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Water Productivity and Yield of Wheat as Affected by Irrigation Systems and Water Deficit Under New Valley Conditions

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Abstract

Improving the irrigation water productivity of wheat under water shortage and high evaporation such as New Valley conditions is crucial. Two field experiments were carried out during the two successive winter seasons of 2014/2015 and 2015/2016 on the Experimental Farm, Agricultural Research Station at El-Kharga, the New Valley Governorate. The experiment was laid out in strip plot design with four replications. Irrigation methods (flood, sprinkler and drip) were allocated horizontally; while, irrigation regimes (25, 50 and 75% soil moisture depletion, SMD) were arranged vertically.

Results reveal that applying drip and sprinkler irrigation methods increased grain yield of wheat by 19.86-33.72% and 4.83-13.14% in both seasons, respectively as compared with flood irrigation method.

The maximum mean values of grain yield (2825 and 2609 kg fed^{-1}) were obtained under the 25% SMD regime in the both seasons.

Seasonal ET_a mean values were 1614 and 1706 m^3 fed^{-1} under flooding irrigation method; 1586 and 1676 m^3 fed^{-1} under sprinkler irrigation method; 1559 and 1653 m^3 fed^{-1} under drip irrigation method in the first and second seasons, respectively.

The crop water productivity (CWP) mean values for grain and straw yields of wheat were 1.67 and 2.77 kg m^{-3} in the first season being 1.64 and 2.60 kg m^{-3} in the second season, respectively. The IWP followed the same trend; the values of irrigation water productivity (IWP) were 1.42 and 2.36 kg m^{-3} in the first season and 1.40 and 2.22 kg m^{-3} in the second season for grain and straw yields of wheat, respectively.

Comparing with flood irrigation method, the gross return (grain + straw) per consumptive water in ET unit under drip irrigation was increased by 23.97 and 32.04%. Moreover, this revenue was enhanced to 81.42 and 94.06% for irrigation water unit in both seasons, respectively.

It could be concluded that applying drip irrigation at 50% SMD improved yield and water productivity of wheat as well as saving irrigation water.

Keywords: Wheat productivity, Water productivity, irrigation systems, irrigation regimes

Introduction

New Valley has hyper-arid climate which is the same climatic characteristics of the Western desert. In these condition and the resembling conditions, water scarcity is the main limited factor on crop productivity, where it is difficult to apply full crop water requirements to sustain maximal growth and yield (Abdel-Mawgoud *et al*., 2009). So, applying the suitable water management strategy is important. There are numbers of water management strategies to save irrigation water, improve fertilizer use efficiency and reduce production cost, consequently maximize economical returns. These strategies included applying deficit irrigation, choosing the efficient irrigation method and irrigation scheduling.

Wheat (*Triticum sp*) is one of the most important staple food grains of human. Usually, it is planted under surface and sprinkler irrigation methods under the New Valley conditions. Meanwhile, drip irrigation can be practiced successfully to irrigate wide range of crop variety especially in vegetables, orchard crops, flowers and plantation crops but on the other hand, limited studies had been conducted under field crops like wheat (Chouhan *et al*., 2015). Drip and sprinkler irrigation methods are more preferable than traditional surface methods. It is necessary to develop new irrigation scheduling approaches as well as designed to ensure the optimal use of allocated water. Irrigation scheduling based on deficit irrigation requires careful evaluation to ensure enhanced efficiency of use of increasingly scarce supplies of irrigation water.

Therefore, this study was conducted to evaluate the effect of irrigation regimes under flood, sprinkler and drip irrigation methods on wheat and water productivity in the New Valley region.

Materials and Methods

A field experiment was carried out during the two successive winter seasons of 2014/2015 and 2015/2016 at the Experimental Farm, Agricultural Research Station of El-Kharga, the New Valley Governorate to study the effect of irrigation methods and water deficit on wheat productivity and water use efficiency (WUE) under New Valley conditions. The treatments were three irrigation methods (flood, sprinkler and drip) and three irrigation regimes (25, 50 and 75% soil moisture depletion, SMD).

Monthly meteorological data collected from El-Kharga Weather Station are show in Table 1.

Table 1. Meteorological data of the experimental site according to El-Kharga agro-meteorological station during the two growing seasons.

