Dewedar, O.M.; Plauborg, Finn; Marwa, M.A.; El-shafie, A.F.; Ragab, R. 2021. **Improving water saving, yield, and water productivity of bean under deficit drip irrigation: field and modelling study using the SALTMED model.** *Irrigation and Drainage*, 70 (2). 224-242, which has been published in final form at https://doi.org/10.1002/ird.2539

IMPROVING WATER SAVING, YIELD AND WATER PRODUCTIVITY OF BEAN UNDER DEFICIT DRIP IRRIGATION: FIELD AND MODELLING STUDY USING SALTMED MODEL[†]

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ABSTRACT

A field experiment was conducted over two successive seasons 2017 and 2018 in Egypt. The aim was to study the effect of irrigation systems (surface and subsurface drip irrigation) and irrigation amounts (100, 80 and 60% of crop evapotranspiration, ETc) on the yield of bean crop (*Phaseolus vulgaris)* and evaluate the SALTMED model performance on simulation of soil moisture, total dry matter and yield. Despite the highest yield values being achieved with the 100% of ETc treatment, there were no significant differences between the 100 and 80%. This means a 20% water saving can be achieved without significantly compromising the yield. Yield and water productivity under subsurface irrigation was slightly higher than under surface drip irrigation. This is because under subsurface drip irrigation there is no wetted surface area contributing to evaporation losses as is the case for surface drip. In addition, the soil moisture under subsurface drip, is kept within the root zone for the longest possible time without subjecting the crop to water stress. The SALTMED model accurately simulated soil moisture, total dry matter, yield and water productivity. Hence the model could be applied as crop, water and land management tool under current and future Egyptian climatic conditions.

KEY WORDS: deficit irrigation; drip irrigation; water productivity; SALTMED model; yield.

[†] Amélioration des économies d'eau, du rendement et de la productivité de l'eau des haricots sous irrigation goutte à goutte: étude de terrain et de modélisation à l'aide du modèle SALTMED

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RĖSUMĖ

Une expérience de terrain a été menée sur deux saisons successives 2017 et 2018 en Egypte. L'objectif était d'étudier l'effet des systèmes d'irrigation (irrigation goutte à goutte de surface et souterraine) et les quantités d'irrigation (100, 80 et 60% de l'évapotranspiration des cultures, ETc) sur le rendement de la culture de haricots (Phaseolus vulgaris) et d'évaluer les performances du modèle SALTMED sur simulation de l'humidité du sol, de la matière sèche totale et du rendement. Malgré les valeurs de rendement les plus élevées obtenues avec le traitement à 100% d'ETc, il n'y avait pas de différences significatives entre les 100 et 80%. Cela signifie qu'une économie d'eau de 20% peut être obtenue sans compromettre considérablement le rendement. Le rendement et la productivité de l'eau sous irrigation souterraine étaient légèrement plus élevés que sous irrigation goutte à goutte de surface. En effet, sous irrigation goutte à goutte souterraine, il n'y a pas de surface mouillée contribuant aux pertes par évaporation comme c'est le cas pour le goutte à goutte de surface. De plus, l'humidité du sol sous goutte-à-goutte souterrain est maintenue dans la zone racinaire le plus longtemps possible sans soumettre la culture à un stress hydrique. Le modèle SALTMED simulait avec précision l'humidité du sol, la matière sèche totale, le rendement et la productivité de l'eau. Par conséquent, le modèle pourrait être appliqué comme outil de gestion des cultures, de l'eau et des terres dans les conditions climatiques égyptiennes actuelles et futures.

MOTS CLÉS: irrigation déficitaire; irrigation goutte à goutte; productivité de l'eau; modèle SALTMED; rendement.

INTRODUCTION

Egypt is located in a semi-arid zone and its climate is characterized by hot dry summers and mild winters. Egypt relies on the River Nile as its main resource of fresh water (95%) to meet the increasing demands for water from agricultural, industrial, and domestic sectors. With about 95% of the population living along the Nile Valley and in the Nile Delta, any changes in water supply due to climate change, with the certainty of increased demographic pressure, would pose a serious risk to the whole country. The agriculture sector is, and will remain, the largest user of water (above 85%) and, therefore, faces the greatest challenge in its efforts to rationalize water use (El-Noemani *et al.*, 2015a). Water scarcity is one of the serious problems facing crop cultivation in Egypt, and it is necessary to reduce the consumption of irrigation water through developing and improving innovative technologies that would allow irrigation water saving (Abdelraouf *et al.*, 2013; El-Metwally *et al*., 2015). In semi-arid and arid countries with high population growth and limited fresh water, there is a lot of pressure on the agricultural sector to reduce the fresh water consumption for irrigation to make more water available to the industrial and urban sectors (Abdelraouf and Abuarab, 2012; Hozayn *et al*., 2016, 2020). Increasing water use efficiency of crops is an important goal (Bakry *et al*., 2012).

The government's strategic plans for future development recognize the importance of saving water – approximately 13.5 billion m^3 $year^{-1}$ – from agricultural activities in the Nile Delta (Ministry of Agriculture and Land Reclamation (MALR), 2014). The increasing demands of the agricultural sector for the limited water supply have led farmers to modernize irrigation systems. One aspect of these modernizations is the installation of drip irrigation systems. Drip irrigation systems are characterized by high water use efficiency. Another advantage of this irrigation system is the precision in water and fertilizers application under adequate design conditions (Pedras and Pereira, 2001; El-Shafie *et al*., 2018; Dewedar *et al*., 2019). Therefore, it is very important, when facing future changes in water availability, to develop a sustainable water management plan. For this reason, using drip irrigation systems (surface and subsurface) is very important as it is characterized by saving and precision in water application to reduce the water demand. This will be essential in future projects.

Bean (Phaseolus vulgaris, L.) is one of the most widely consumed legumes in the world because it contains a high level of protein and is grown in many different regions and environments. It is one of the most important vegetable crops in Egypt. In 2017, the cultivated area was 27,300 ha with a total production of 284,000 tons and Egypt exported about 8% of it. The water consumption of the bean crop is between 300 – 500 mm per season depending on the climate (Food and Agriculture Organization of the United Nations (FAO), 2019). Water stress is one of the major constraints faced by common bean farmers in Egypt and elsewhere.

A number of studies demonstrated that SALTMED model gave a precise simulation of crop yield, dry matter and soil moisture content (Ragab, 2002; Malash *et al*., 2005a; Malash *et al*., 2005b; Hirich *et al*., 2012; Pulvento *et al*., 2013; Ragab, 2015; Kaya *et al*., 2015; Afzal *et al*., 2016; Ćosić *et al*., 2017; El-Shafie *et al*., 2017; Abdelraouf and Ragab 2018; Marwa *et al*., 2020). The advantages of using calibrated and validated models are that they are cheaper and faster than performing field experiments and a larger level of detail that can be obtained from a simulation (El-Shafie *et al*., 2018). For this reason, SALTMED model (Ragab, 2015) is a useful tool for assessing the impact of surface and subsurface drip irrigation systems on crop and soil.

Therefore, the objectives of this investigation were to study the effect of the irrigation system (surface and subsurface drip irrigation) and irrigation treatments (100, 80 and 60% of the crop evapotranspiration ETc) on growth, yield and dry matter of the bean crop (Pharsalus vulgaris, L.) and evaluate the performance of the SALTMED model in predicting soil moisture content, yield and dry matter.

MATERIALS AND METHODS

The experimental site and crop

The field experiment was carried out at the Agricultural Research Station of the National Research Centre, El-Nubaria, Egypt (latitude of 30° 30’ N and longitude 30° 20’ E) in the North West of the Nile delta of Egypt. The average monthly weather data at the experimental site during the two growing seasons are given in Table I. The field experiment included two irrigation systems during two successive seasons of 2017 and 2018. The beans (*Phaseolus vulgaris, L.)* were sown on 5 September and harvested on 29 November during the two growing seasons. Seeds were sown in rows 0.7 m apart on ridges that were spaced 0.1 m apart. Thinning was practiced before the first irrigation to secure two plants per hill. Green pods were picked four times, during the harvesting stage for the two growing seasons. Fertilizer requirements of bean crop were applied in the same amount for all treatments, according to the recommendations of the Horticulture Research Institute (ARC), Ministry of Agriculture and Land Reclamation, Egypt. The soil of the experimental site is classified as sandy soil *(Entisol-TypicTorripsamments)*. Representative soil samples from the different parts of the experimental area were taken from the depths 0-15, 15-30, 30-45 and 45-60 cm. Soil samples from similar depths were mixed thoroughly and a composite sample was taken for each depth for different analyses.The main physical properties were determined in situ and in the laboratory at the beginning of the trial and are reported in Table II.

Table I. Average of the monthly weather data at the experimental site during the two growing seasons of 2017 and 2018

Month	Precipitation	Wind speed	Relative humidity	Maximum temperature	Minimum temperature	Average temperature	Solar radiation
	(mm day^{-1})	(m s^{-1})	(%)	(°C)	(°C)	(°C)	(MJm^{-2} day^{-1})
First season 2017							
Sep. 2017	0.0	3.2	60.2	31.9	21.1	25.7	27.7
Oct. 2017	0.7	3.3	61.4	27.7	18.5	22.5	18.9
Nov. 2017	0.7	2.7	66.2	23.0	14.7	18.2	14.1
Second season 2018							
Sep. 2018	0.0	3.3	60.6	32.3	22.3	26.6	23.3
Oct. 2018	0.1	3.2	61.4	29.0	19.8	23.7	19.0
Nov. 2018	0.7	2.6	63.1	24.5	16.1	19.7	14.4

Irrigation water was obtained from an irrigation channel (Nile water) going through the experimental area. The water had a pH of 7.3, electrical conductivity (EC) of 0.37 dS m^{-1} and contained a suitable amount of cations and anions (Table III). Soil particle size distribution was determined using the Pipette method, as described by Gee and Bauder (1986). Soil moisture content at field capacity (FC) and permanent wilting point (PWP) were measured according to Gardner (1986). Soil saturated hydraulic conductivity (k) was determined under a constant head technique (Klute and Dirksen, 1986).

Table II. Soil physical properties

Soil depth, cm	Particle Size distribution, %				Texture class	% on volume basis			HC cm h^{-1}	BD g cm^{-3}	P (cm^3 voids cm^{-3} soil)
	Course sand	Fine sand	Silt	Clay		FC	PWP	AW			
0-15	8.4	77.6	8.5	5.5	Sandy	16	8	8	6.68	1.69	0.36
15-30	8.6	77.7	8.3	5.4	Sandy	16	8	8	6.84	1.69	0.36
30-45	8.5	77.5	8.8	5.2	Sandy	16	8	8	6.91	1.69	0.36
45-60	8.8	76.7	8.6	5.9	Sandy	16	8	8	6.17	1.67	0.37

FC: field capacity, PWP: permanent wilting point, AW: available water, HC: saturated hydraulic conductivity (cm h^{-1}), BD: bulk density (g cm^{-3}) and P: porosity (cm^3 voids cm^{-3} soil).

