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USE OF UNSATURATED HYDRAULIC CONDUCTIVITY FUNCTION IN CALCULATING CAPILLARY FLOW FROM GROUNDWATER

Nameer T. Mahdi[1] and Hussein A. Mohammed [2]
[1]Department of Desertification Combat, College of Agriculture, University of Baghdad, Iraq
[2]Scientific Researcher, Iraq

Abstract

A field experiment was conducted north of Baghdad to calculate the capillary flow of groundwater using the unsaturated hydraulic conductivity function and determining the extent of groundwater contribution as one of the water balance factors in meeting the water requirement for cabbage. Four irrigation systems were carried out in the management of cabbage cultivation, namely, Micro-Sprinkler Irrigation (MSI), Drip Irrigation (DI), Subsurface Drip Irrigation (SDI), and Furrow Irrigation (comparison treatment). The water balance equation was used to determine the actual water requirement of cabbage (actual water consumption, ETa), with following up the moisture depletion in the soil to a depth of 60 cm and measuring other water balance factors. Another experiment was carried out to determine the unsaturated hydraulic conductivity function by following up the changes of moisture content and the moisture stress for different depths of the soil during the water infiltration under conditions of unsaturated flow while preventing evaporation from the soil surface. The results showed that the contribution of groundwater to meet the water requirement for cabbage varieties with different irrigation systems. The depth of capillary water height was 24.44, 27.75, 28.89, and 12.04 mm.season^{-1} of the MSI, DI, SDI, and FI irrigation systems, respectively, with a contribution percentage ranging from 3-8. % of actual evapotranspiration. The contribution of groundwater and added water according to the irrigation schedule affected the water balance, which was reflected in the actual water consumption values of the plant, as the values differed according to the different irrigation systems and reached 405.82, 380.68, 364.70 and 393.44 mm.season^{-1} for the MSI, DI, SDI and FI irrigation systems, respectively. It was observed that as the amount of added irrigation water decreased, the contribution of groundwater increased. It is evident from the above that the flow calculations of the capillary water height are important in the water balance. As well as, it can be used to meet the water requirement of the plant by reducing the added water during managing small irrigation systems to increase the contribution of groundwater, especially if the groundwater is of good quality and close to the soil surface.

Keyword: Micro-irrigation systems, unsaturated flow, Water balance, Tensiometers, modeling, actual evapotranspiration.

Introduction

The calculations of the exact amount of capillary water flow into the soil require good data on the soil hydraulic conductivity as a function of the moisture content K(θ) or a function of the water potential K(ψ) (Neyshabouri *et al.*, 2013). Many computer simulation models have been developed to estimate the changes in soil moisture content in the plant's rhizosphere, as well as the state and movement of ions, fertilizers, pollutants, and chemical transformations in the soil, all require information about the soil hydraulic properties under unsaturated conditions (Zhang, 2005). In addition, the water-conductivity data measurement is required and necessary in experimental work to assess the water consumption of plants (Hardarson, 1990). The unsaturated hydraulic conductivity of field soils is a very important natural characteristic that influences the properties of water infiltration and capillary height and it includes in the calculations of actual water consumption by crops (Shokri and Salvucci, 2011). The relationship between volumetric moisture content and moisture stress was used for field data using Tensiometers to measure moisture stress. As well as, to assess the state of low moisture content in the soil profile in calculating the unsaturated water conductivity as a function of changing the moisture content (K (θ)) of great importance in determining the capillary water flow in the soil, the relationship was defined by the following equation (Villagra, *et al.* 1994):

$$K(\theta)=\frac{\left[L\left(\frac{d\theta}{dt}\right)\right]}{\left(\frac{dh}{dz}\right)} \qquad ...(1)$$

Where K(θ) is the unsaturated hydraulic conductivity is a function of volumetric moisture content, (dh/dz) is the slope of measured water potential by means of Tensiometers at depth L of soil, and (dθ / dt) is the moisture content changes with time.

