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A Calculation Method of Soil Water Resources Based on SCS-CN Model

Xiao Meng

Department of Hydraulic Engineering, Agricultural University of Hebei, Baoding 071000, Hebei, China

Xianbing Wu

Department of Hydraulic Engineering, Agricultural University of Hebei, Baoding 071000, Hebei, China

Abstract

Soil water resources are the most important water resources for agricultural production and ecological environment. However, currently, there has been yet no consensus on the concept and calculation method of soil water resources. According to water balance theory and recharge of soil water resources, this paper firstly defined soil water resources in terms of agriculture and then proposed a calculation method of soil water resources based on soil conservation service curve number model (SCS-CN model). Besides, the annual dynamic variation of soil water resources in hydrological years with different frequency and the soil water resources of main crops in their growth periods were calculated by taking the example of Baoding Plain, Hebei, China. Studying the variation of soil water storage in years with different frequency is of vital significance for addressing annual regulation of soil water. Additionally, defining soil water resources of crop in growth period can effectively guide irrigation, save irrigation water, and scientifically, rationally balance water demand and supply of crop in growth period. Confronting the increasing shortage of water resources, scientifically, reasonably evaluating soil water resources in a region and efficiently utilizing these

resources can effectively reduce irrigation resources from surface water and groundwater and make full use of soil water resources for agricultural production. This research is of vital significance for promoting the sustainable development of water-saving agriculture, effectively mitigating the crisis of water resources and improving ecological environment.
Key words: SOIL WATER, SOIL WATER RESOURCES, SCS-CN MODEL, WATER-SAVING AGRICULTURE

Introduction

Soil water resources serve as the most important water resources for agricultural production and ecological environment. Since the early 19th century, people have realized the importance of soil water. Afterwards, owing to further studies and soil water which exists as a resource in nature , many scholars have recognized the resource attribute of soil water and included soil water in total regional water resources [1, 2]. This idea has replaced the traditional idea that total regional water resources only consisted of surface water and groundwater.

The concept of soil water resources was discussed by many scholars in previous researches at home and abroad. For instance, M.E. Lvovich, a geographer and hydrographer in Former Soviet, firstly put forth the concept of soil water resources and defined total soil humidity as soil water resources [3]. In China, scholars had different understanding about soil water resources. For example, Feng discussed that soil water resources referred to the water in soil layer which frequently participated in water cycle in soil, especially water in root layer that could be used by plant and the water amount could restore. Liu also analyzed the concept of soil water resources and defined effective precipitation as soil water resources. Xia held that soil water resources denoted the annual average total evaporation capacity of land surface of different years in a region [4]. Others argued that the total water content of soil in a region was soil water resources [5]. However, a clear and specific definition for the concept of soil water resources has not yet been reported.

Under the condition of the growing shortage of water resources, scientifically, rationally evaluating soil water resources in a region and efficiently utilizing these resources can effectively reduce irrigation resources from surface water and groundwater and make full use of soil water resources for agricultural production. Currently, scholars have put forth varied calculation methods of soil water resources from various perspectives. However, a unified calculation method has not been reported yet. On the basis of water balance theory and recharge of soil water resources, this research firstly defined soil water resources from the view of agriculture and then put forward the SCS-CN model-based calculation method of soil water resources. This paper aims to clarify soil water resources in a region so as to provide a guidance for fully using the resources in agricultural production and for the sustainable development of water-saving agriculture.

The concept of soil water resources

Soil water refers to the water containing in the pore of unsaturated zone in soil, is stored and migrated in the zone which ranges from surface to the position above water table in water cycle process in nature. The occurrence modes of soil water consisted of gaseous water, adsorbed water, capillary water and gravity water [6]. The former two, as unavailable water, were unavailable to crops. While gravity water, as surplus water, was easily discharged from root layer. Capillary water, as effective water which was intermediate, could be readily absorbed and utilized by crops. This part of effective water was regarded as the water between wilting coefficient and field water capacity [7].

The water in shallow soil pore in root layer which could be absorbed, used by crops and restored was called farmland water resources. It included the recharge from artificial irrigation and nature, among which, the water from natural recharge was soil water resources. Therefore, in this research, soil water resources were defined as the water in shallow soil pore which was stored in crop root layer and could be absorbed and employed by crops and restored in the case of natural recharge.

Only in terms of agriculture, soil water from precipitation was resources. Given that crop root layer usually ranged from surface to 2 m underground, this range was taken as the range of evaluation layer for evaluating soil water resources.