Table III. Chemical properties of the irrigation water

pH	EC	Soluble cations, meq l^{-1}				Soluble anions, meq l^{-1}				SAR
	dSm^{-1}	Ca^{++}	Mg^{++}	Na^{+}	K^{+}	CO_3^{--}	HCO_3^{-}	SO_4^{--}	Cl^{-}	
7.3	0.5	2.15	0.50	3.00	0.31	0.01	2.33	1.45	2.17	4.61

EC = electric conductivity, SAR = sodium adsorption ratio

Experimental design. Hydraulically tested surface drip irrigation, SDI and subsurface drip irrigation, SSDI systems have been implemented at the experimental site. The laterals of the surface and subsurface drip irrigation network were 16 mm in diameter.

The selected emitters were designed to give a discharge of 4.0 l h^{-1} at operation pressure of 1.0 bar. The spacing between emiters was 30 cm while the spacing between laterals was 70 cm. The subsurface lateral drip lines were installed at 15 cm below soil surface. The field experiment was designed as split plot. The total experimental area was (30 m x 36 m), divided into two main plots of (15 m x 36 m). Half of the area (one of the two main plots) has been equipped with the surface drip irrigation system (SDI) and the other half (the other main plot) with the subsurface drip irrigation system (SSDI). Each main plot has been divided into three subplots, each of which has an area of (5 m x 18 m). Each subplot recieved three water application levels, 100, 80 and 60% of ETc. An area of (1 m x 30 m) was left between the plots to prevent interference effects between the irrigation treatments.

Irrigation requirement of bean crop. The experiment involved three irrigation application levels, 100, 80 and 60% of potential crop evapotranspiration, ETc. The irrigation was applied every three days based on the following Eq. 1:

$$IRg = (ET_O \times Kc \times Kr) / (Ei - R + LR) \quad (1)$$

Where IRg is the total/gross irrigation requirement, mm/day, ET_O is the reference evapotranspiration, mm/day (This was obtained from the Central Laboratory for Climate - Agricultural Research Centre, Egyptian Ministry of Agriculture at El-Nubaryia farm and calculated according to Penman-Monteith equation), Kc is the crop coefficient (Allen *et al.*, 1998), Kr is the reduction factor of the evaporation from exposed soil ground cover, Ei is the irrigation efficiency, %, R is the water received as rainfall, mm, LR is the amount of water required for the leaching of salts accumulated in the root zone, mm.

Soil moisture content. The soil moisture content was measured using the profle probe for both the surface and subsurface drip irrigation systems.

Bean yield. For each treatment, the total weight of harvested beans was recorded. The yield was expressed as kg beans harested per 1 m^2 and the total yield was expressed as ton $hectare^{-1}$.

Water productivity of bean crop. WP_{bean} was evaluated as reported by James (1988) using Eq. 2:

$$WP = Ey/Ir \quad (2)$$

Where: WP is the water productivity of bean ($kg_{bean}\ m^3{}_{water}{}^{-1}$), Ey is the economical yield ($kg\ ha^{-1}$); Ir is the applied amount of irrigation water ($m^3{}_{water}\ ha^{-1}\ season^{-1}$).

SALTMED model. The SALTMED model (V. 3.04.25) has been selected for this study. More details about the SALTMED model can be found in Ragab (2002, 2005), Ragab (2015), Ragab *et al*. (2015) and Ragab *et al*. (2005a, 2005b). The model is a free download at the International Commission on Irrigation and Drainage (ICID) web site: https://www.icid.org/wg_crop.html.

The SALTMED model can handle all irrigation systems, including surface drip irrigation (SDI) and subsurface drip irrigation (SSDI). The model has been applied in different countries and for different field managements (Ragab, 2020). The reference evapotranspiration (ETo) is calculated by the model according to Allen *et al*. (1998) and the weather data were obtained from the *in situ* field weather station (temperature, relative humidity, radiation, wind speed and rainfall). The soil profile was divided into two layers of 0.00 – 0.25 m and 0.25 – 0.50 m and the soil physical properties for each layer were determined by field and laboratory measurements.

Model calibration. The calibration was conducted against the soil moisture content, yield and total dry matter for the fully irrigated 100% ETc under surface and subsurface drip irrigation for 2017 season. The simulated and measured values were compared. In order to achieve a good agreement, fine-tuning the relevant SALTMED model parameters has been carried out. In the case of calibration of soil moisture, soil parameters such as bubbling pressure, saturated hydraulic conductivity, saturated soil water content and pore distribution index, 'lambda' were fine-tuned until good agreement between the simulated and observed values has been achieved. Additionally, the crop coefficient (Kc), basal crop coefficient (Kcb) and fraction cover (Fc) were part of the calibration as they were obtained from published data and required slightly adjusted. For dry matter and yield calibration, the crop growth parameters especially the photosynthesis efficiency, was fine-tuned. Table IV, shows the main input parameters for beans crop used in the SALTMED model.

Model validation. The validation was carried out using the remaining treatments (using the calibrated parameters). The validation included a comparison of the simulated and observed dry matter, yield, and soil moisture for 2017 and 2018 seasons, both irrigation systems (surface drip irrigation and subsurface drip irrigation) and for the remaining irrigation application levels (80 and 60% of ETc).

Model performance is commonly evaluated by statistical and graphical methods (plots of simulated versus measured values). The statistical methods produce indicators for the goodness of fit level. These include, the widely used coefficient of determination R^2, root mean square error (RMSE) and the coefficient of residual mass (CRM). The RMSE is calculated as:

$$RMSE = \sqrt{\frac{\sum(y_o - y_s)^2}{N}} \tag{3}$$

Where y_o is the observed value, y_s is the simulated value and N is the total number of observations. The coefficient of determination R^2 statistics is calculated as:

$$R^2 = \left(\frac{1}{N}\frac{\sum(y_o - \bar{y_o})(y_s - \bar{y_s})}{\sigma_{y_o} - \sigma_{y_s}}\right) \tag{4}$$

Where y_o^- is the averaged observed value, y_s^- is the averaged simulated value, σ_{y_o} is the standard deviation of the observed data and σ_{y_s} is standard deviation of the simulated data. The coefficient of residual mass (CRM) is calculated as:

$$\mathrm{CRM} = \frac{(\sum y_o - \sum y_s)}{\sum y_o} \tag{5}$$

For the model's best goodness of fit, the values of RMSE, CRM and R^2 should be close or equal to 0.0, 0.0, and 1.0, respectively.

Table IV. SALTMED model calibrated input soil and crop parameters values

Parameter	Developmental stage	Values
Sowing (date)	First and Second seasons	5 Sep.
Days to harvest (day after Sowing)		87
Days for emergence and initial stage		17
Days for development stage		30
Days for middle stage		30
Days for late stage		10
	Initial stage	0.5
Leaf Area Index (LAI)	Middle stage	3.5
	End stage	4.0
Minimum root depth (m)		0.0
Maximum root depth (m)		0.5
Unstressed crop yield (t ha^{-1})		11.2
Harvest index		0.3
Pore size distribution index, Lambda		0.2
Root width factor		0.3
Max. depth for soil evaporation, mm		150
Residual soil water content, $m^2\,m^{-2}$		0.001
Air entry value/bubbling pressure, cm		27.0

Statistical analysis. The data obtained from the two seasons' study were statistically analysed using the analysis of variance method and the means were distinguished by the Duncan's multiple range test (Duncan, 1955).

RESULTS AND DISCUSSION

Model calibration

Soil moisture calibration. The simulated soil moisture content, SMC for soil layers 0-0.25 and 0.25- 0.50 m for the fully irrigated 100% ETc under surface and subsurface drip irrigation were compared with the measured values during the 2017 season. Figure 1 shows the time series of the observed and simulated soil moisture. The figure shows that there is a strong correlation between the observed and simulated soil moisture content for the irrigation treatments. The simulated values were close to the observed values for both soil layers. The correlation between the observed and simulated soil moisture content is shown in Figure 2. The coefficient of determination, R^2 reached 0.929 and 0.934 for 0-25 cm layer under surface and subsurface drip irrigation, respectively. Also, R^2 values for the soil layer 25 - 50 cm were 0.900 and 0.935, under surface and subsurface drip irrigation, respectively. There were no large variations between observed and simulated data in soil moisture of all the soil layers. The variations in soil moisture in both layers are very small due to the frequent irrigation, which kept the soil moisture at a high value. The calculated RMSE was 0.0084, 0.0081, 0.0071 and 0.0080 and the CRM was -0.0276, -0.0404, -0.0096 and -0.0343 for the 0-25 and 25-50 cm soil layers, under surface and subsurface drip irrigation, respectively. The results indicate the model was successfully calibrated and the calibrated parameters can now be used for the validation.

Yield and dry matter calibration. Yield and total dry matter for the fully irrigated 100% Etc treatment under surface and subsurface drip irrigation were calibrated by fine-tunning the crop growth parameters that affect biomass production, such as photosynthesis efficiency. The model showed a good agreement between the observed yield (10.0 and 10.2 t ha^{-1}) and simulated yield (10.1 and 10.1 t ha^{-1}) with the low deviation (-0.246% and 0.429%) for surface and subsurface drip irrigation, respectively. In addition, the observed total dry matter was successfully calibrated with only a difference of -5.01% and 0.68% between the observed (19.0 and 19.9 t ha^{-1}) and simulated values (20.0 and 19.8 t ha^{-1}) for surface and subsurface drip irrigation, respectively (Table IV). This indicates the model was successfully calibrated and the calibrated parameters can now be used for the validation.