Month	Min. Temp. (°C)	Max. Temp. (°C)	Mean Temp. (°C)	Mean humidity (%)	Wind speed (ms^{-1})	Precip. (mm)
2014 - 2015						
November	19.8	33.7	27.0	34.1	3.2	0.0
December	13.9	28.6	21.4	43.7	2.6	0.0
January	6.4	22.2	14.4	46.9	2.2	0.0
February	9.1	25.2	17.3	41.5	2.6	0.0
March	14.5	29.6	22.6	31.8	3.4	0.0
April	15.1	32.0	24.5	25.5	3.4	0.0
2015-2016						
November	22.9	35.4	29.3	36.2	3.4	0.0
December	14.9	28.4	22.0	47.1	2.7	0.0
January	6.8	20.9	14.0	49.3	2.6	0.0
February	15.0	35.2	24.6	32.0	2.6	0.0
March	15.9	28.8	22.2	34.0	6.0	0.0
April	21.3	37.4	28.7	24.0	3.0	0.0

The physical and chemical analyses of experimental soil and irrigation water (Table: 2 and 3) were determined according to Piper (1950), Jackson (1973) and Klute (1986).

The experiment was laid out in strip plot design with four replications. Irrigation methods were allocated horizontally; while, irrigation regimes were arranged vertically.

Wheat (*Triticum sp., cv.* Sids 12) grains were hand drilled at the rate of 60 kg fed^{-1} on 20 and 15 November during 2014/15 and 2015/16 seasons, respectively. The experimental plot area was 36 m^2 (6x6m) there were 30 rows in each experimental unit spaced 0.2 m and 6 m long under all studied irrigation methods.

Table 2. Some physical and chemical characteristics of the experimental soils.

Characteristics	**Growing season**					
	1st Season			**2nd Season**		
	Depth (cm)					
	0-20	20-40	40-60	0-20	20-40	40-60
Sand %	81.31	59.11	54.18	82.11	59.02	55.27
Silt %	8.57	5.44	4.93	7.80	4.93	5.48
Clay %	10.12	35.45	40.89	10.09	36.05	39.25
Soil texture	Loamy Sand	Sandy clay	Sandy clay	Loamy Sand	Sandy clay	Sandy clay
Water Saturation % (v v^{-1})	41.73	47.86	49.11	41.97	47.70	49.30
Field Capacity% (v v^{-1})	24.15	27.57	27.81	24.31	27.26	28.09
Wilting point% (v v^{-1})	11.34	14.00	13.94	11.47	13.65	14.26
Available water% (v v^{-1})	12.81	13.57	13.87	12.84	13.61	13.83
Bulk density (g cm^{-3})	1.59	1.36	1.33	1.60	1.33	1.34
$CaCO_3$ %	3.60	0.80	0.70	3.45	0.60	0.69
pH (1:1 suspension)	7.62	7.85	7.68	7.70	7.81	7.55
EC (1:1 extract) dS m^{-1}	0.44	0.76	2.86	0.54	0.70	2.71

Table 3. Some properties of irrigation water

Character	**Values**
EC dSm^{-1}	0.48
pH	6.76
Ca^{+2} meq l^{-1}	1.09
Mg^{+2} meq l^{-1}	1.13
Na^{+1} meq l^{-1}	1.43
K^{+1} meq l^{-1}	1.07
CO_3^{-2} +HCO_3^{-1} meq l^{-1}	2.30
Cl^{-1} meq l^{-1}	1.64
SO_4^{-2} meq l^{-1}	0.75
SAR	1.35
Fe (ppm)	1.29
Mn (ppm)	0.10

Under flood and drip irrigation systems, plots were bounded with buffer zone (3 m width) to avoid the horizontal seepage. Meanwhile, it was separated by 2 m alleys under sprinkler irrigation system.

The irrigation treatments started at 20 days after sowing. All experimental units received equal amounts of water during germination.

Nitrogen fertilizer was applied at a rate of 30 kg fed^{-1} as ammonium nitrate (33.5% N) in four equal doses, beginning with the first irrigation until heading. Before sowing, phosphorus and potassium fertilizers were applied at the rate of 30 and 24 kg fed^{-1} as super phosphate (15% P_2O_5) and potassium sulphate (48% K_2O), respectively.