Other methods have been used to calculate the unsaturated hydraulic conductivity of porous media from moisture description curves, data and mathematical models have been developed to calculate the hydraulic conductivity from the curve data of (Campbell 1974; Mualem 1976; Van Genuchten 1980 and Poulsen *et al.*, 2002). Other methods have adopted a simple method for calculating the hydraulic conductivity and do not require measurements of Tensiometers in the field. One of these methods that have been tested is the method described (Libardi *et al.*, 1980), where the hydraulic conductivity is described as follows:

$$k(\theta)=k_0\exp[\beta(\theta_0-\theta)] \qquad ...(2)$$

Where β is the constant, k_0 and θ_0 are the values of hydraulic conductivity and moisture content at saturation, respectively. The values of β and k_0 are calculated using field data and applying the following relationship:

$$\ln\left[z\left(\frac{d\theta}{dt}\right)\right]=\beta(\theta_0-\theta)+\ln k_0 \qquad ...(3)$$

After drawing the absolute values of $Z\left(\frac{d\theta}{dt}\right)$ against (θ_0 −θ) on a semi-log paper, β is obtained from the relationship gradient and ln k_0 from the intersection point. (Libardi *et al.*, 1980) pointed out the possibility of determining and calculating the amount of capillary height and the contribution of groundwater that moved to the root zone using mathematical models based on water soil properties such as unsaturated hydraulic conductivity, water potential slope. As well as, the changes of moisture content with depth, time, and depth of groundwater, and they used a mathematical model from which to calculate the rate of capillary water movement upward for each type of soil and all conditions. It proved practically appropriate and it was possible to create the appropriate conditions required to obtain the highest or lowest water consumption. However, the rate of capillary water height and evaporation from the soil surface depends on the depth of the groundwater and the amount of moisture stress on the soil surface. Besides that, the evaporation increased leads to an increase in the moisture stress, accordingly the capillary water height increases and reaches its maximum value depending on the depth of the groundwater and the characteristics of the soil in terms of texture and geometry of distribution the soil pores size (Li *et al.*, 2014). The depth of groundwater level has a role in the contribution of groundwater to nutrition the plant root area, and the contribution decreases with increasing depth of the groundwater, as when the groundwater depth changed from one meter to four meters, the contribution rate decreased by 90%. Some experiments showed that the groundwater depth of 1m, it contributed to supplying the plant roots with water at a rate ranging between 70-80% and at the depth of 2 m by 24-38%, and the contribution rate decreased at the depth of 4 m to less than 5% (Abdul Rehman *et al.*, 1977 And Suleiman *et al.*, 1986). Furthermore, Fahd *et al.* (2002) confirmed that groundwater with a depth of 2.7 m contributed to supplying the root zone with water at a rate ranging between 7.2-15.7% of the water consumed as actual evapotranspiration according to experimental treatments. Capillary height increases the soil's ability to supply the active root zone with moisture in the vadose zone and determines its ability to support plant growth and production (Shokri and Salvucci, 2011). Finally, (Chakraborty *et al.*, 2009) observed the possibility of expressing the water balance in the root zone during a specific time by changing the moisture stored in the root zone. They used a mathematical model to determine the amount of water transferred up in the effective root zone of the capillary flow and the amount of contribution per unit area. This experiment aims to estimate the unsaturated hydraulic conductivity function in a field method and then use this function to calculate the amount of capillary water flowing from the groundwater level, and by applying the water balance equation, the contribution of groundwater determines the amount of actual water consumption of cabbage.

Materials and Methods

An experiment was carried out in the field north of Baghdad (latitude 33° 24' 06" N, longitude 44° 22' 46" E, and at an altitude 26 m above sea level, 2 kilometers from the Tigris River), Iraq. Field soils were described morphological and were classified as sedimentary, with a texture of silt loam classified with a Typic Torrifluvent group, where the soil samples were taken from the field and the depths 0-0.3 and 0.3-0.6 m. The samples air-dried in vitro and harrowing with a wooden hammer and passed through a 2 mm diameter sieve, which analyzed for each depth to estimate the texture using the pipette method. Moreover, the bulk density of the soil was estimated using the core sample, while its organic matter content was estimated using a black and walked method. Finally, the electrical conductivity ECe and pH of the saturated paste extract were also estimated. Table 1 shows some of the physical and chemical properties of the field soil before planting, where the properties were estimated according to methods described by (Klute *et al.*, 1986; Pagr *et al.*, 1982).