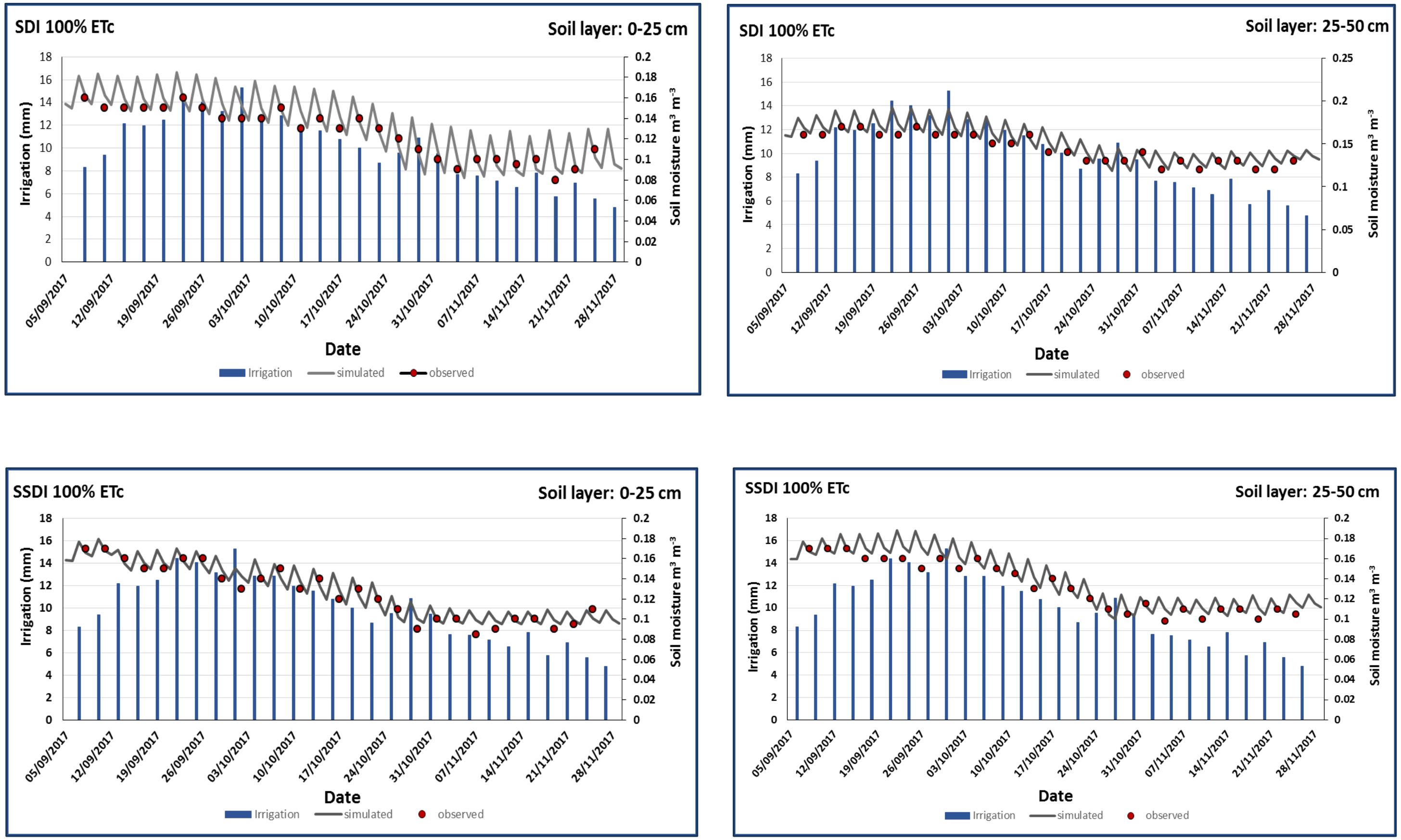


Figure 1. Observed and simulated soil moisture in both layers for the 100% ETc treatment under surface and subsurface drip irrigation during the 2017 season, simulated with SALTMED as calibration. Irrigation events are plotted as a bars

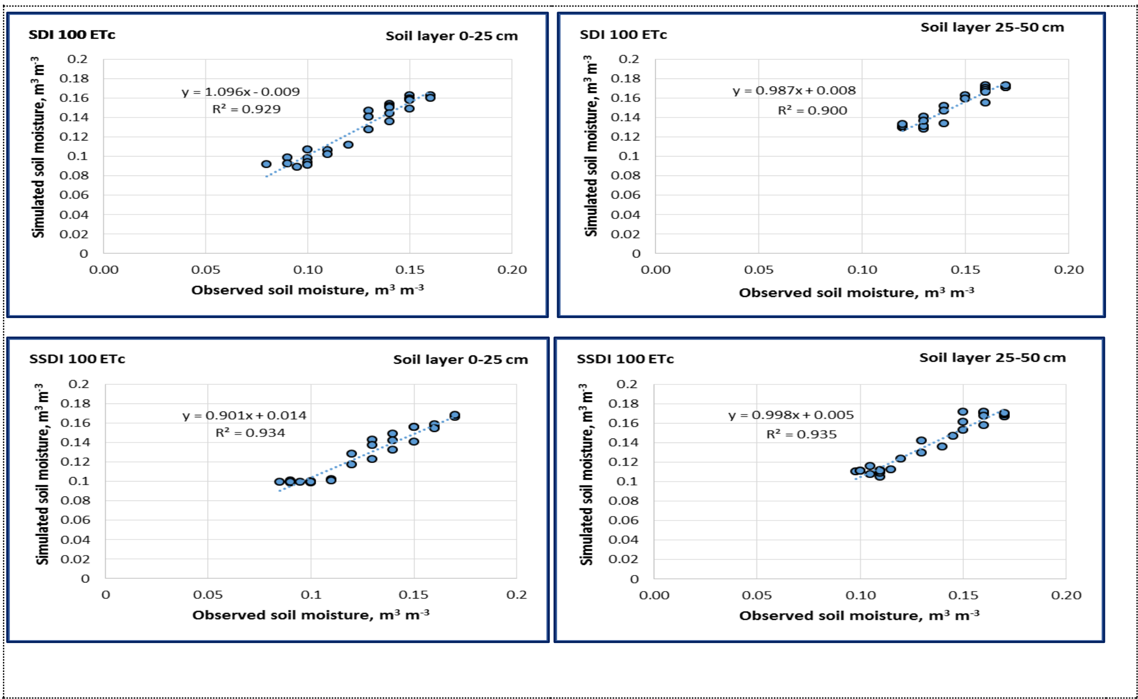
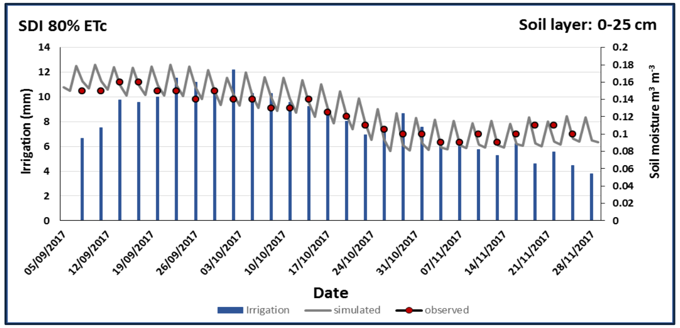


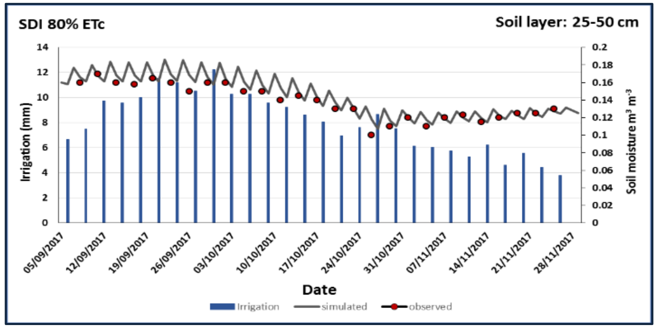
Figure 2. Correlation between observed and simulated soil moisture for the 100% ETc treatent under surface and subsurface drip irrigation during the 2017 season, simulated with SALTMED as calibration

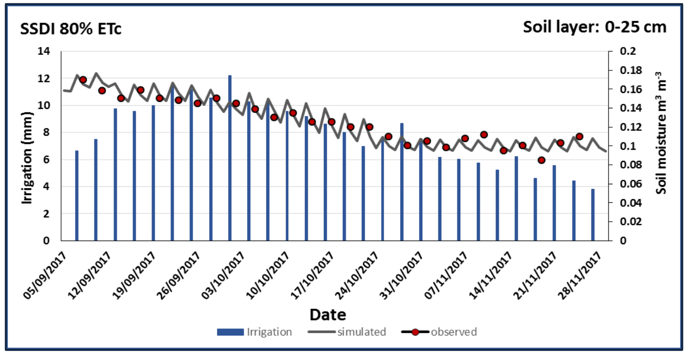
Effect of irrigation systems, water regime and model validation

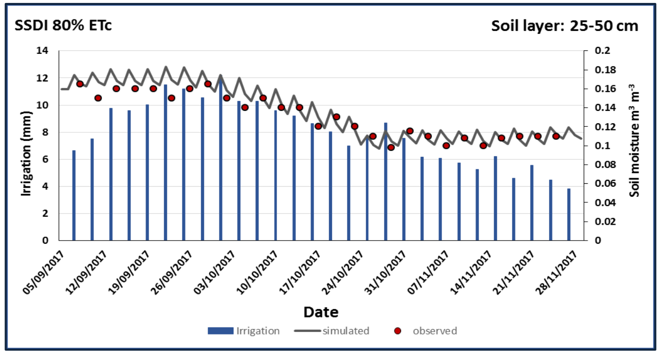
Soil moisture content

The validation of the SALTMED model was carried out on the remaining treatments, excluding the calibrated treatment (100% ETc in 2017), by comparing simulated with observed data of soil moisture content, yield and total dry matter for 80 and 60% of ETc under surface and subsurface drip irrigation system for the 2017 and 60, 80 and 100% ETc for the 2018 season. Under the two irrigation systems, for all water applications, the soil water content was lower at the top layer of the soil profile 0 - 25 cm compared with the 25 - 50 cm layer. This is due to the fact that the top layer is losing more water than the deeper layer via soil evaporation, as also observed by Hirich *et al*. (2012). The soil water content changed during the two seasons, following the same trend and being slightly lower towards the end of the mid-season, due to the high water uptake by the plant during this period (Afzal *et al*., 2016). The soil water content was higher with subsurface drip irrigation system than with surface drip irrigation for both layers in the two seasons. This may mainly be due to the lower soil surface evaporation losses of the subsurface drip irrigation system that keeps sufficient available water in this layer (El-Noemani *et al*., 2015a; Wahba *et al*., 2016; Marwa *et al*., 2017; Youssef *et al*., 2018). The time series of the observed and simulated soil moisture in Figures 3 and 4 (A, B) shows the variation of the soil moisture content under surface and subsurface drip irrigation systems at 80 and 60% of ETc during both seasons 2017 and 2018.


