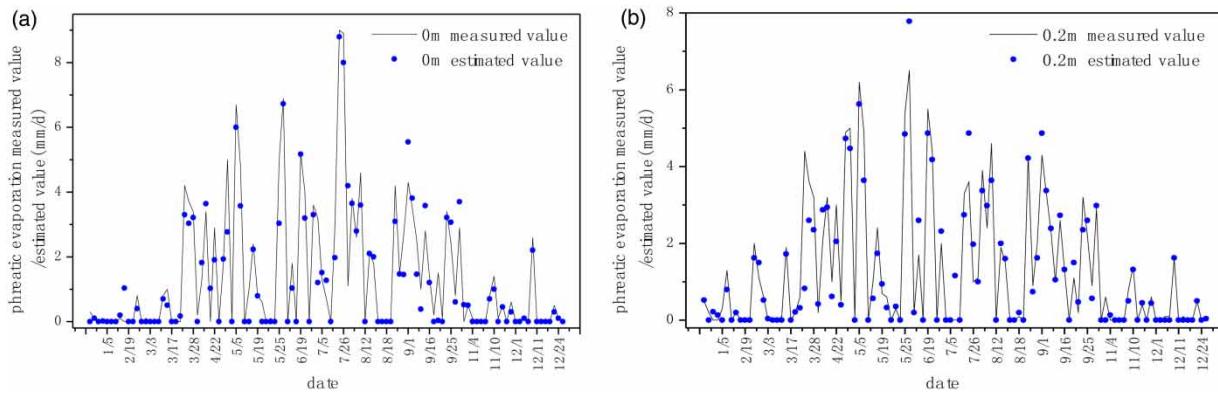


Figure 12 | Comparison of the predicted and measured values of phreatic evaporation under rainfall conditions in Fluyo-aquic soil from (a) depth = 0 m (b) depth = 0.2 m.

Table 3 | Evaluation results of the model

Soil type	Lime concretion black soil		Fluyo-aquic soil	
	0 m	0.2 m	0 m	0.2 m
MAE	0.36	0.55	0.36	0.28
RMSE	0.63	0.82	0.65	0.53
R ²	0.89	0.82	0.86	0.81

Mathematical model of phreatic evaporation under rainfall condition in lime concretion black soil:

$$Eg = E_0^{1.02} e^{-2.69H} + \frac{1}{(H+1)^{4.93}} \cdot \frac{-0.48P^{0.52}}{0.4 - 1.49e^{-0.04t}} \quad (27)$$

Model of phreatic evaporation under rainless condition in Fluyo-aquic soil:

$$Eg = E_0^{1.09} e^{-0.29H} \quad (28)$$

Governing equations of phreatic evaporation under rainless condition in Fluyo-aquic soil:

$$Eg = E_0^{1.09} e^{-0.29H} + \frac{-3.4P^{0.29}}{0.3 - 2.98e^{-0.06t}} \cdot \frac{1}{7.47(H - 0.44)^2 + 18.24} \quad (29)$$

where Eg denotes phreatic evaporation intensity (mm/d); E_0 is the phreatic evaporation intensity (mm/d) when the water table depth is zero (a value which generally approximates

surface water evaporation); H is the water table depth (i.e. phreatic surface depth or buried depth of phreatic groundwater) (m); P represents rainfall (mm), t represents rainfall duration (h).

CONCLUSIONS

This paper analyzed the law and mechanisms of phreatic evaporation and the trends involving the depth of the phreatic water table and surface water evaporation. In order to reveal the laws, mechanisms, and equations governing phreatic evaporation, we probed questions on how the depth of the phreatic surface and surface water evaporation influenced the magnitude of phreatic evaporation and its coefficient.

At the same buried depth, phreatic evaporation increased with an increase in surface water evaporation. When the surface water evaporation increased to a certain extent, phreatic evaporation tended to a certain limit value accordingly. Under the same surface water evaporation conditions, phreatic evaporation decreased gradually with increasing depth. The greater the water surface evaporation, the more intense the trend of phreatic evaporation decreases with depth. The coefficient of phreatic evaporation had no relationship with depth. The phreatic evaporation coefficient varied with the depth of the phreatic water table and was influenced by different surface water evaporation levels.

The existing empirical formula of phreatic evaporation was improved and the exponential calculation models of phreatic evaporation under rainless condition for lime concretion black soil and Fluyo-aquic soil were established.

Based on the model, we could calculate the estimated value of phreatic evaporation under rainfall conditions and then calculate the difference between the estimated value and the measured value. After that, the reduction of phreatic evaporation under rainfall conditions relative to that in rainless days was obtained.

The relationship between the decrease in phreatic evaporation and the buried depth of phreatic groundwater, rainfall, and rainfall duration was identified. The reduction of phreatic evaporation in lime concretion black soil increased with depth, and the increasing trend slowed down until it approached zero. The reduction of the phreatic evaporation in Fluyo-aquic soil decreased first and then increased with depth – reaching the minimum value at a depth of 0.4 m. Phreatic evaporation decreased in two different soil textures with increasing levels of rainfall and decreased with an increase in rainfall duration in an inverted S-shaped manner.

Based on the relationship between phreatic evaporation reduction and the depth of phreatic groundwater, rainfall, and rainfall level, the models of phreatic evaporation for lime concretion black soil and Fluyo-aquic soil were established. Combining the model of phreatic evaporation under rainless conditions and the model of phreatic evaporation reduction, the integrated models of phreatic evaporation under rainfall conditions for two different soil textures were established. As a result of model fitting and modification, the model presented can improve the calculation accuracy of phreatic evaporation and future predictions.

Based on the measured data collected by the lysimeter, models of phreatic evaporation under rainfall and rainless conditions were proposed in this paper. These improved functions can be used to calculate phreatic evaporation with a higher degree of accuracy under the conditions accounted for in this paper. It is of great significance to further study and refine the models of phreatic evaporation – especially, as it relates to agriculture in farmlands and crop fields in both rainy and rainless periods.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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