Experiments treatments and the experimental design

In the experiment, four methods were used to irrigate the cabbage crop, which are Micro-Sprinkler Irrigation (MSI), Drip Irrigation (DI), Subsurface Drip Irrigation (SDI) and Furrow Irrigation (FI). The experiment was carried out according to the Randomized Complete Block Design RCBD with four replicates. The experiment data were statistically analyzed according to the analysis of variance method using the Statistical Analysis System (2012). Comparisons were made between the arithmetic means, according to the least significant difference LSD at a 0.05 probability level.

Table 1 : Physical, chemical and hydraulic properties of the soil

Parameter	**Soil layer**	
	0.0–0.3 m	**0.3-0.6 m**
Sand (g kg^{-1})	261.00	133.00
Silt (g kg^{-1})	536.00	457.00
Clay (g kg^{-1})	203.00	410.00
Texture	Silt Loam	Clay
Bulk Density (Mg m^{-3})	1.41	1.51
Volumetric water content at 33 Kps (cm^3 cm^{-3})	0.232	—
Volumetric water content at 1500 Kps (cm^3 cm^{-3})	0.111	—
Available water (cm^3 cm^{-3})	0.121	—
Electrical Conductivity (dSm^{-1})	3.55	3.20
pH	7.76	7.64
CEC ($Cmol_c$ kg^{-1} soil)	350.00	—
Organic matter (g kg^{-1})	1.86	1.24

The irrigation was carried out after depletion of 50-55% of available water, where the amount of irrigation water in each irrigation was calculated based on the measurements of the soil moisture content before irrigation. The gravimetric method was used to estimate the soil moisture content, moreover, the volumetric moisture content was found at the specified depth and time. From the data of the gravimetric method calculations, the equation mentioned by (Allen *et al.*, 1998) was used to calculate the depth of water to be added to compensate for the depleted moisture.

$$d = (\theta_f - \theta_w) \times D \qquad ...(4)$$

Where d is the depth of added water (mm), θ_{fc} is volumetric water content at field capacity (cm^3cm^{-3}), θ_w is volumetric water content before irrigation (cm^3cm^{-3}), and D is the soil depth, which is equal to the depth of the effective root (m).

Tensiometers were used to observe changes in the moisture stress associated with the change in moisture content as an indicator and follow the water movement in the soil and the extent of the groundwater contribution to supply the root zone with water. Tenchomiters were distributed in four experimental units representing different experimental treatments, by placing two Tenchomiters in each treatment at the depths of 0.3m and 0.6m, continuous readings of the moisture stress were taken daily. The water balance equation was used to calculate the actual evapotranspiration ETa of cabbage during the growing season (Allen *et al.*, 1998).

$$ETa = I + P + C \pm \Delta S \qquad ...(5)$$

Where ETa is the actual evapotranspiration (mm), I the irrigation water depth (mm), P is the precipitation (mm), C is the groundwater contribution in capillary height (mm), and ΔS is the soil moisture storage at the beginning and end of the growing season (mm).

Groundwater contribution experiment

Accurate calculations of water flow in the field were performed. As it was possible to obtain good data for water conductivity, through the soil moisture measurements and by applying computer software, moisture changes in the soil were simulated and calculate the extent of groundwater contribution to plant nutrition. Therefore, a field experiment was conducted to measure the contribution of the groundwater as mentioned, by (Hardarson, 1990). A 2 x 2 m basin surrounded by a 0.1 m high soil shoulder was done, and the water was added to the basin with a depth of 0.15 m, where the addition process was conducted in three batches, and each batch of water with a depth of 0.05 m. Once the water addition is finished, the basin is covered to prevent evaporation from it. Soil moisture content was measured at 0.2 m depth and 0.3 m depth for 96 hours. Soil samples were taken from these two depths by auger and for every 6 hours to observe the change of moisture content as volumetric water content (θ, $cm^3\ cm^{-3}$). By applying the water balance equation (equation 5), the amount of water that the groundwater contributes to supplying the root zone with water has been calculated.