SDI 80% ETc
Soil layer: 0-25 cm
Irrigation (mm)
Soil moisture m³ m⁻³
Date
05/09/2017
12/09/2017
19/09/2017
26/09/2017
03/10/2017
10/10/2017
17/10/2017
24/10/2017
31/10/2017
07/11/2017
14/11/2017
21/11/2017
28/11/2017
Irrigation
simulated
observed


SDI 80% ETc
Soil layer: 25-50 cm
Irrigation (mm)
Soil moisture m³ m⁻³
Date
Irrigation
simulated
observed


SSDI 80% ETc
Soil layer: 0-25 cm
Irrigation (mm)
Soil moisture m³ m⁻³
Date
Irrigation
simulated
observed


SSDI 80% ETc
Soil layer: 25-50 cm
Irrigation (mm)
Soil moisture m³ m⁻³
Date
Irrigation
simulated
observed

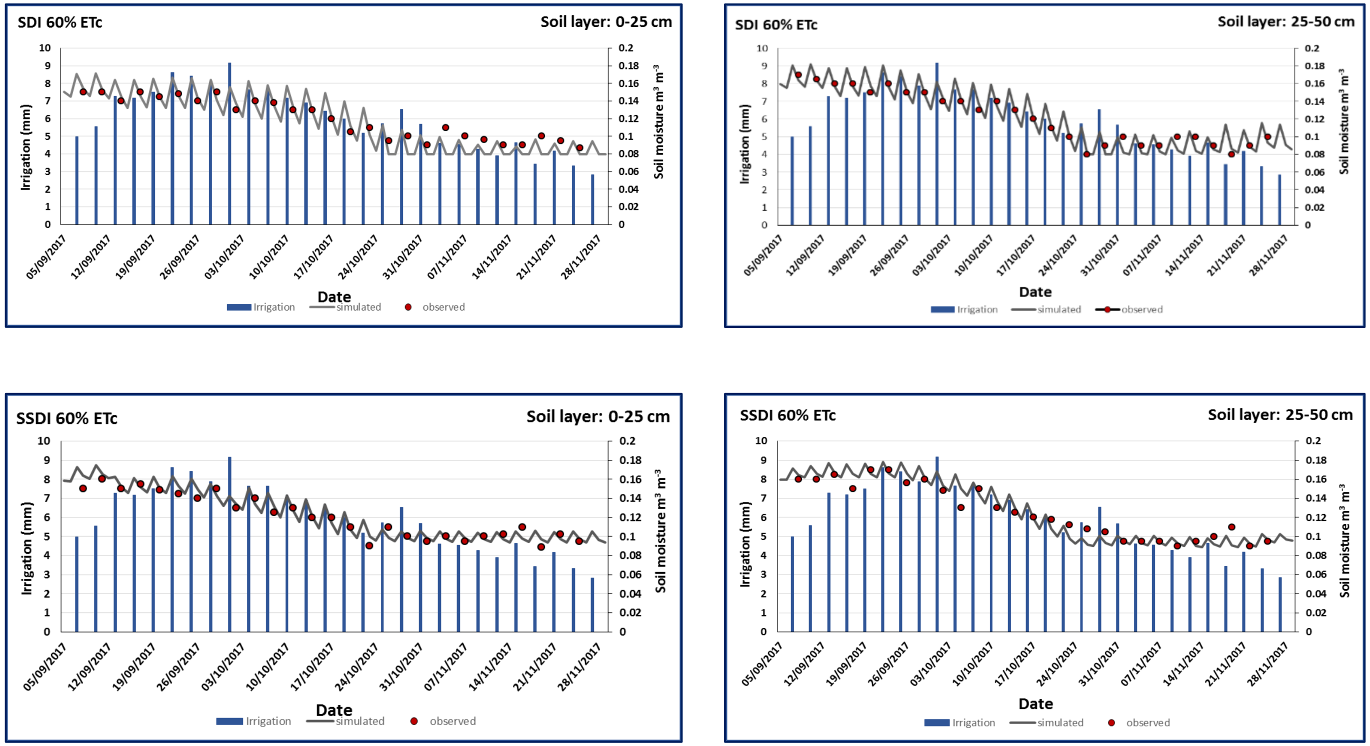
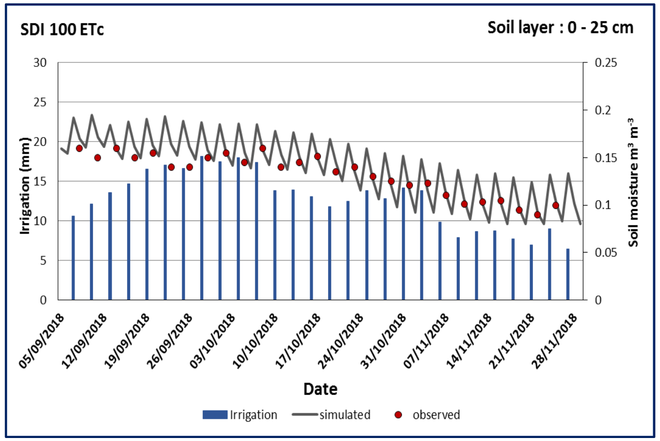
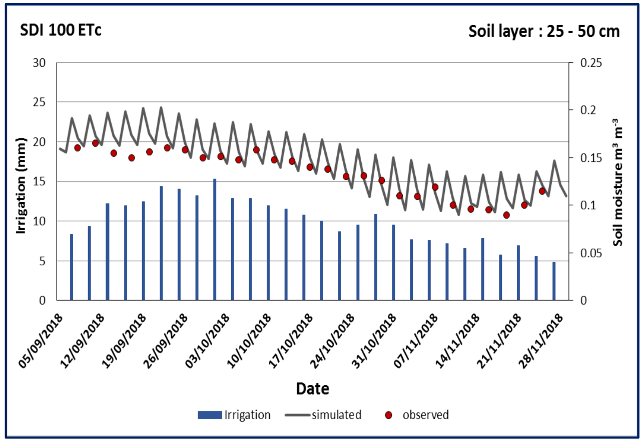
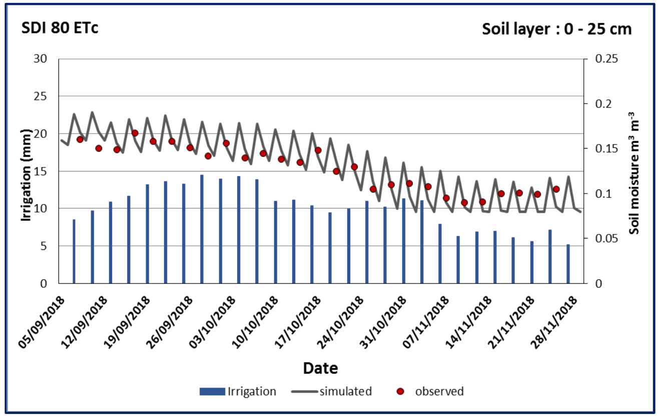


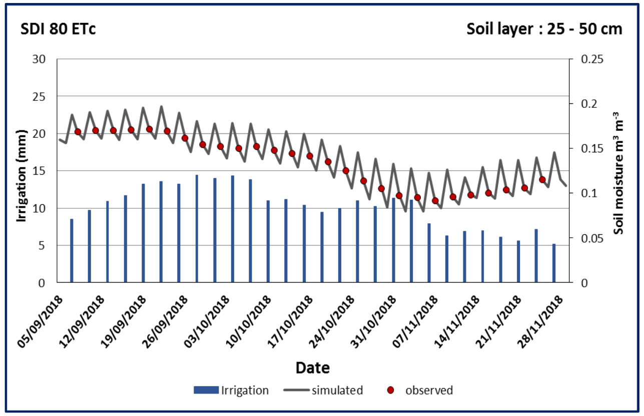
Figure 3. Observed and simulated soil moisture in both layers; 0 - 25 and 25 - 50 cm under the surface and subsurface drip irrigation, 80 and 60% of ETc during the first season 2017, simulated with SALTMED as validation


SDI 100 ETc
Soil layer : 0 - 25 cm
Irrigation (mm)
Soil moisture m³ m⁻³
Date
05/09/2018
12/09/2018
19/09/2018
26/09/2018
03/10/2018
10/10/2018
17/10/2018
24/10/2018
31/10/2018
07/11/2018
14/11/2018
21/11/2018
28/11/2018
Irrigation
simulated
observed


SDI 100 ETc
Soil layer : 25 - 50 cm
Irrigation (mm)
Soil moisture m³ m⁻³
Date
05/09/2018
12/09/2018
19/09/2018
26/09/2018
03/10/2018
10/10/2018
17/10/2018
24/10/2018
31/10/2018
07/11/2018
14/11/2018
21/11/2018
28/11/2018
Irrigation
simulated
observed

80%


SDI 80 ETc
Soil layer : 0 - 25 cm
Irrigation (mm)
Soil moisture m³ m⁻³
Date
05/09/2018
12/09/2018
19/09/2018
26/09/2018
03/10/2018
10/10/2018
17/10/2018
24/10/2018
31/10/2018
07/11/2018
14/11/2018
21/11/2018
28/11/2018
Irrigation
simulated
observed


SDI 80 ETc
Soil layer : 25 - 50 cm
Irrigation (mm)
Soil moisture m³ m⁻³
Date
05/09/2018
12/09/2018
19/09/2018
26/09/2018
03/10/2018
10/10/2018
17/10/2018
24/10/2018
31/10/2018
07/11/2018
14/11/2018
21/11/2018
28/11/2018
Irrigation
simulated
observed

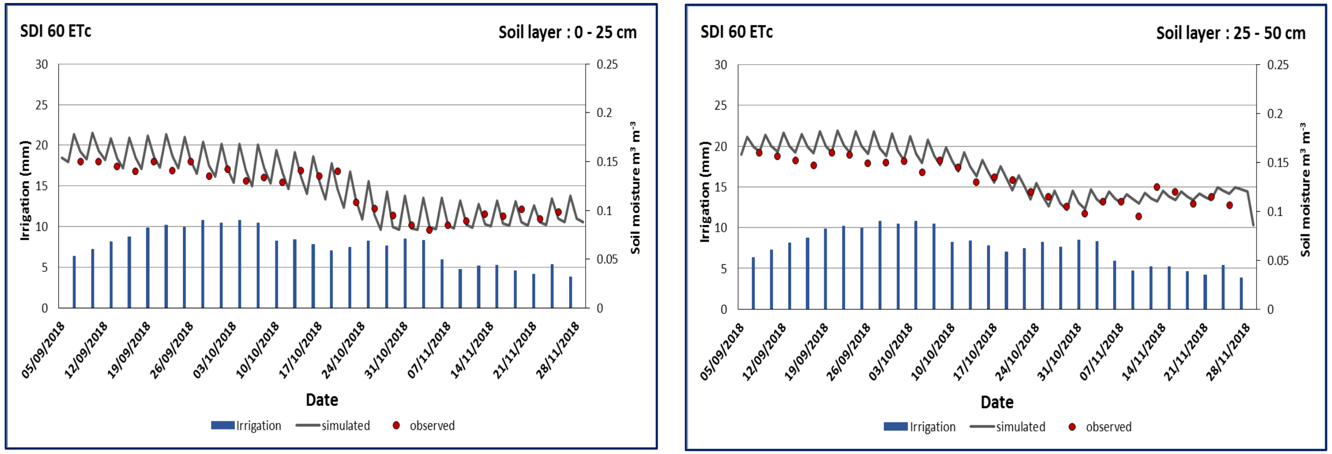
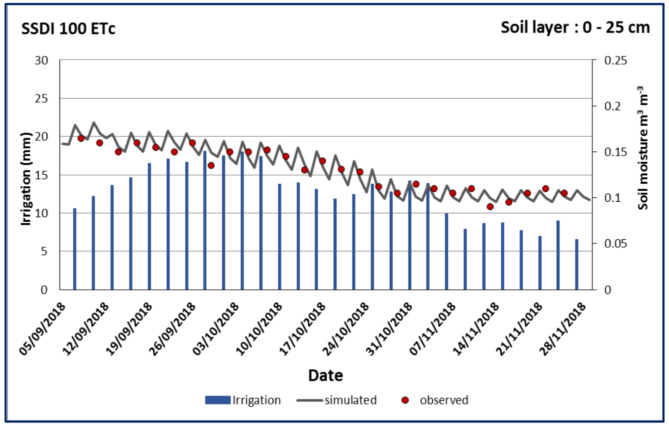
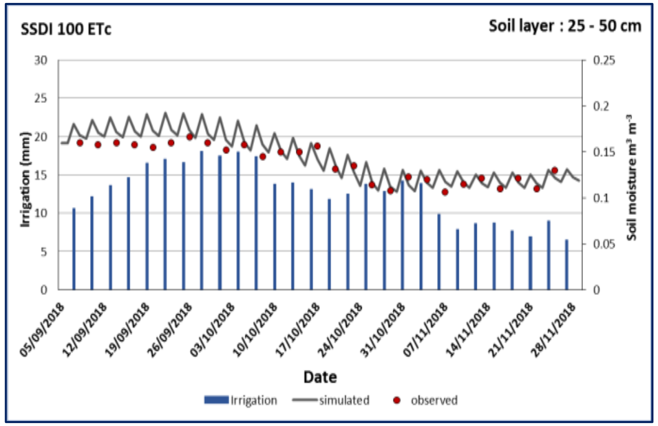
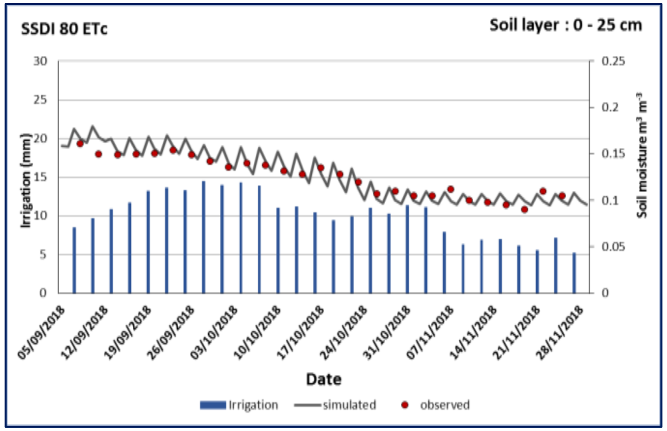