All other cultural practices were followed as recommended for wheat crop during the two growing seasons under this region condition.

Irrigation system description

The used sprinkler irrigation system was a solid set system with spacing of 12×12 m between laterals and between sprinklers. Sprinkler flow rate was 1.2-1.5 m^3 h^{-1} at 2-3 bars.

Drip irrigation system was used in this experiment. The lateral lines were polyethylene tube of 16 mm in diameter with built-in dripper of 30 cm apart and having a discharge rate of 4 L h^{-1}. Laterals were installed at 50 cm apart.

Soil-plant-water relationships

Actual crop evapotranspiration was measured directly by measuring changes in soil water content using Time Domain Reflectometry (TDR); model MP-917 at 0 to 0.6 m soil depth, according to Israelson and Hansen (1962) as follows:

$$ETa = \sum_{i=1}^{n=4} (\theta_2 - \theta_1) \times d / 100$$

Where: ET_a, n, θ_1, θ_2 and d are actual crop evapotranspiration, number of layers, soil moisture % before irrigation (v v^{-1}), soil moisture % 24 h after irrigation (v v^{-1}) and soil depth (cm), respectively.

The amounts of irrigation water applied were measured by flow meter under sprinkler and drip irrigations. Meanwhile, calibrated contracted rectangular weir to measure water amounts under free flow conditions for all treatments for surface irrigation. The head of the water (h) was monitored and the discharge (Q) was determined using Francis (1883) equation.

$$Q = 3.33 h^{3/2} (L - 0.2h)$$

Where:
Q =Discharge Q, in cubic foot per second (cfs)
h = Head on the weir, in foot
L = Length of the weir, in foot

The daily pan evaporation data was used for scheduling irrigation. Irrigation treatments were given once in three days interval. The pan was located near the experimental research station field. The following equation (Doorenbos and Pruitt, 1977) was used to calculate the potential evapotranspiration (ET_p):

$$ET_p = E_{pan} \times K_{pan}$$

where:
E_{pan} = pan evaporation (mm day^{-1})
K_{pan} = pan coefficient (0.7)

At harvest, one square meter was chosen randomly from each experimental unit to determine biological, grain and straw yields.

Crop and irrigation water productivity (IWP) can be expressed as physical productivity (PWP) and economical water productivity (EWP) according to Molden (1997). It was calculated as follows:

$$PWP\,(kg\,m^{-3}) = \frac{Grain\ yield\ or\ straw\ yield\ (kg\ fed^{-1})}{Total\ amount\ of\ irrigation\ water\ applied\ (m^{3}\ fed^{-1})}$$

$$EWP\,(L.E\,m^{-3}) = \frac{Gross\ value\ of\ product\ (L.E\ fed^{-1})}{Total\ amount\ of\ irrigation\ water\ applied\ (m^{3}\ fed^{-1})}$$

Statistical analysis

The results were statistically analyzed according to Gomez and Gomez (1984), using the computer MSTAT.C statistical analysis package by Freed *et al*. (1989). The least significant differences (L.S.D) probability level of 5% was manually calculated compare the differences among means.

Results and Discussion

1. Wheat productivity

As shown in Table 4, irrigation methods have significant effect on most grain and biological yields of wheat; meanwhile, this effect on straw yield was insignificant in both seasons.

Drip-irrigated wheat plants registered the highest mean values of grain, straw and biological yields of wheat (2583, 4263 and 6845 kg fed^{-1} in the first season and 2677, 4211 and 6889 kg fed^{-1} in second season, respectively). The increment percentages of studied trait due to drip irrigation were 19.86 and 33.72%, 12.72 and 11.73%, 15.29 and 19.37% over flood irrigation in both seasons, respectively. The sprinkler irrigation came in the second rank; it was increased grain yield by 4.83 and 13.14% as compared with flood irrigation method in the first and second seasons, respectively. Straw and biological yields were increased as affected by sprinkler irrigation when compared with flood irrigation method in the second season only.

