Evaluation of prototype machine for planting discontinuous ridges to optimize efficiency of surface irrigation system in Ras sudr-South of Sinai

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Surface irrigation is the dominant method of on-farm irrigation in Egypt as well as worldwide. Furrow watering is considered as one of the main types of surface irrigation. Most of the cultivated crops are grown under such type of watering. Under the present situation of water shortage that facing Egypt resulted in capita share from water for different purposes becomes less than the water poverty edge and expected more decreasing to reach the scarcity level in the few coming decades. Moreover, Egypt is the solely country in the world that its agriculture is depending mainly on irrigation, i.e. irrigated agriculture due to the high arid condition of the country, especially in areas which face problems in the crops productivity due to the high salinity in soil or irrigation water where, these systems reduce the impact of salinity on plant growth. The main purpose of this research is carrying out the discontinuous ridges in short lengths (discontinuous ridges system, DRS) to give irrigation water chance to fill all space around the short ridges from four direction which cause fast wetness of ridges to increase the horizontal infiltration rate of water into ridges and decrease the water loss by vertical infiltration. To carry out DRS the developed machine was manufactured for installing ridges in different lengths and sowing field crops on these ridges. A field experiment was conducted at Ras-Sudr Research Station in South Sinai Governorate to evaluate the performance of the developed machine and study its impact on the efficiency of furrow surface irrigation system and yield of millet crop. The evaluation process was achieved by carrying out five levels of ridges lengths (0.5m, 1m, 1.5m, 2m and 30m) and three levels of irrigation rate (70%, 85% and 100% from total water irrigation applied). The effects of these treatments were studied on the machine performance, surface irrigation system efficiency, soil salinity, yield of millet crop (fresh forage) and productivity of irrigation water. The results showed that the system of cutting irrigation ridges into short lengths (0.5m, 1m, 1.5m and 2m) reduced the actual field capacity and the field efficiency of the machine about 10% and 9%, respectively, and increased the fuel consumption rate and pulling force of the machine about 19% and 37%, respectively compared to continuous ridges of length (30m). In general, the results showed that the best treatment achieved the highest stored water, consumptive water, stored water efficiency, consumptive water efficiency, and millet crop yield, at the irrigation level of 100% and the ridge length of one meter. The lowest level of soil salinity and the highest irrigation distribution uniformity achieved at an irrigation level of 100% and a ridge length of 0.5 m. The highest productivity of irrigation water achieved at an irrigation level of 85% and a ridge length of one meter. While, the lowest values of all study measurements were achieved at the irrigation level 70% and the ridge length 30m. The optimum ridge length and water application level were about 1.25m and 90% respectively, which achieved the highest productivity of irrigation water.

Keywords: discontinuous ridges, furrow surface irrigation, soil management, soil salinity, water saving.
INTRODUCTION