A calculation method of soil water resources based on SCS-CN model

Model construction

The calculation of soil water resources included calculating the soil water resources in different periods and the daily variation of soil water storage in evaluation layer.

The recharge of soil water resources derived from precipitation. Concerning a precipitation, the recharge of soil water resources in evaluation layer was obtained by removing unavailable precipitation loss, surface runoff, and the recharge of the soil under evaluation layer and groundwater from a precipitation. The equation is established as follows:

$$w_s = P - P_w - R_s - R_g \qquad (1)$$

Where w_s (mm) denotes the recharge of soil water resources from a precipitation;

P (mm) is a precipitation;

P_w (mm) refers to unavailable precipitation from the precipitation;

R_s (mm) is surface runoff from the precipitation;

R_g (mm) denotes the recharge of the soil under crop root layer and groundwater.

The total recharge of soil water resources in diffe- rent periods (W_s) was calculated by removing the total unavailable precipitation, the total surface runoff, and the total recharge of the soil under evaluation layer and groundwater from the total precipitation in each period. The equation is expressed as:

$$W_S = \sum P - \sum P_w - \sum R_s - \sum R_g \qquad (2)$$

Due to evaporation, soil water storage was continuously consumed. If a precipitation occurred on a calculation day, soil water storage was recharged. By relying on the variation of soil water storage with time, to simplify the calculation, day was selected as calculation interval to analyze the variation of the soil water storage in evaluation layer. The formula is

$$W_{N+1} = K(W_N + P_y) \qquad (3)$$

Where W_N (mm) is the soil water storage in evaluation layer on the n_(th) day;

W_{N+1} (mm) refers to the soil water storage in evaluation layer on the n+1_(th) day;

K denotes the coefficient by considering evaporation loss;

P_y (mm) is effective precipitation on the n_(th) day, and $P_y = P - P_w - R_s - R_g$.

After knowing W_N, P_y and K, the daily variation of the soil water storage in evaluation layer was acquired based on Equation (3). In the case that the value of W_{N+1} was greater than the maximum water holding capacity of evaluation layer soil W_m, $W_{N+1} = W_m$. At this time, effective precipitation continued to recharge the soil under evaluation layer and groundwater. The recharge of the soil under evaluation layer and groundwater from precipitation on the n_(th) day R_g is calculated based on the storage model as follows:

$$R_g = K(W_N + P_y) - W_m \qquad (4)$$

The daily dynamic variation of the soil water storage in evaluation layer in the region was determined by calculating the value on each day.

Parameter determination

Surface runoff R_s

The surface runoff of a precipitation was calculated based on SCS-CN model. The model, put forward by Soil Conservation Service of USDA, was a runoff curve number method applicable to mall and medium-sized basins. It was extensively applied to determine the precipitation-runoff relationship when the data of precipitation process were inaccessible. Total surface runoff was determined according to factors of soil and precipitation. Among them, soil factors were primarily obtained through 3 factors: soil infiltration characteristics, initial water content in soil and land use patterns. Based on this model, there were few data requirements-the data of precipitation process were unnecessary but the total precipitation. Therefore, it had the advantages of few parameters, simple calculation, high accuracy and readily available data [8]. The calculation of R_s by using SCS model had the following demands: single land use pattern and farming measure, homogeneous soil, and even precipitation. The model is constructed as follows:

$$R_s = \begin{cases} (P - I_a)^2 / P + S - I_a & P \ge I_a \\ 0 & P < I_a \end{cases} \qquad (5)$$

Where I_a (mm) is initial loss;

S (mm) denotes possible maximum retention, which is the upper limit of later loss.

Owning to it was difficult to calculate I_a, to simplify the calculation, a variable was removed and an empirical correlation was introduced [9].

$$I_a = mS \quad 0.10<m<0.25 \qquad (6)$$

Where m is empirical coefficient and usually m =0.2 in real application.

By substituting Equation (6) into Equation (5), we obtain

$$R_s = \begin{cases} (P - 0.2S)^2 / P + 0.8S & P \ge 0.2S \\ 0 & P < 0.2S \end{cases} \qquad (7)$$

Given that S had a wide range, a dimensionless parameter CN was introduced to calculate the value of S.

$$S = \frac{25400}{CN} - 254 \qquad (8)$$

Where CN is runoff curve number.

Runoff curve number, as a dimensionless number, reflected the influence of underlying surface of the basin on runoff yield of precipitation while it did not demonstrate the effects of precipitation density on runoff yield. A detailed table of *CN* value was listed in section 4 of Engineer Handbook of USA [10].