Results and Discussion

Calculating the groundwater contribution

Figure 1 showed the change in the groundwater level for the period from September to January, and the average depth of the groundwater at the experiment site was 1.36 m from the soil surface. The groundwater level contributed to feeding the root zone of the cabbage plant with water and contributed to the water requirement of the cabbage plant during the fall season for 126 days. Table 2 showed volumetric moisture content data (cm^3cm^{-3}) for 0.2 and 0.3 m depths from the soil surface for 96 hours, as well as the arithmetic mean of volumetric moisture content of moisture content measurements. The data in Table 2 are sufficient to estimate the unsaturated hydraulic conductivity ($K(\theta)$) and to be consistent with the application of equation 2, this requires some major steps to perform the calculations of $K(\theta)$. The graphical matching of the time data t(h) and the arithmetic mean of the volumetric moisture content $\bar{\theta}$ were performed and the exponential function was obtained. as shown in Figure 2

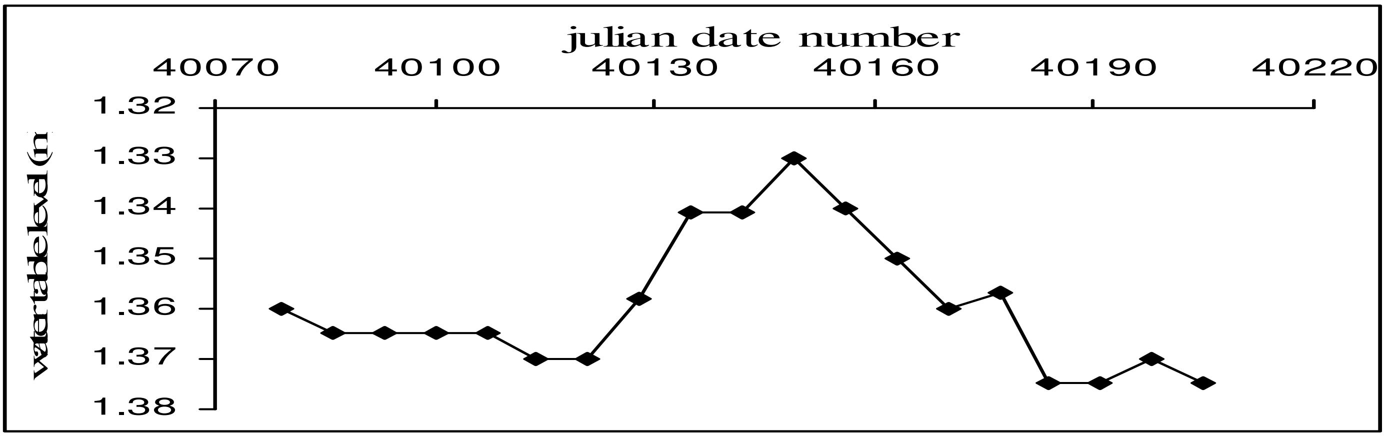

Fig. 1 : water table level during 126 day at fall season

Table 2 : Volumetric water content θ ($cm^3\ cm^{-3}$) for two depth 0.2 and 0.3 m at 96 hour

Time	Soil depth, z (m)		Average
t(h)	0.20	0.30	$\bar{\theta}$
	Volumetric water content θ ($cm^3\ cm^{-3}$)		
0	0.462	0.461	0.4615
6	0.449	0.440	0.4445
12	0.418	0.416	0.4170
24	0.391	0.387	0.3890
36	0.363	0.354	0.3585
48	0.322	0.319	0.3205
60	0.292	0.290	0.2910
72	0.278	0.265	0.2715
84	0.266	0.251	0.2585
96	0.267	0.263	0.2651