Water scarcity in most developing countries imposes a large economic burden on governments, and efficient use of irrigation water is considered a top priority to conserve this resource. Due to the limited atmospheric precipitation and lack of appropriate spatial and temporal distribution, is classified as an arid and semi-arid country. However, a rapidly growing population, urbanization, and development of both economic and agricultural areas have increased demands for water resources (Machekposhti et al. 2017). On a global basis, 69% of all water with drawn for human use is currently consumed by agriculture, most in the form of irrigation with very low use efficiency (30-40%). Surface irrigation methods having relatively lower water use efficiency when compared to the pressurized systems are responsible for this. Surface irrigation is widely practiced throughout the world, more than 95% of world’s irrigated area (UN/WWAP, 2003 and Prinz 2004). Surface irrigation is the most common executed irrigation system in Egypt as well as worldwide. This wide spread implementation might be due to its low capital cost, no special technical experience regarding operation and maintenance is needed and no specific equipment are required as well as the long practical background among local farmers regarding usage of such system. On the other hand, surface irrigation among other methods has the lowest irrigation efficiency. Deep percolation particularly in the upper part of the irrigated field as well as the less-uniformity of irrigation water above soil surface are the main causes of the lower efficiency of surface irrigation. In average, losses of irrigation water under this method is about 45% causing several acute problems such as leaching of nutrient elements and raising of water table. Consequently, reduction in crop yield, crop-water and/or fertilizer productivity could be predicted. Egypt is the solely country in the world that its agricultural production is irrigated, i.e. no rain fed agriculture from the economic point of view is practiced due to the very dry condition with mean annual rainfall of less than 250 mm. Under the present situation of rapid increasing of population and the limited water supply, annual capita share from water for different purposes is decreasing to less than the water poverty edge of 1000 m³ and is expected to be less than the water scarcity level of about 500 m³ in the few coming decades. At this situation it is hardly to make any progress in any sector of development. Agriculture is the main sector in water consumption with about 85% from national water supply (El-Beltagy and Abo-Hadeed, 2008). Surface irrigation is one of the irrigation methods in which water is distributed over the field by over land flow. It is favored over other methods of irrigation (sprinkler, drip) on the basis of simplicity of maintenance and the use of unskilled Labor, minimum capital investment, although it is the historical choices of farmers but it is of low efficiency. Furrows are small channels having a continuous nearly uniform slope and usually perpendicular to the field supply canal and infiltration occurs vertically and laterally through the wetting perimeter of the furrow (Mohamed, 1982). EWUP (1984) reported that a relative safe estimation is that 40 percent or more of the water diverted for irrigation was wasted at farm level through either deep percolation or surface run-off. As reported by Graterol et al. (1993), the great evapotranspiration and deep percolation in the conventional furrow irrigation (CFI) system did not increase yields. This may be so because a greater portion of the evapotranspiration and deep percolation (Dp) could be due to non-productive water losses arising from evaporation from the higher amount of wet soil surface or from deep percolation. Hanson (1993) mentioned that efficient furrow irrigation requires reducing deep percolation and surface runoff losses. Water that percolates below the root zone (deep percolation) is lost to crop production, although deep percolation may be necessary to control salinity. Deep percolation can be reduced by improving the evenness of the applied water and preventing over irrigation. Charles (1995) reported that furrow spacing is easy to adjust when furrows are used to irrigate permanent such as threes or vines, and the number of furrows / rows can be varied. The same effect can be acieration every other furrow on row crops when it is desired to infiltrate a small depth of water during irrigation process. Raine and Bakker (1996) found that in traditional surface (e.g. bay, border check) irrigation systems, the whole surface of the soil is flooded and water flow through the soil is principally one dimensional. In these systems, water applied in excess of the soil-water holding capacity drains out of the bottom of the root zone and assists in the leaching of salts out of the root zone. However, two (e.g. furrow) dimensional water flow occurs within the soil where only part of the soil surface is wetted (e.g. furrow, LEPA, micro-irrigation applied to the surface). Similarly, three-dimensional water and salt movement occurs where the water is placed at some point below the surface (e.g. sub-surface drip irrigation) within the root zone. Hence, under these conditions excess water application does not necessarily translate into deep drainage and