Unavailable precipitation P_w

Unavailable precipitation was primarily composed of plant interception, sink filling capacity, and evaporation in rainy period. It was unavailable water from precipitation and could not infiltrate or recharge soil water resources. Given that the three types of water were associated with multiple factors, it was difficult to determine their values when there was a precipitation in the region. Therefore, in the calculation, by assuming that the unavailable precipitation could be evaporated on one day, it was approximately be calculated as daily evaporation capacity $E_{\max}$ in the region.

$E_{\max}$ is obtained by using Hamon's formula.

$$E_{\max} = 218.527 D_L \frac{e^{17.28T_a/(T_a+273.3)}}{T_a + 273.3} \quad (9)$$

Where D_L (h) is length of day; T_a refers to temperature.

Calculation of K and W_m

K was the coefficient by considering evaporation loss and determined by regional evaporation capacity. Regional evaporation capacity correlated with meteorological factors and regional humidity. When the soil water storage in evaluation layer reached the maximum value W_m, regional evaporation also reached the maximum value $E_{\max}$. $E_{\max}$ was the function of date t, namely, $E_{\max}(t)$. If the soil water content in evaluation layer stood at W_m on date t, real regional evaporation $E(t) = E_{\max} \times (t)$; if there was insufficient regional water supply, that is, the soil water content in evaluation layer $W_a(t) < W_m$, real regional evaporation $E_{\max}(t)$ was less than evaporation capacity $E_{\max}(t)$. Then we obtained that $E(t)/E_{\max}(t) < 1$, and the ratio was less with the decrease of soil water content. When the soil water content in evaluation layer was W_a, assuming regional evaporation $E(t)$ satisfied the proportion relationship.

$$E(t) = (1 - K) W_a(t) \quad (10)$$

When the maximum value of soil water content in evaluation layer W_m was reached, its daily evaporation was $E_{\max}$. We obtain

$$E_{\max} = (1 - K) W_m \quad (11)$$

namely,

$$K = 1 - E_{\max} / W_m \quad (12)$$

Where W_m denotes the maximum water holding capacity of the soil in crop root layer. The maximum water holding capacity referred to that there was no soil water leakage in crop root layer. On this basis, the maximum allowable water content of the soil in crop root layer $\theta_{\max}$ was taken as field water capacity θ_f while the minimum water content θ_w was used as wilting coefficient θ_w [11]. By idealizing the soil in crop root layer as homogeneous soil, the maximum water holding capacity of the soil in this layer is

$$W_m = \int_0^H n(\theta_f - \theta_w) dh = n(\theta_f - \theta_w) H \quad (13)$$

Where n is soil porosity in crop root layer; H denotes soil thickness of this layer, and its value is 2 m.

Calculation example

Based on the hydrological data of Baoding Plain, Hebei, China from 1956 to 2000, the annual dynamic variation of soil water resources in hydrological years with different frequency and the soil water resources of different crops in their growth periods were calculated by using the model of soil water resources. Baoding Plain, as part of Hebei Plain, is the major grain producing region in Hebei, China and mainly produces the crops of winter wheat, summer maize and cotton. It plants two crops a year and annual average precipitation is 575.9 mm. The considerable amount of agricultural water is over 70% of the total water in the region.

The annual variation of soil water resources

By utilizing the model of soil water resources, the annual dynamic variation of soil water resources in hydrological years with different frequency is obtained, as shown in Figure 1.

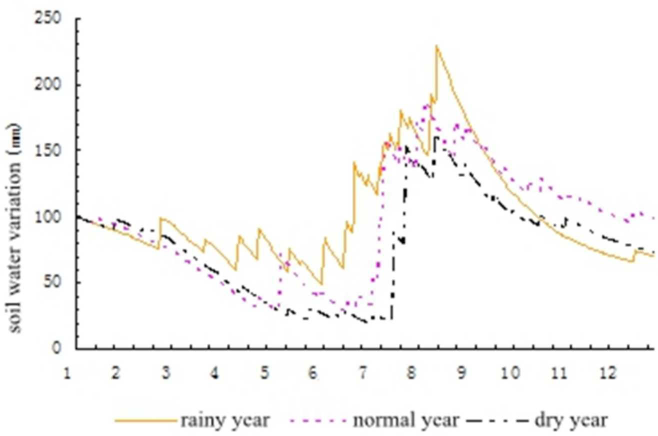

Figure 1. The annual dynamic variation process of soil water resources in hydrological years with different frequency