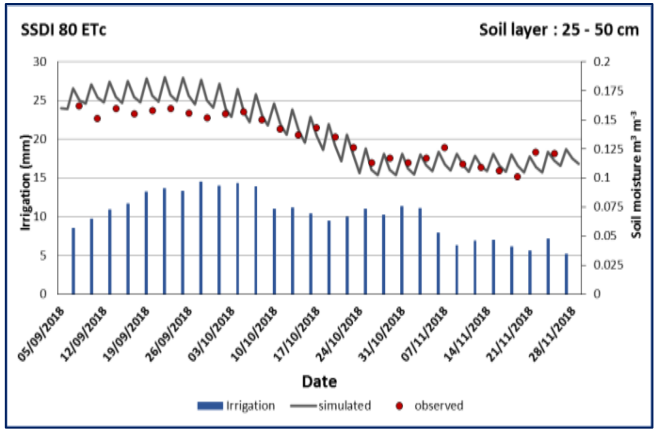
Figure 4 (A). Observed and simulated soil moisture in both layers; 0-25 and 25-50 cm under surface drip irrigation, 100, 80 and 60% ETc during the second season 2018, simulated with SALTMED as validation

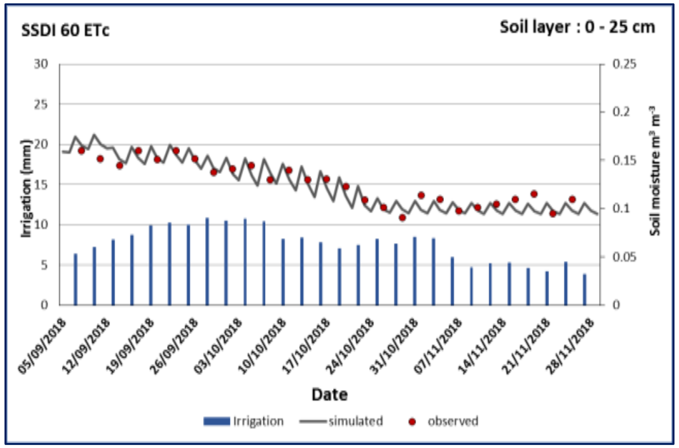
Soil water content for both layers (0-25 and 25-50 cm) under surface and subsurface drip irrigation system at 100, 80 and 60% of ETc were simulated for the two seasons. In general, the model showed a good match between observed and simulated data for all treatments. Moreover, the model recorded high values for R^2 in both seasons under both irrigation systems with all irrigation levels, R^2 ranged between 0.891 and 0.961 in Figures 5 and 6, respectively. These results are in agreement with studies carried out by Kaya *et al*. (2015), Ragab *et al*. (2015), Afzal *et al*. (2016) and El-Shafie *et al*. (2017).


SSDI 100 ETc
Soil layer : 0 - 25 cm
Irrigation (mm)
Soil moisture m³ m⁻³
Date
Irrigation
simulated
observed


SSDI 100 ETc
Soil layer : 25 - 50 cm
Irrigation (mm)
Soil moisture m³ m⁻³
Date
Irrigation
simulated
observed


SSDI 80 ETc
Soil layer : 0 - 25 cm
Irrigation (mm)
Soil moisture m³ m⁻³
Date
Irrigation
simulated
observed


SSDI 80 ETc
Soil layer : 25 - 50 cm
Irrigation (mm)
Soil moisture m³ m⁻³
Date
Irrigation
simulated
observed



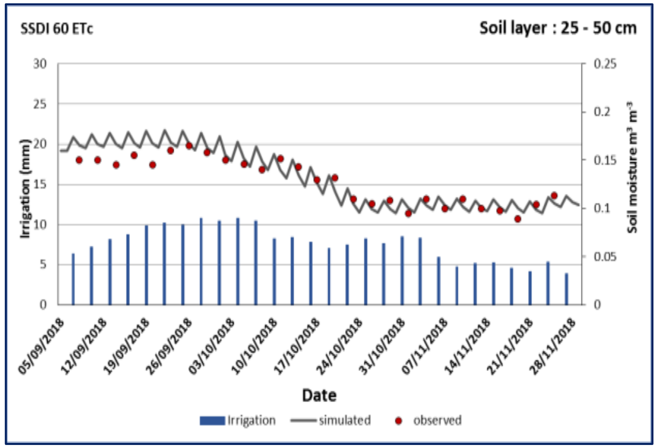


Figure 4 (B). Observed and simulated soil moisture in both layers; 0-25 and 25-50 cm under subsurface drip irrigation, 100, 80 and 60% ETc during the second season 2018, simulated with SALTMED as validation

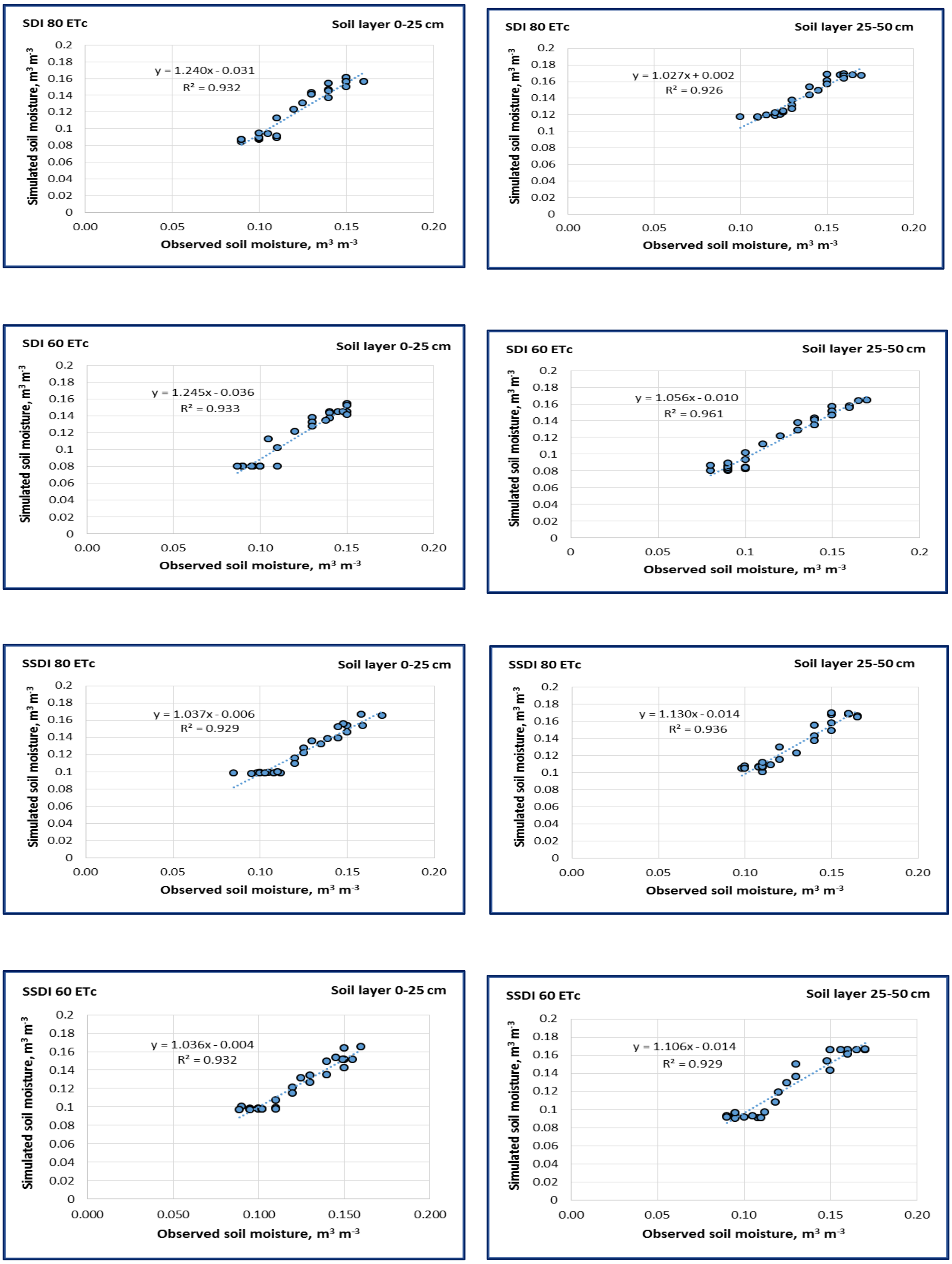
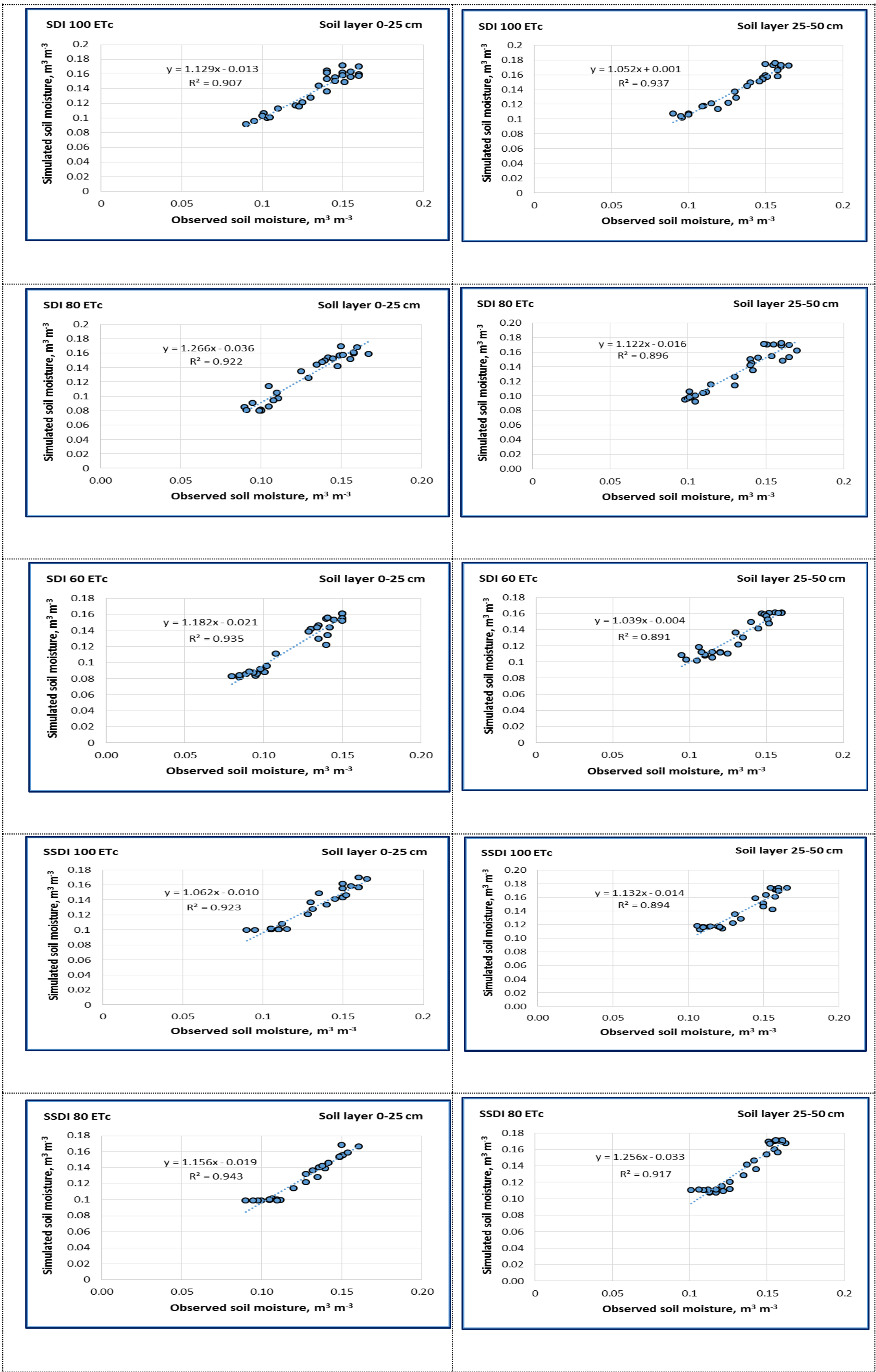