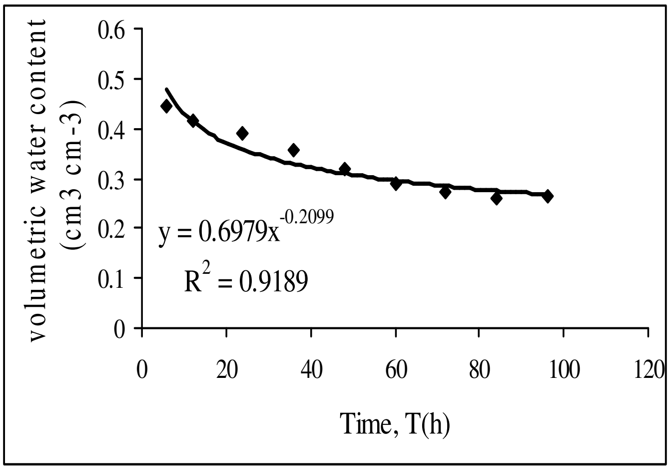

Fig. 2 : The relationship between time and the mean of volumetric water content

Figure 2 showed good correspondence between time and average volumetric moisture content expressed by the following exponential correlation equation, where equation 6 was derived to find the gradient of the relationship, so the following gradient equation was obtained

$$\bar{\theta} = 0.6979T^{-0.2099} \qquad ...(6)$$

$$\frac{d\bar{\theta}}{dT} = -0.14649T - 1.2099 \qquad ...(7)$$

Table 3 showed the main steps to perform the calculations. Gradient data $\frac{d\bar{\theta}}{dt}$ is placed in column 2 of the Table. The gradient was calculated from the exponential curve resulting from matching data with t data.

Table 3 : Basic data needed to estimate K(θ)

$\bar{\theta}$	$\frac{d\bar{\theta}}{dt}$	$z\left(\frac{d\bar{\theta}}{dt}\right)$	$\ln\left[z\left(\frac{d\theta}{dt}\right)\right]$	$\theta_0 - \bar{\theta}$
1	2	3	4	5
0.4615	—	—	—	0.0000
0.4445	0.016762	0.503	-0.687	0.0170
0.4170	0.007246	0.217	-1.526	0.0445
0.3890	0.003132	0.094	-2.365	0.0725
0.3585	0.001918	0.058	-2.855	0.1030
0.3205	0.001354	0.041	-3.203	0.1410
0.2910	0.001034	0.031	-3.473	0.1705
0.2715	0.000829	0.025	-3.694	0.1900
0.2585	0.000688	0.021	-3.880	0.2030
0.2650	0.000585	0.018	-4.042	0.1965

* z = 0.3 m. $\theta_0 = 0.4615$ cm^{3}cm^{-3}

A relationship between the data of ln (z (dθ/dT)) and the data of ($\theta_0 - \bar{\theta}$) was drawn and it matched, the next straight-line relationship was obtained.

$$\ln\left[z\left(\frac{d\theta}{dt}\right)\right] = -15.875\left(\theta_0 - \bar{\theta}\right) - 0.8511 \quad R^2 = 0.950 \; ...(8)$$

As shown in Figure (3), Equation (2) was used after β was replaced by the value of the linear relationship gradient in Figures (3) and K_0 with the value of the intersection point to be formulated according to the following:

$$k(\theta) = 0.4269 \exp\left[-15.875\left(\theta_0 - \bar{\theta}\right)\right] \qquad ...(9)$$

The water conductivity is calculated as a function of the volumetric moisture content change at each value of θ values, using the Tenchomiters readings in the field in calculating the slope in the water potential, and from data of K(θ) (Equation 9), the water flow was calculated by applying the following Darcy Law:

$$q = -K(\theta)\frac{dH}{dz} \qquad ...(10)$$

Where q is the water flow (mm sec^{-1}), this represents the amount of groundwater contribution C (mm) during the experiment period, according to the following equation:

$$C = \sum q \times \Delta t \qquad ...(11)$$

C data were entered into the water balance equation (equation 5) to calculate the effect of the groundwater contribution on ET$_a$ values.