runoff is about 40% of total water supply which irrigation water losses by infiltration and surface 21% for surface runoff. Significant quantities of for the evaporation from water surface, and 18- temporary irrigation network and in the fields, 5-6% (saturation), 20-25% for infiltration within the irrigation water has been used as follows: 51-54% variable furrow inflow on irrigation performance. For a field with highly variable soil characteristics, in decreasing order of their relative impact on furrow irrigation performance, were furrow inflow rate, infiltration, geometry, and roughness. For a field with highly variable soil roughness and infiltration characteristics, spatially varying infiltration may have a greater impact than variable furrow inflow on irrigation performance. According to karajeh et al. (2000), under conventional furrow irrigation (CFI) option, irrigation water has been used as follows: 51-54% of the total water supply was used to moisten soil (saturation), 20-25% for infiltration within the temporary irrigation network and in the fields, 5-6% for the evaporation from water surface, and 18-21% for surface runoff. Significant quantities of irrigation water losses by infiltration and surface runoff is about 40% of total water supply which reduced water supply to the irrigated lands and decreased the efficiency of agricultural production as well as the reliability of drainage systems. This irrigation system has speed up the processes of decomposition and removal of organic elements and mobile forms of nutrients in the root zone that eventually, brought to soil fertility losses. According to Jurriens and Lenselink, (2001) furrow irrigation is most widely used among the surface irrigation methods. It is designed on the basis of soil, crop, topography, size and shape of the irrigated area. A furrow irrigation system has several design variables that affect its performance. These are the inflow rate, the length of the run in the direction of the flow, the time of irrigation cutoff and soil infiltration characteristics. These parameters have been extensively studied by many authors in order to design an optimum furrow to achieve maximum application efficiency. The inflow rate design, which is affected by the slope, the length of the furrow and the intake rate of the soil, can be adjusted by the designer to achieve a good uniformity and to irrigate to the required depth in a reasonable time. Water application efficiency is influenced principally by the amount of water applied, the intake characteristics of the soil and the rate of advance of water in the furrows. Abdel wahab, (2002) mentioned that surface irrigation method is characterized by its low application and distribution efficiencies. This may be due to inadequate management and/or improper design. Osman (2002) found that using gated pipe mean while water saving was (29.64%, 29.9%, 14.5% and 19.7%) in cotton, wheat, corn and rice respectively compared with traditional (flooding) system. Hassan (2004) reported that using gated pipe system increased wheat yield by 6.5% when compared with the traditional method. Due to good condition of plant growth, regulating and controlling of water application to affect the soil water balance. Amer (2007) reported that, in surface irrigation water flow by gravity from one end of the field towards the downstream end. The time until the water leading front reaches the either end of the field is called the advance phase. During flow process, water infiltrates into the soil (root zone) basically in one dimension. Radial flow, at least initially, occurs in furrow irrigation. Once the water reaches the downstream end it either runs off the field (free draining) or embanked depending on the downstream boundary conditions. The flow process included infiltration run off or embanked and continues until the end of irrigation. The time after the leading front reaches the other end of the field and until the irrigation is called storage phase. In this phase the water depth above the surface
and consequently the flow rate gradually decreases and is called depletion phase to zero. Raine and Walker, (2004) found that using optimal management of furrow irrigation and adequate design, it is possible to achieve water use efficiency of 90%. Surface systems are simple, have low energy consumption and require comparatively low initial capital. However, they are often associated with a high labour requirement and low water use efficiency (Smith et al. 2005). Conventional furrow irrigation (CFI), where every furrow is irrigated during consecutive watering, is known to be less efficient particularly in areas where there is shortage of irrigation water. CFI usually causes excessive deep percolation at the upper part of the furrow, insufficient irrigation at the lower part and considerable runoff, resulting in low application efficiencies and distribution uniformities. Proper furrow irrigation practices can minimize water application and irrigation costs, save water, control soil salinity build up and result in higher crop yields (Michael, 2008). As compared to other methods of surface irrigation, furrow method has several distinct advantages: when the available irrigation streams are small, for land of uneven topography, water in the furrows contacts only one-half to one-fifth of the land surface, using furrows irrigation necessitates the wetting of only part of the surface (20% to 50%), thus reducing evaporation losses, lessening the puddling of heavy soils, earlier cultivation is possible which is a distinct advantage in heavy soils, adapted to use without erosion on a wide range of natural slopes by carrying the furrows across a sloping field rather than down the slope, reduces labour requirements in land preparation and irrigation, no wastage of land in field ditches compared to 8 check basin method, Nearly all row crops can be irrigated using furrow method rather than flooding (Michael, 2008). Surface irrigation includes 94% of the application methods of irrigation water at field level, where the water is spread over the field by gravity. The majority of the remaining 6% is irrigated by methods that require energy, hydraulic pressure and pipe systems such as sprinkler irrigation and drip irrigation, (ICID, 2014). Furrow irrigation is widely used, demands a huge primary investment, and requires uniform distribution; however, its water use efficiency never exceeds 60-70% with an average of 50-55% and is influenced by such factors as furrow geometric parameters (lengths, slope, and cross-section), flow rate, plant age, and soil texture and structure (Valipour, et al., 2015).