Furthermore, the obtained data indicate that the increasing water stress tends to significantly decrease the yield. Generally, the maximum mean values of grain, straw and biological yields (2825 and 2609, 4973 and 4609, 7798 and 7218 kg fed^{-1}) are obtained under the 25% SMD regime in the respective seasons, respectively. The minimum mean values of grain, straw and biological yields were recorded (1678 and 1894, 2477 and 3259, 4155 and 5153 kg fed^{-1}). The previous results could be explained that irrigation at 25% SMD save sufficient soil moisture in the root zone which increased the capacity of wheat plant in photosynthesis and increase spike length, grain weight spike^{-1}, number of grains spike^{-1}, 1000- grain weight which were reflected on increasing grain yield fed^{-1}. The previous results are in full agreement with those reported by Mekkei and El Haggan (2014), Tabassam *et al*. (2014), Zahoor (2014) and Kouzegaran *et al*. (2015).

Grain yield of wheat was significantly affected by the interaction between irrigation system and irrigation regimes in both seasons. Meanwhile, this interaction has insignificant effect on straw and biological yields. Using drip irrigation at 25% SMD regime gave the highest mean values of grain yield (3067 and 385 kg fed^{-1}) and biological yield (7970 and 7364 kg fed^{-1}). Maximum value of straw yield was recorded by flood, sprinkler and drip methods with 25% SMD in the first and the second seasons, respectively.

2. Water Indices

2.1. Actual Evapotranspiration (ET_a):

The obtained data in Table 5 showed that there are some small differences of the seasonal ET_a under different irrigation methods in both seasons. Seasonal ET_a mean values of both seasons were 1614 and 1706 m^3 fed^{-1} under flooding irrigation method; 1586 and 1676 m^3 fed^{-1} under sprinkler irrigation method; 1559 and 1653 m^3 fed^{-1} under drip irrigation method in the first and second seasons, respectively. Data also show that the mean values of seasonal ET_a under drip and sprinkler irrigation were less by about 1.75 and 3.42% in the first season; 1.71 and 3.06% in the second season compared with flood irrigation, respectively. The saved amounts of water by sprinkler and drip irrigation methods were 28 and 55 m^3 fed^{-1} in the first season; 29 and 52 m^3 fed^{-1} in the second season. The saved water may be due to the application efficiency of these irrigation methods (Mohamed, 2007).

Seasonal evapotranspiration of wheat was increased as the available soil moisture increased in the root zone area. Where, the values of seasonal water consumptive use for wheat were 1831, 1551 and 1377 m^3 fed^{-1} in the first season and 1938, 1634 and 1464 m^3 fed^{-1} in the second season under irrigation at 25, 50 and 75% SMD, respectively. It is clear that the seasonal ET_a mean values were decreased as affected by increasing soil moisture depletion. These data indicate that using irrigation at 50 and 75% SMD saved water by 15.29 and 24.79% in the first season; 15.72 and 24.50% in the second season compared to SMD of 25%, respectively. The most probable explanation for these findings is that more available soil moisture provided a chance for more luxury water use, which ultimately led to increase transpiration (Abd-El-Hafez *et al.*, 1999, Abdel Aziz, 2009 and Hassan, 2016).

Also, data reveal that increasing soil moisture depletion up to 50 and 75% decreased seasonal ET_a by 15.56-15.61 and 25.01-24.33% under flood irrigation method; 15.78-15.77 and 25.53-24.74% under sprinkler irrigation method; 14.51-15.80 and 23.81-24.42% under drip irrigation method compared to their respective values of 25% SMD within each system in both season, respectively. It is mean that increasing water stress up to 50 and 75% SMD saved 299 to 473 m^3 fed^{-1} under flood irrigation method, 298 to 474 m^3 fed^{-1} under sprinkler irrigation method; 280 to 446 m^3 fed^{-1} under drip irrigation method.

2.2. Irrigation Water Applied (IWA) and Water Application Efficiency (WAE):

The seasonal irrigation water applied and water application efficiency values of wheat were greatly affected by the irrigation methods and the soil moisture depletion (SMD) treatments (Table, 5).