Figure 5. Correlation between observed and simulated soil moisture for the 80 and 60% ETc under surface and subsurface drip irrigation during 2017 season, simulated with SALTMED as validation


SDI 100 ETc
Soil layer 0-25 cm
y = 1.129x - 0.013
R² = 0.907
Simulated soil moisture, m³ m⁻³
Observed soil moisture, m³ m⁻³
SDI 100 ETc
Soil layer 25-50 cm
y = 1.052x + 0.001
R² = 0.937
Simulated soil moisture, m³ m⁻³
Observed soil moisture, m³ m⁻³
SDI 80 ETc
Soil layer 0-25 cm
y = 1.266x - 0.036
R² = 0.922
Simulated soil moisture, m³ m⁻³
Observed soil moisture, m³ m⁻³
SDI 80 ETc
Soil layer 25-50 cm
y = 1.122x - 0.016
R² = 0.896
Simulated soil moisture, m³ m⁻³
Observed soil moisture, m³ m⁻³
SDI 60 ETc
Soil layer 0-25 cm
y = 1.182x - 0.021
R² = 0.935
Simulated soil moisture, m³ m⁻³
Observed soil moisture, m³ m⁻³
SDI 60 ETc
Soil layer 25-50 cm
y = 1.039x - 0.004
R² = 0.891
Simulated soil moisture, m³ m⁻³
Observed soil moisture, m³ m⁻³
SSDI 100 ETc
Soil layer 0-25 cm
y = 1.062x - 0.010
R² = 0.923
Simulated soil moisture, m³ m⁻³
Observed soil moisture, m³ m⁻³
SSDI 100 ETc
Soil layer 25-50 cm
y = 1.132x - 0.014
R² = 0.894
Simulated soil moisture, m³ m⁻³
Observed soil moisture, m³ m⁻³
SSDI 80 ETc
Soil layer 0-25 cm
y = 1.156x - 0.019
R² = 0.943
Simulated soil moisture, m³ m⁻³
Observed soil moisture, m³ m⁻³
SSDI 80 ETc
Soil layer 25-50 cm
y = 1.256x - 0.033
R² = 0.917
Simulated soil moisture, m³ m⁻³
Observed soil moisture, m³ m⁻³

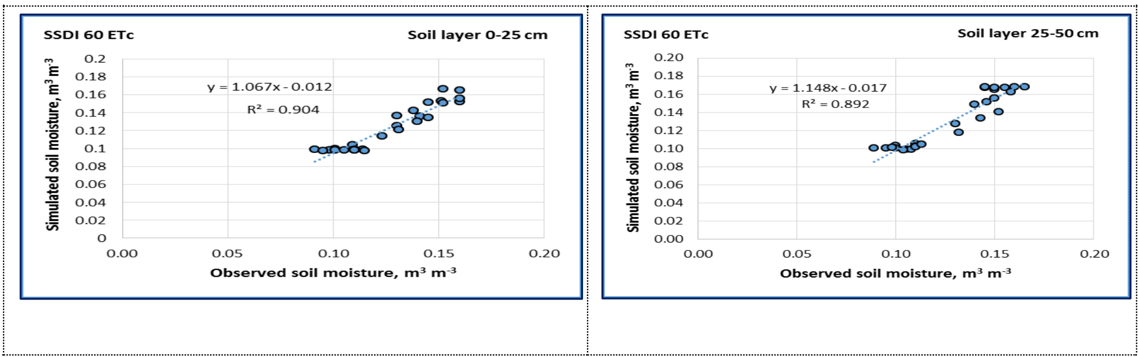


Figure 6.Correlation between observed and simulated soil moisture for the 100, 80 and 60% ETc under the surface and subsurface drip irrigation during 2018 season, simulated with SALTMED as validation

The calculated statistical indicators RMSE and CRM are shown in Table V. Values of $0.006 \leq RMSE \leq 0.011$, and $-0.058 \leq CRM \leq 0.054$ for both layers with all water regimes under surface and subsurface drip irrigation system in both seasons indicate there is a good match between observed and simulated values.

The results of the validation also confirmed the capability of the model to simulate soil water content under the surface and subsurface drip irrigation system.

Table V. The coefficient of determination R^2, RMSE and CRM for soil moisture in both layers for all irrigation treatments under surface, SDI and subsurface, SSDI drip irrigation during the 2017 and 2018 seasons

Seasons	Irrigation system	Etc %	Soil layers (cm)							
			0-25				25-50			
			Regression line	R^2	RMSE	CRM	Regression line	R^2	RMSE	CRM
2017	SDI	100*	y = 1.10x - 0.009	0.93	0.008	-0.023	y = 0.987x + 0.008	0.90	0.008	-0.040
		80	y = 1.24x - 0.031	0.93	0.010	0.009	y = 1.03x + 0.002	0.93	0.008	-0.039
		60	y = 1.25x - 0.036	0.93	0.011	0.054	y = 1.06x - 0.010	0.96	0.007	0.025
	SSDI	100*	y = 0.901x + 0.014	0.93	0.007	-0.001	y = 0.998x + 0.005	0.93	0.008	-0.034
		80	y = 1.04x - 0.006	0.93	0.007	0.012	y = 1.13x - 0.014	0.94	0.008	-0.023
		60	y = 1.04x - 0.004	0.93	0.006	-0.004	y = 1.11x - 0.014	0.93	0.009	0.006
2018	SDI	100	y = 1.13x - 0.013	0.91	0.010	-0.034	y = 1.05x + 0.001	0.94	0.010	-0.058
		80	y = 1.27x - 0.036	0.92	0.011	0.014	y = 1.12x - 0.016	0.90	0.001	-0.001
		60	y = 1.18x - 0.021	0.93	0.009	-0.005	y = 1.04x - 0.004	0.89	0.008	-0.006
	SSDI	100	y = 1.06x - 0.009	0.92	0.007	0.013	y = 1.13x - 0.014	0.89	0.009	-0.029
		80	y = 1.16x - 0.019	0.94	0.007	-0.002	y = 1.26x - 0.033	0.92	0.009	-0.015
		60	y = 1.07x - 0.012	0.90	0.009	0.028	y = 1.15x - 0.017	0.89	0.010	-0.019

* Calibrated

Bean yield and dry matter

Figure 7 represents yield and dry matter of bean crop under surface and subsurface drip irrigation. The data show that, the trend regarding the interaction between the irrigation system and water applied on the yield and total dry matter was similar for both seasons. The highest values of yield and total dry matter were obtained at 100% ETc and the lowest values were associated with 60% ETc, with small variations between surface and subsurface drip irrigation.