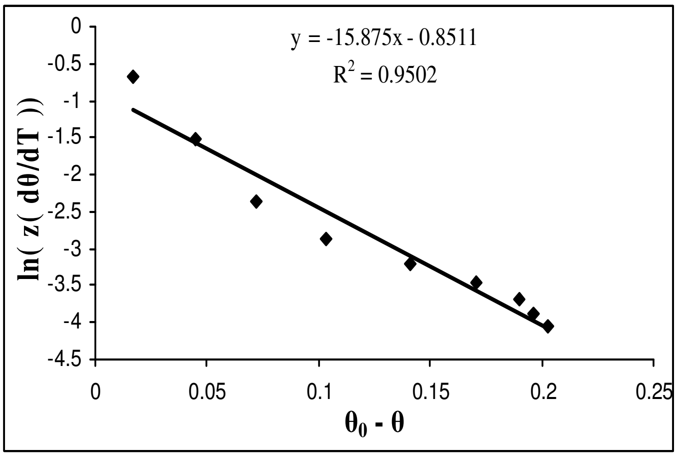

Fig.3. the relationship between ($\theta_0 - \bar{\theta}$) and ln(z(dθ/dt))

Actual evapotranspiration and groundwater contribution depth (mm)

The water balance equation in Table 4 showed the actual evapotranspiration (ETa) of cabbage, which differed according to the different irrigation methods, as it reached 405.82, 380.68, 364.70, and 393.44 mm.season^{-1} for (MSI), (DI), (SDI) and (FI), respectively. It was observed that the highest value of ETa was in the treatment MSI compared to other irrigation treatments, the increasing percentage in ETa for MSI compared to the DI and SDI and FI was 6.6, 11.2 and 3.1%, respectively. This increase may be attributed to an increase in evaporation from the sprinklers during the spraying process, as well as the evaporation from the soil surface. The increasing percentage in ETa for the FI treatment compared to the DI and SDI treatments was 3.3 and 7.8%, respectively**.** This is due to the increase in the amount of added water and the wet area, which increases the evaporation from the soil surface, therefore the ETa values increase. As for the treatment DI, the increasing percentage in ETa was 4.4% compared to the treatment of SDI, this is due to the difference in the additional location, the amount of water used, and the number of irrigation carried out in the experiment.

The results of Table 4 showed the amounts of capillary water height during the growing season of the cabbage plant, as they reached 24.44, 27.75, 28.89, and 12.04 mm.season^{-1} for (MSI), (DI), (SDI) and (FI), respectively. The contribution percentages of groundwater from total water consumption were 6.02, 7.29, 7.92, and 3.06% for irrigation treatments, respectively, and the greatest amount was in the SDI treatment, which led to further deepen the plant roots and then extracting amounts of groundwater to meet the water needs for the plant. The contribution of groundwater increased as plant age progressed and roots developed and expanded, especially in the maturing stage and yield formation. It was also evident from the results that the contribution of groundwater increases with the decrease in the amount of added irrigation water in order to meet the water requirement of cabbage, as when the added water decreased by 8-13%, the actual evapotranspiration (ETa) decreased by 6%, which increased the contribution of the groundwater by about 7%.

Table 4 : Water requirement for Cabbage under different irrigation systems

Treatments	No. of irrigation	Applied irrigation water (mm)	Precipitation (mm)	Groundwater contribution (mm)	Percentage of contribution (%)	ET_a (mm)
MSI	14	346.78	34.60	24.44	6.02	405.82
DI	19	318.33	34.60	27.75	7.29	380.68
SDI	13	301.21	34.60	28.89	7.92	364.70
FI	15	346.80	34.60	12.04	3.06	393.44