The amounts of applied irrigation water were decreased with increasing soil moisture depletion in both seasons. The highest mean values of applied irrigation water were recorded by flood irrigation method (2761 and 2933 m^3 fed^{-1}) followed by sprinkler irrigation method (2151 and 2273 m^3 fed^{-1}). Meanwhile, drip irrigation method (1831 and 1931 m^3 fed^{-1}) in both seasons, respectively came in the third rank with lowest applied water. On the contrary, drip irrigation gave the highest mean value of application efficiency (85.01 and 85.55%). Meanwhile, sprinkler irrigation came in the second rank with 77.43 and 77.31%. Poor water application efficiency was observed by flood irrigation method (58.46 and 58.20%) in both seasons, respectively. These may due to drip irrigation has the potential to increase irrigation efficiency because it can apply water both precisely and uniformly at a high irrigation frequency compared with surface and sprinkler irrigation methods.

Moreover, the data presented in Table 5 pointed out that increasing water stress decreased the amounts of irrigation water. Low water stress (25% SMD) treatment gave the highest values followed by the moderate soil water stress (50% SMD) treatment. Whereas, higher soil water stress conditions (75% SMD) recorded the lowest mean values in both seasons, respectively. Partially, different trend was detected by the application efficiency, where it was increased by increasing soil moisture depletion up to 50%. The obtained results agreed with those obtained by Al-Jamal *et al*. (2001) who stated that the irrigation efficiency for irrigation system in the non-stressed ones was less than that with stressed treatments.

Concerning the interaction between irrigation methods and water deficit, the obtained results revealed that irrigation at 50% SMD followed by 75% SMD under drip irrigation method achieved the highest mean values of water application efficiency (86.89 and 87.17%) and (84.24 and 84.77%) in both seasons, respectively. Meanwhile, the lowest value was at SMD of 25% under flooding irrigation method (57.73 and 57.21%) in both seasons, respectively.

2.3. Physical Water Productivity:

Physical Water productivity (PWP) can be increased by increasing yield and/or reducing water use. This term can be divided into crop water productivity (CWP) and irrigation water productivity (IWP). The CWP and IWP terms defined as the yield per unit of water used in ET or irrigation water, respectively.

Data in Table 6 show the effect of irrigation methods on physical irrigation water productivity of grain and straw yields of wheat. Physical water productivity was showed the highest values for grain and straw yields of wheat under drip method followed by sprinkler then flood methods. The

CWP values were 1.67 and 2.77 kg m^{-3} in the first season and 1.64 and 2.60 kg m^{-3} for grain and straw yields of wheat in the second season, respectively. The IWP followed the same trend; the values of IWP were 1.42 and 2.36 kg m^{-3} in the first season and 1.40 and 2.22 kg m^{-3} in the second season for grain and straw yields of wheat, respectively. These results are in agreement with those obtained by Chouhan *et al*. (2015), they reported that water productivity of drip irrigated wheat was 24.24% more than the border irrigated wheat.

The effect of irrigation regimes on CWP and IWP for grain and straw yields of wheat was significant in the most cases. Data indicate that CWP and IWP values for grain yield are increased with increasing water stress up to 50% SMD. However, these traits for straw yield haven't clear response trend to irrigation regimes. These results are in harmony with those of El-Hadidi *et al*. (2015) who stated that WP increases under DI, relative to its value under full irrigation.

The interaction effect of irrigation methods and irrigation regimes on CWP and IWP was insignificant. Moreover, the data show that the highest values of these traits were obtained under drip irrigation at 50% SMD followed by 75% SMD under the same irrigation method. On contrary, the lowest values of CWP and IWP were recorded by flood irrigation at 75% SMD.

2.4. Economical Irrigation Water Productivity

Economical water productivity (EWP) is a measure to capture the value of economic gains made through consumption of the unit amount of water (LE m^{-3}). Economical water productivity follows the same trend of physical water productivity. The effect of irrigation methods on grain EWP was significant (Table, 7). Irrigated wheat plants with drip irrigation were more profit than that irrigated with sprinkler and flood irrigation methods per irrigation water unit. Drip irrigation was gave the highest values of ECWP grain yield (6.26 and 6.14 LE m^{-3}) and straw yield (3.05 and 2.86 LE m^{-3}). The EIWP was followed the same trend, it is reach to 5.32 and 5.25 LE m^{-3} for grain yield; 2.59 and 2.45 LE m^{-3} for straw yield. Comparing with flood irrigation method, the gross return (grain + straw) per consumptive water in ET unit under drip irrigation was increased by 23.97 and 32.04%. Moreover, this revenue was enhanced to 81.42 and 94.06% for irrigation water unit in both seasons, respectively. This may be due to reduce water losses in deep percolation, in surface runoff and in evaporation from the soil, consequently enhancing water application efficiency compared to flood irrigation method.