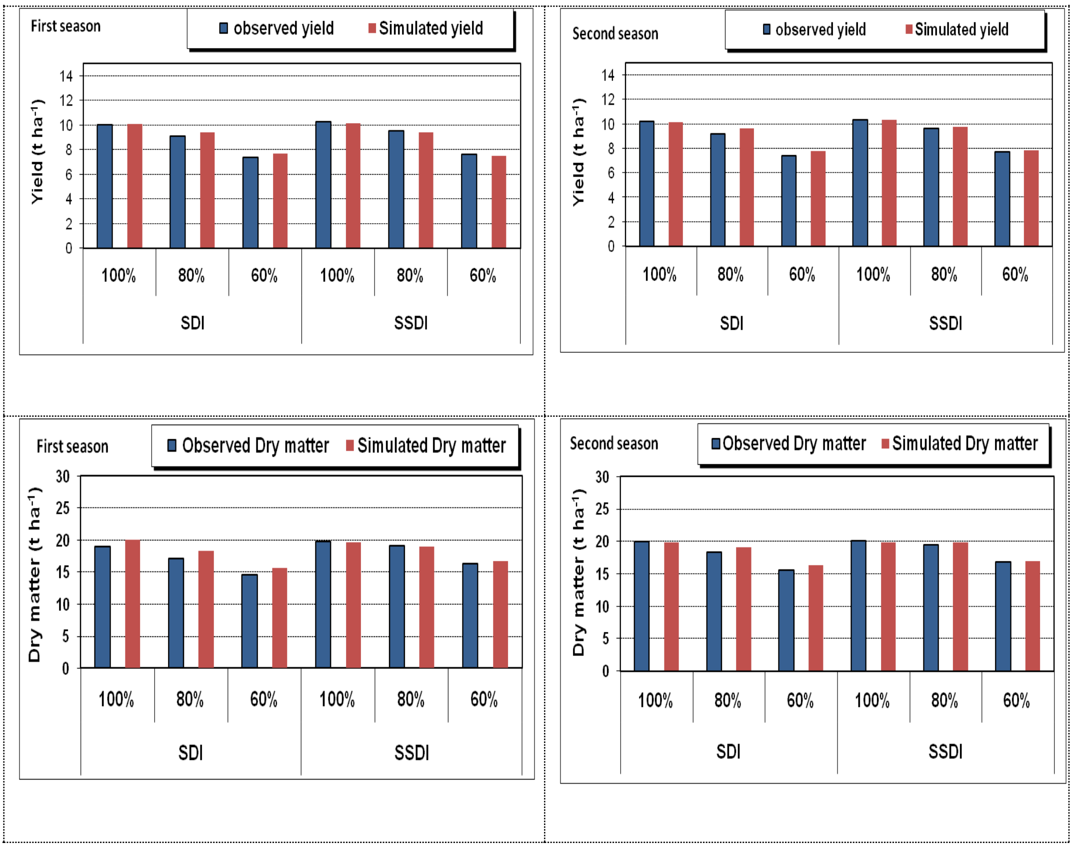


Figure 7. Bean crop yield and dry matter (t ha^{-1}) under two irrigation systems and irrigation treatments. Results of 100% ETc of 2017 of surface and subsurface drip were obtained by calibration

The highest values of yield were 10.0 and 10.2 t ha^{-1} and the highest values of total dry matter were 19.0 and 19.9 t ha^{-1} under subsurface drip irrigation with 100% ETc for 2017 and 2018 seasons, respectively.While the lowest values of yield and total dry matter were 7.35 and 14.6 t ha^{-1} in the first season, and 7.42 and 15.5 t ha^{-1} in the second season at 60% ETc under surface drip irrigation. The decrease in both fresh and dry matter of stressed plants revealed the influence of plant water uptake reduction on the photosynthesis which influenced both the dry matter production and the fresh yield. The fresh yield results reported here are in agreement with those obtained by Sezen *et al*. (2005), Gençoğlan *et al*. (2006), Sezen *et al*. (2008) and El-Noemani *et al*. (2015 b), who noticed that plants grown under the highest levels of water supply gave the highest records of green pod yield, while plants grown under deficit irrigation showed the lowest values.

The model showed a good agreement between the observed yield (10.0 and 10.2 t ha^{-1}) and simulated yield (10.1 and 10.1 t ha^{-1}) with low deviation (-0.246 and 0.429%) for surface and subsurface drip irrigation, respectively. In addition, the observed and simulated total dry matter was successfully validated with only a difference of -5.01% and 0.68% between the observed (19.0 and 19.9 t ha^{-1}) and simulated yield (20.0 and 19.8 t ha^{-1}) for surface and subsurface drip irrigation, respectively.

Table VI illustrates the difference between observed and simulated values of yield and dry matter for all applied water treatments under both irrigation systems for the 2017 and 2018 seasons. The model showed a good correlation between observed and simulated data. The simulated yields under surface drip and subsurface drip irrigation system with all water-applied levels were close to observed ones. The correlation coefficient (R^2) of yield was 0.975 and 0.983 and dry matter was 0.916 and 0.953, for 2017 and 2018 seasons, respectively (Figure 8). Those high correlations between measured and simulated values of yield and dry matter were accompanied by low deviation for 2017 and 2018, which ranged between -4.86% and 1.37% for yield, and -7.99% and 1.36% for dry matter, respectively.

In addition, RMSE showed that, there is a very good degree of matching between measured and simulated data. RMSE was 0.191 and 0.235 for yield and 0.767 and 0.508 for dry mater in the 2017 and 2018 season, respectively. CRM indicates that the model slightly underestimated the observed values, -0.005 and -0.019, for yield, and -0.298 and -0.016 for dry mater in the 2017 and 2018 season, respectively. However, the CRM values indicate that the underestimation is insignificant. Those results are in line with Pulvento *et al*. (2013), Afzal *et al*. (2016), Ćosić *et al*. (2017) and El-Shafie *et al*. (2017).

Table VI. Observed and simulated yield and dry matter data of bean under surface and subsurface drip irrigation and tretments of 100, 80 and 60% ETc

Year	Irrigation system	ETc, %	Yield t ha $^{-1}$			Dry matter t ha $^{-1}$		
			Observed	Simulated	Relative difference %	Observed	Simulated	Relative difference %
2017	Surface drip irrigation	100*	10.0 a	10.1	-0.24	19.0	19.9	-5.01
		80	9.11 b	9.37	-2.92	17.1	18.2	-6.6
		60	7.3 d	7.68	-4.48	14.6	15.7	-7.3
	Sub surface drip irrigation	100 *	10.2 a	10.1	1.28	19.7	19.5	0.82
		80	9.5 ab	9.42	1.01	19.1	18.9	1.016
		60	7.6 c	7.51	1.37	16.3	16.7	-2.21
	RMSE				0.19			0.767
	CRM				-0.005			-0.030
	R^2				0.97			0.91
2018	Surface drip irrigation	100	10.2 a	10.1	0.42	19.9	19.7	0.675
		80	9.21b	9.6	-4.39	18.2	19.0	-7.98
		60	7.4 d	7.8	-4.86	15.4	16.3	-5.17
	Sub surface drip irrigation	100	10.3 a	10.3	-0.36	20.1	19.8	1.35
		80	9.6 ab	9.7	-1.6	19.4	19.8	-2.12
		60	7.71 c	7.82	-1.33	16.8	16.9	-0.727
	RMSE				0.23			0.51
	CRM				-0.019			-0.016
	R^2				0.98			0.95

*Calibrated. (a, ab, b, c, d) is a statistical analysis that shows the significant differences. The values have different letters are significantly different, while the values have similar letters are not significantly different

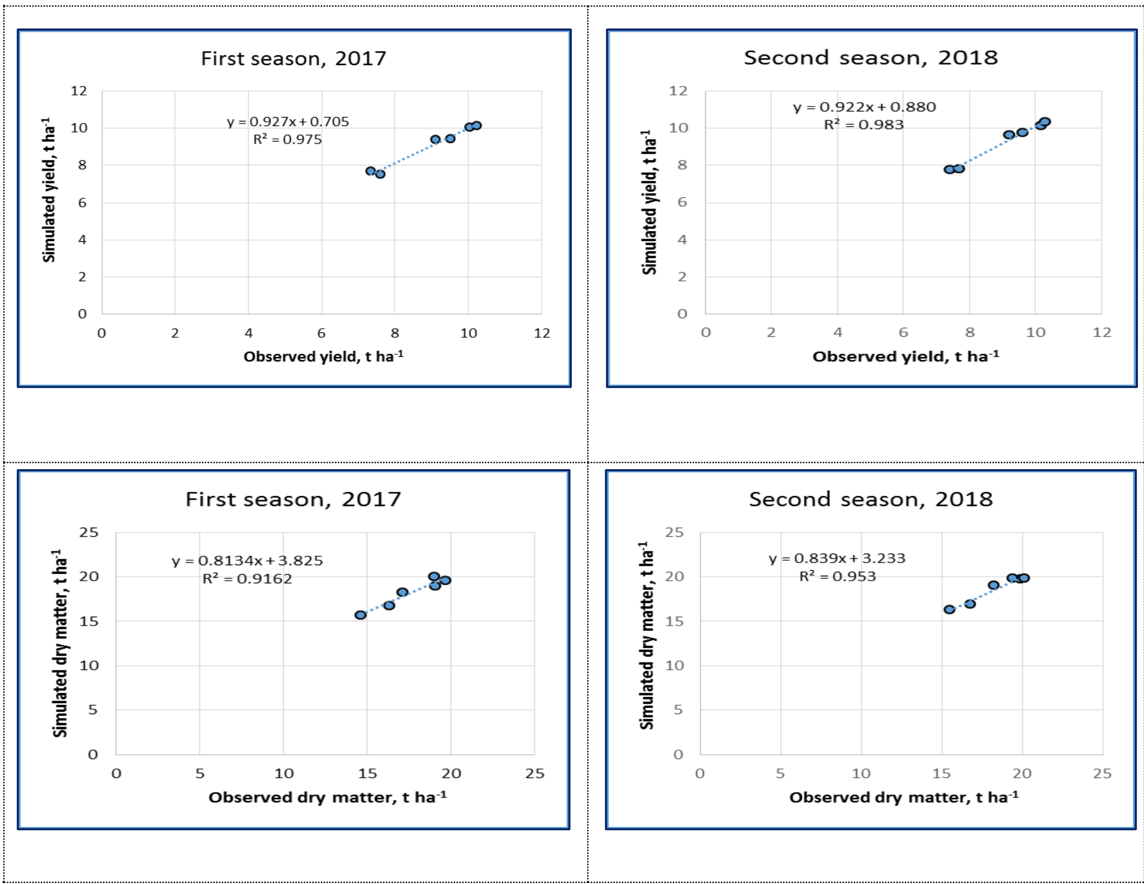


Figure 8. Correlation between observed and simulated yield and dry matter for 2017, first season, and 2018, second season

Water productivity of bean

The water productivity is expressed as the amount of marketable yield produced in kg per cubic metre of irrigation water applied. Figure 9 shows crop water productivity of green been yield (kg m^{-3}) for both seasons. The water productivity followed the same trend in the two experimental seasons. The 60% ETc treatment had the highest values, followed by 80% and then 100%, which had the lowest values, with both the surface and subsurface drip irrigation system. The yield and water productivity of the subsurface drip irrigation system were slightly higher than for surface drip irrigation system in the two seasons. Table VII shows observed and simulated water productivity and its relative difference and the statistical indicators during both seasons. In the two seasons, under surface drip irrigation system, the water productivity for bean yield was (3.59 - 3.14), (4.07-3.56) and (4.39- 3.82) kg m^{-3} for 100, 80 and 60% ETc, respectively. While the water productivity values under subsurface drip irrigation were (3.67-3.18), (4.26-3.71) and (4.55-3.97) kg m^{-3} for 100, 80 and 60% of ETc, respectively. These results are in agreement with Abd El-Mageed *et al*. (2016) and Abd El-Wahed *et al*. (2017).

Overall, the water productivity in relation to the irrigation system showed that the water productivity of the subsurface drip irrigation system is higher than that of the surface drip irrigation system.

Figure 10 indicates that the statistical indicators obtained from comparing simulated with observed data showed a good agreement between measured and simulated water productivity values. CRM showed that, the model simulated dry matter with an insignificant underestimate, where CRM was -0.007 and -0.021 while RMSE was 0.101 and 0.049 during 2017 and 2018 season, respectively.