Tables 5, 6, 7, and 8 showed the contribution of groundwater for each stage of the four cabbage growth stages, the duration of each stage, the contribution percentage of the total groundwater for the stage, as well as the depth of the daily contribution of the groundwater. The results of Table 5 showed the contribution of groundwater in treatment MSI as it was 1.38 mm in the crop development stage of the total groundwater contribution (24.44 mm). The contribution of groundwater in the Midseason stage increased to 4.64 mm, after that the contribution of groundwater in the maturity stage increased to 8.70 mm. In the harvest stage, the groundwater contribution is 9.72 mm. It was observed from the above that the contribution of groundwater in the treatment of sprinkler irrigation followed a logical behavior, as the contribution increased with the increase of plant growth and deepening the roots and the moisture depletion from the soil increased (Fahd *et al*., 2002). Table 6 showed a different behavior of the groundwater contribution in the treatment DI, as it was in the crop development stage 1.89 mm from the total contribution depth of groundwater, and the contribution in the Midseason stage increased and reached 9.04 mm. The contribution of groundwater decreased slightly to 8.14 mm in the maturity stage. As for the last harvest stage, its groundwater contribution was 8.67 mm. Table 7 showed the groundwater contribution for the treatment SDI, as the groundwater contribution reached 3.91 mm in the crop development stage of the total groundwater contribution, while in the Midseason stage, the contribution increased by about 7.90 mm. The groundwater contribution was 8.40 mm in the maturity stage, and in the harvest stage, the contribution was 8.68 mm. The highest contribution of groundwater was in the treatment SDI, as the extraction of groundwater amounts increased to meet part of the water requirement of the plant, where the groundwater contribution percentage reached 7.92% of the total water consumption. As for the treatment FI, it showed the lowest contribution of groundwater in meeting the water needs of cabbage for the different growth stages as shown in Table 8, as it reached 1.03 mm in the crop development stage. The contribution of groundwater in the Midseason stage increased to 3.41 mm in the maturity stage, groundwater contributed at a 3.72 mm depth, and in the harvest stage of 3.88 mm depth.

Table 5 : The amount of groundwater contribution during the cabbage growth stages for MSI treatment

MSI	Cabbage growth stages*				Aggregate
	Crop development	Midseason	Maturity	Harvest	
Growth stages periods, days	30	35	31	30	126
groundwater contribution for growth stages, mm.	1.38	4.64	8.70	9.72	24.44
Daily groundwater contribution, mm.	0.05	0.13	0.28	0.32	—

* Cabbage growth stages according to Doorenbos and Kassam (1979).

Table 6 : The amount of groundwater contribution during the cabbage growth stages for DI treatment

DI	Cabbage growth stages				Aggregate
	Crop development	Midseason	Maturity	Harvest	
Growth stages periods, days	30	35	31	30	126
groundwater contribution for growth stages, mm	1.89	9.05	8.14	8.67	27.75
Daily groundwater contribution, mm	0.06	0.26	0.26	0.29	—

Table 7 : The amount of groundwater contribution during the cabbage growth stages for SDI treatment

SDI	**Cabbage growth stages**				**Aggregate**
	Crop development	**Midseason**	**Maturity**	**Harvest**	
Growth stages periods, days	30	35	31	30	126
groundwater contribution for growth stages, mm	3.91	7.90	8.40	8.68	28.89
Daily groundwater contribution, mm	0.13	0.23	0.27	0.29	—

Table 8 : The amount of groundwater contribution during the cabbage growth stages for FI treatment

FI	**Cabbage growth stages**				**Aggregate**
	Crop development	**Midseason**	**Maturity**	**Harvest**	
Growth stages periods, days	30	35	31	30	126
groundwater contribution for growth stages, mm	1.03	3.41	3.72	3.88	12.04
Daily groundwater contribution, mm	0.03	0.10	0.12	0.13	—

From the previous results, it was observed that the depth of groundwater contribution is relatively small, but it affects the water balance calculations. The decrease in the percentage of the groundwater contribution may be attributed to the cabbage root, as it is of a shallow root system with little depth, its maximum depth of 0.6 m. The majority of the cabbage roots are found in the top of the soil (0.4-0.5 m) with a rapid decrease in root density with depth. Therefore, the percentage of extracting amounts of groundwater to meet the water needs of the plant is limited and that most of the water extracted from the soil is within the surface layer and for a depth of 0.4 - 0.6 m. In addition, the plant growing season was during the cold months of the year (November, December, and January), and most of the temperatures were low, which reduced the evaporation process from the soil surface and reduced the capillary water height. Generally, calculations of the amount of groundwater consumed by the plant are important because they form part of the total water consumption of the plant. There is an increase in the water consumption of cabbage plant, and there was a difference between the amount of added water and the amount of water consumed, so the value of the groundwater contribution and its percentage influenced the water consumption calculations, and the contribution differed according to the different irrigation methods.

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