Data in Table 7 show that ECWP and EIWP mean values followed the same trend of CWP and IWP, where were increased with increasing water stress up to 50% SMD. The highest values of ECWP and EIWP were observed by 50% SMD followed by 25% SMD regime. Meanwhile, the lowest values were recorded by 75% SMD regime. In this regard, Ali *et al*. (2007) applied drip irrigation (DI) on wheat crop and evaluates economics of DI under both water and land limiting conditions. They reported that 60% DI at V and PF stage was found more beneficial among other DI strategies in considering additional land under irrigation which satisfied the objectives of DI.

The interaction between irrigation methods and irrigation regimes was insignificant, while the data show that applying 50% SMD under drip irrigation method improved ECWP and EIWP (grain + straw) by 15.92 and 75.25% in the first season; 30.78 and 99.33% in the second season, respectively compared to flood irrigation method with 25% SMD.

Conclusion

It can conclude that applying drip irrigation at 50% SMD to improve yield and water productivity of wheat as well as saving irrigation water.

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تأثير نظم الري ونقص الماء على الإنتاجية المائية ومحصول القمح تحت ظروف الوادي الجديد

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الملخص

يهدف هذا البحث إلى تحسين الإنتاجية المائية ومحصول القمح تحت ظروف الوادي الجديد. أجريت تجربة حقلية في مزرعة محطة البحوث الزراعية بالخارجة– محافظة الوادي الجديد خلال موسمي ٢٠١٤/٢٠١٥ و٢٠١٥/٢٠١٦. استخدم تصميم الشرائح المنشقة في أربعة مكررات. تم اختيار ثلاث طريق ري (الري بالغمر، الري بالرش، الري بالتنقيط) مع ثلاث مستويات من استنزاف رطوبة التربة (٢٥، ٥٠، ٧٥٪ استنزاف من رطوبة التربة).

أوضحت النتائج أن استخدام الري بالتنقيط أو الري بالرش أدى لزيادة محصول الحبوب من القمح بزيادة قدرها ١٩,٨٦–٣٣,٧٢٪ موسمي الدراسة على التوالي مقارنة مع الري بالغمر.

أعلى قيم لمحصول الحبوب من القمح (٢٨٢٥ و٢٦٠٩كجم للفدان) تم الحصول عليها من نباتات القمح المروية عند استنزاف ٢٥٪ من الماء الميسر بالتربة.

بلغ الاستهلاك المائي الموسمي للقمح ١٦١٤ و١٧٠٦ م^3 للفدان باستخدام نظام الري بالغمر و١٥٨٦ و١٦٧٦ م^3 للفدان باستخدام نظام الري بالرش، كما وصل إلى ١٥٥٩ و١٦٥٣ م٣ للفدان باستخدام نظام الري بالتنقيط في موسمي الدراسة على التوالي.

وصلت قيم الإنتاجية المائية المحصولية إلى ١,٦٧ و٢,٧٧ كجم/ م^3 في الموسم الأول و ١,٦٤ و٢,٦٠ كجم/ م^3 لكل من محصولي الحبوب والقش في الموسم الثاني على التوالي. سلكت الإنتاجية المائية لمياه الري نفس الاتجاه وكانت قيمها ١,٤٢ و٢,٣٦ كجم/ م^3 في الموسم الأول و١,٤٠ و٢,٢٢ كجم/ م^3 في الموسم الثاني لكل من محصول الحبوب والقش على التوالي.

العائد الكلي (حبوب وقش) لكل وحدة مياه مستخدمة في إنتاج المحصول باستخدام الري بالتنقيط زاد بنسبة ٢٣,٩٧ و٣٢,٠٤٪ مقارنة بالري بالغمر. بالإضافة لذلك، فان هذا العائد زاد إلى ٨١,٤٢ و٩٤,٠٦٪ لمياه الري المضافة في موسمي الدراسة على التوالي.

مما سبق يمكن التوصية باستخدام نظام الري بالتنقيط عند استنزاف ٥٠٪ من رطوبة التربة لتحسين المحصول والإنتاجية المائية للقمح وكذلك توفير مياه الري.