Investigating the annual variation of soil water storage in years with different frequency was very significant for addressing annual regulation of soil water [12]. Figure 1 indicates that in a year with any frequency, soil water storage presented obvious water storage and supply stages, and the variation was consistent with precipitation distribution. Roughly in July, with the approach of rainy season, soil water developed into recovery period and recovered quickly. Nearly in August, soil reached the peak water in a year, with a relatively high water content. However, the peak period lasted for a short time and soil water began to regress. From middle September to November, as temperature lowered, evaporation decreased and slight precipitation came, soil water was again introduced to a short recovery period. However, finally owning to the evaporation was slightly greater than the precipitation in this period, soil was in a slow water consuming period. In December, a stable water period of soil approached, and it continued until March when soil thawed. From March to middle and late June, soil was in a sharp water consuming period which lasted long and caused spring drought. However, due to this period was a key period for the growth of crops, it was also a key period for supplemental irrigation [13]. In addition, Figure 1 reveals that in a dry year, soil maintained a relatively low water content and water content varied slightly. There is usually only one peak for the water content being observed with low absolute water content. However, in a rainy year, soil always presented a high water content and the recovery period of soil water came earlier than that in normal and dry years. Besides, the absolute value of the peak water content was high.

The calculation of soil water resources of major crops in their growth periods

The soil water resources of winter wheat, summer maize and cotton in Baoding Plain in different growing stages and in their growth periods were calculated and analyzed in rainy, normal and dry years respectively. The soil water resources of major crops in different growing stages are displayed in Table 1.

Table 1. The soil water resources of major crops in different growing stages (mm)

winter wheat	sowing -tillering	tillering-turning green	turning green-jointing	jointing-heading	heading-filling	filling-maturity
rainy year	0.00	32.70	39.70	26.10	24.10	39.20
normal year	23.50	23.00	0.00	14.00	39.50	5.50
dry year	18.50	25.00	5.80	0.00	5.80	17.00
summer maize	sowing-jointing		jointing-heading		heading-maturity	
rainy year	122.40		76.30		94.80	
normal year	108.20		150.00		54.40	
dry year	7.40		158.40		67.70	
cotton	sowing-flower bud		flower bud-flowering	flowering-open boll	open boll-maturity	
rainy year	89.40		117.10	217.10	0.00	
normal year	59.00		19.40	285.00	40.00	
dry year	22.80		7.30	225.40	26.60	

The soil water resources of major crops in their growth periods are shown in Table 2.

Table 2. The soil water resources of major crops in their growth periods (mm)

crops	winter wheat	summer maize	cotton
rainy year	161.80	293.50	423.60
normal year	105.50	312.60	403.40
dry year	72.10	233.50	282.10

Table 2 reveals that in a rainy year the recharge of soil water resources to crop in growth period was usually higher than that in a normal year, while that in a normal year was higher than that in a dry year. Among the crops of winter wheat, summer maize and cotton, the recharge of soil water resources to winter wheat in growth period was the lowest. However, owning to that the growth periods of summer maize and cotton were in or witnessed rainy season, the recharge of soil water resources to them was significantly higher than that of winter wheat. Therefore, to ensure the normal growth and yield of winter wheat, this crop in growth period has to rely on irrigation to supplement the insufficient recharge of soil water resources. This is also the reason why the irrigation water of winter wheat accounts for the highest proportion of the total agricultural water.

Conclusions

Based on the recharge of soil water resources and the water balance theory, a calculation method of soil water resources was determined. Additionally, the annual dynamic variation of soil water resources in hydrological years with different frequency and the soil water resources amount of main crops in their growth periods were calculated and analyzed by taking the example of Baoding Plain, Hebei, China. Knowing the variation law of annual soil water storage with different frequencies is of vital significance for handling annual regulation of soil water. Furthermore, by mastering soil water resources of main crops in their growth periods, their water demands, water surplus and deficit of crops in their growth periods can be investigated. On this basis, crop irrigation can be effectively guided, soil water resources can be fully used to save irrigation water and the balance between water demand and supply of crop in growth period can be ensured scientifically and rationally. Meanwhile, more than 80% of precipitation in crop growth period is transformed to soil water resources, which is far higher than the resources of surface water and groundwater. Given the considerable amount of soil water resources, the utilization of these resources needs to be highly stressed in agricultural production. With growing shortage of water resources, scientifically, reasonably, and efficiently utilizing soil water resources has vital and far-reaching significance for effectively reducing irrigation resources from surface water and groundwater, facilitating the development of water-saving agriculture, relieving water resources crisis and improving ecological environment to a great extent.

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