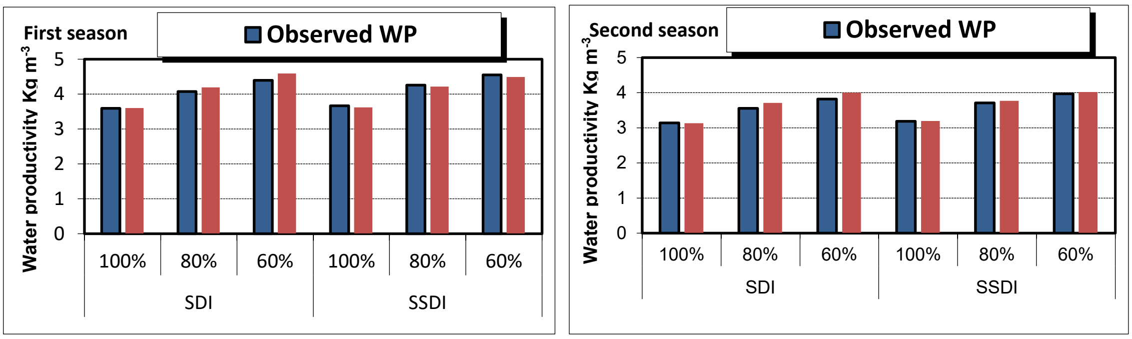


Figure 9. Water productivity of bean crop under two irrigation systems and three irrigation treatments for 2017, first season, and 2018, second season

Table VII. Observed and simulated water productivity of beans

Irrigation system	ETc %	First season, 2017 Irrigation amount, m^3	Water productivity kg m^{-3} Observed	Simulated	Relative difference %	Second season, 2018 Irrigation amount, m^3	Water productivity kg m^{-3} Observed	Simulated	Relative difference %
Surface drip irrigation	100	2790	3.59	3.60	-0.25	3240	3.14	3.13	0.43
	80	2240	4.07	4.19	-2.92	2590	3.56	3.71	-4.39
	60	1670	4.39	4.59	-4.48	1940	3.82	4.00	-4.86
Sub surface drip irrigation	100	2790	3.67	3.62	1.28	3240	3.18	3.20	-0.36
	80	2240	4.26	4.21	1.02	2590	3.71	3.77	-1.61
	60	1670	4.55	4.49	1.37	1940	3.97	4.02	-1.33
RMSE					0.101				0.049
CRM					-0.007				-0.021
R^2					0.939				0.973

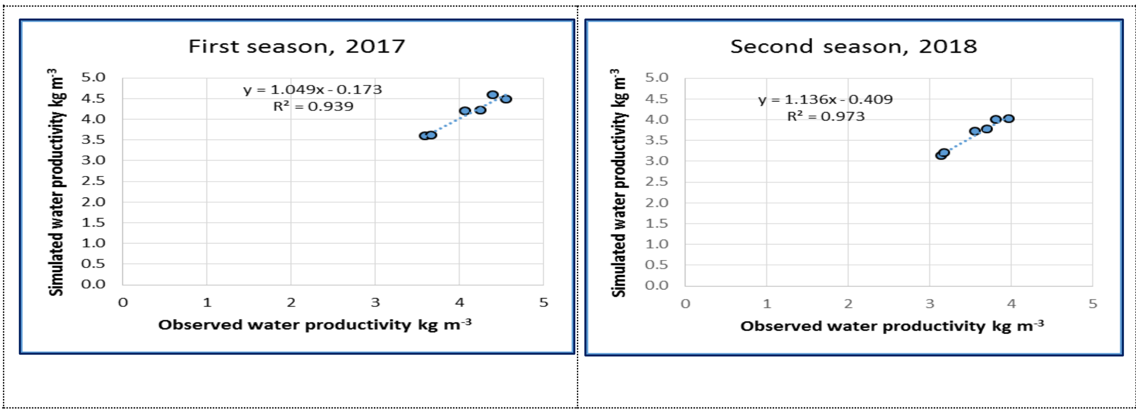


Figure 10. Correlation between observed and simulated water productivity during both seasons

Overall model performance

Figure 11 shows overall coefficient R^2 for all values of bean yield, dry matter, water productivity and soil moisture at all layers under the two irrigation systems with all water treatments.

The values of R^2 proved that SALTMED model is able to simulate the bean crop yield, dry matter and soil and water contents in both seasons, where R^2 values were 0.906, 0.976, 0.933 and 0.960 for soil moisture, yield, dry matter and water productivity, respectively.

The results proved that the model is able to precisely predict soil moisture content, yield, water productivity and dry matter for field crops cultivated under different deficit irrigation levels under both surface and subsurface drip irrigation.

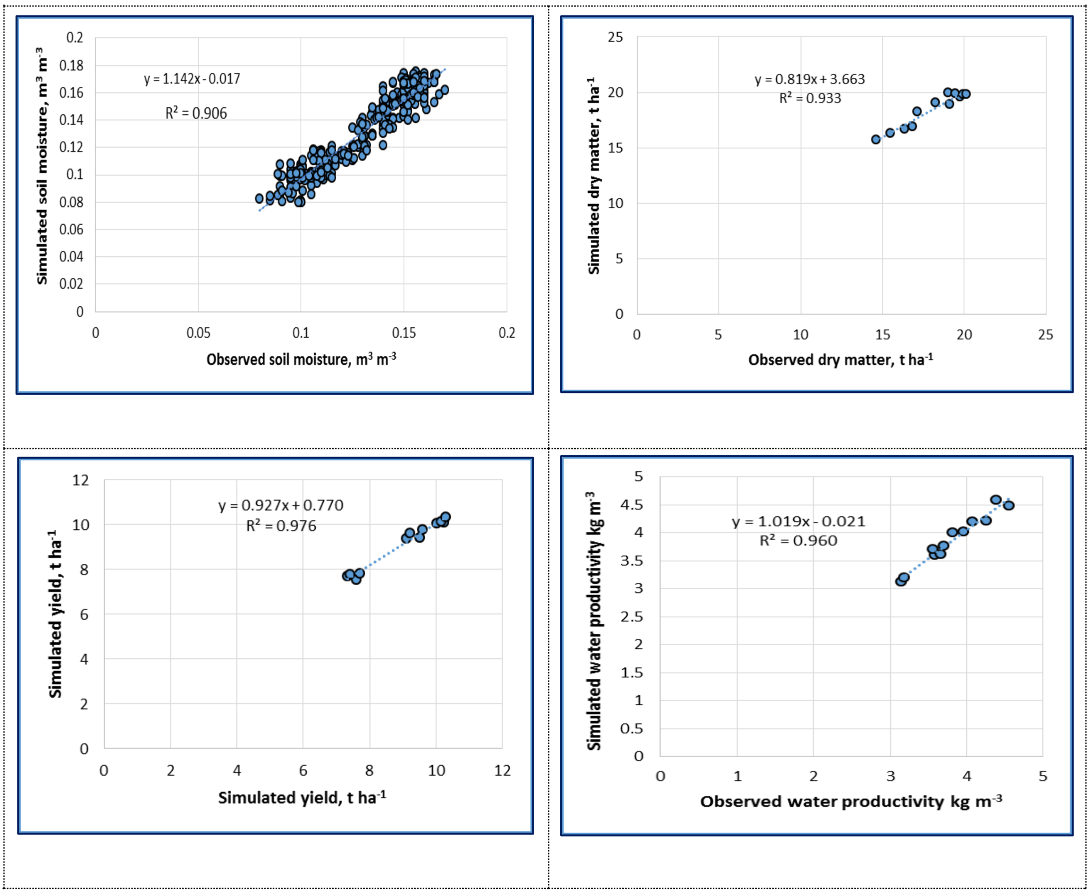


Figure 11. Overall correlations of observed and simulated soil moisture of all layers, yield, dry matter and water productivity for both seasons, two irrigation systems and water treatments

CONCLUSIONS

The highest yields were obtained with the 100% ETc treatment. The difference in yield between the 100% ETc and 80% ETc treatment was, however, not significant. This may be due to the fact that the small decrease of the moisture content when irrigating at 80% ETc within the root zone was not enough to cause water stress to the roots of the bean plant. This means a 20% saving of irrigation water can be achieved without significant reduction in yield. The fact that irrigating with 80% ETc was close to the100% ETc confirms the finding by Ragab *et al.* (2017). These findings indicated that the actual crop water requirement based on actual evaporation is significantly less than the crop water requirement based on ETc calculated from the potential evapotranspiration equations which is the case in this study.

During the first season, the yield of subsurface drip irrigation was higher than the surface drip irrigation by 2.05% for 100% Etc, 4.49% for 80% Etc treatment and 3.60% for 60% Etc treatment with an average of 3.38%. For the three treatments. While in the second season, the yield of subsurface drip irrigation was higher than the surface drip irrigation by 1.32% for 100% Etc, 3.92% for 80% Etc treatment and 3.92% for 60% Etc treatment with an average of 3.17%. For the three treatments and 3.28% for the combined two seasons.

Water productivity with subsurface drip irrigation was higher than with surface drip irrigation. This may be due to the the fact that with subsurface drip irrigation there is no possibility of loosing water by evaporation from the soil surface. With subsurface drip irrigatin, the water is kept in the root zone for the longest possible time, so that the roots of the crop are less subjectied to moisture stress than when using surface drip irrigation.

During the first season, the water productivity of subsurface drip irrigation was higher than the surface drip irrigation by 2.23% for 100% Etc , 4.67% for 80%Etc treatment and 3.64% for 60% Etc treatment with an average of 3.57%. For the three treatments. While in the second season, the water productivity of subsurface drip irrigation was higher than the surface drip irrigation by 1.27% for 100% Etc , 4.21% for 80%Etc treatment and 3.93% for 60% Etc treatment with an average of 3.23%. For the three treatments and 3.4% for the combined two seasons.

The above results indicated that the subsurface drip irrigation would produce slightly higher yield and water productivity than surface drip irrigation. However, the results showed that the main benefit is a water saving of 20% should the crop is irrigated with 80% of Potential crop evapotranspiration, Etc.

The SALTMED model simulated soil moisture, total dry matter and yield for bean under surface and subsurface drip irrigation and irrigation treatment in Egypt with good accuracy. Therefore, the SALTMED model can be used for simulating and predicting crop production, water productivity and crop growth under different 'what if' scenarios of soil, water and climate.

The field experiment and SALTMED modelling study indicated that there were no large variations between observed and simulated data in soil moisture of all the soil layers. The variations in soil moisture in both layers are very small due to the frequent irrigation, which kept the soil moisture high. The irrigation treatments have an effect on yield and total dry matter under both irrigation systems. The 100% ETc treatment had a relatively higher yield and total dry matter and the lowest yields were obtained at 60% ETc, with a small difference between surface and subsurface drip irrigation.The highest values of water productivity were correlated with 60% ETc, followed by 80%, then 100%. The 100% ETc treatment had the lowest water productivity under both surface and subsurface drip irrigation system.

ACKNOWLEDGEMENTS

This research was funded by the Science and Technology Development Fund in Egypt (STDF), Short Term Fellowship program. The authors are grateful to STDF and its staff members for the support to carry out this work. Thanks are also extended to the technical staff of the Water Relations and Field Irrigation Department, National Research Centre.

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