Therefore, this research concentrates on increasing the efficiency of furrow surface irrigation system through discontinuous ridges in short lengths technique DRS to save water loss. So that a developed machine was manufactured for installing ridges in different lengths and sowing field crops on these ridges in one pass of machine. In addition, conducted the field experiment to evaluate the developed machine and DRS technique for sandy loam soil under different levels of irrigation rates and salinity condition to achieve the highest increasing of millet crop yield and saving irrigation water.

**MATERIALS AND METHODS**

The main aim of this research raising efficiency of surface irrigation system in ridges by install short ridges or discontinuous ridges system (DRS) to increase the soil area of ridges facing the irrigation water in the furrows from two sides to four sides as shown in Figures (1) and (2) which, raise horizontal infiltration rate of irrigation water into the ridges compared to vertical infiltration. So that to carry out DRS the prototype of machine was manufactured and conducted field experiment to evaluate both of the performance of machine and effect of DRS on raising the efficiency of surface irrigation system by saving applied irrigation water and increasing millet yield. The field experiment was carried out at Ras-Sudr Experimental Station, South Sinai (latitude: 29° 37' 26'' N, longitude: 32° 42' 43'' E and the elevation from sea surface = 36.2m), on sandy loam calcareous soil which suffers from the problem of soil and irrigation water salinity where, Salts in the soil-water solution decrease the amount of water available for plant uptake. Maintaining a higher soil-water content with more frequent irrigations relieves the effect of salt on plant moisture stress. A sandy loam is soil containing a high percentage of sand, but having enough silt and clay to make it somewhat coherent. The individual sand grains can be readily seen and felt. Squeezed when dry, a sandy loam forms a cast that falls apart readily. If squeezed when moist, a cast can be formed that bears careful handling without breaking. The field experiment was carried out in the summer season 2020 with an experimental area of about one hectare which irrigated by gated pipe irrigation system. Before the soil preparation directly, the average moisture content of soil surface layer (0-30cm) was determined and found to be 18% (d.b.). Soil texture and some chemical properties of the soil and well irrigation water as shown in Table (1).

**Table (1): Soil texture and some chemical properties of the soil and well irrigation water.**

<table>
<thead>
<tr>
<th>Soil Texture</th>
<th>Chemical Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandy Loam</td>
<td>Some parameters</td>
</tr>
<tr>
<td>Water Content</td>
<td>Average moisture</td>
</tr>
<tr>
<td>Salinity</td>
<td>Control</td>
</tr>
</tbody>
</table>

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Table: Particle size distribution and soil properties

<table>
<thead>
<tr>
<th>Texture class</th>
<th>Particle size distribution, %</th>
<th>Texture class</th>
<th>CaCO₃, %</th>
<th>O.M., %</th>
<th>pH</th>
<th>E.C. ds/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse sand</td>
<td>12.3</td>
<td>Fine sand</td>
<td>58.7</td>
<td>19.7</td>
<td>9.3</td>
<td></td>
</tr>
<tr>
<td>Silt</td>
<td>9.3</td>
<td>Clay</td>
<td>19.7</td>
<td>58.7</td>
<td>12.3</td>
<td></td>
</tr>
<tr>
<td>Sandy loam</td>
<td>46.1</td>
<td></td>
<td></td>
<td>0.43</td>
<td>7.76</td>
<td>10.5</td>
</tr>
<tr>
<td>Soil</td>
<td></td>
<td>Water</td>
<td></td>
<td></td>
<td>7.89</td>
<td>4.8</td>
</tr>
</tbody>
</table>

Figure (1): Discontinuous ridges flooded by irrigation water. a) wetness for continuous ridges in two sides and b) wetness for discontinuous ridges in four sides.
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Figure (2): Discontinuous ridges in the field. a) irrigation water around short ridges and b) wetness shape for short ridges.

Specifications of prototype machine:

Overall dimensions of the study machine were 2.85m length, 2.1m width and 1.9m height as shown in Figure (3). The machine installs soil ridges at different lengths and sowing field crops on it. So that the study machine consists of the following parts:

Three hitching points:

The machine was mounted type hitched to the tractor using the three hitching points system. Three hitching points system manufactured from 0.02m thickness iron at height of upper hitch point of 0.6m and lower hitch point spread of 0.6m.

Ridger unit.

Ridger unit consists of three shanks (0.025m thickness) capable of adjustment in the height, each shank connected with a chisel blade (7cm width) and two moldboards capable of adjustment in operation width to form the ridges and furrows as shown in Figures (4) and (5).

Sowing unit:

Sowing unit contains of seeds hopper made from iron sheet with a thickness of 0.002 m at the dimensions of 0.7m length x 0.7m width x 0.5m height as shown in Figure (4). Seed metering mechanism in this seeder gear wheel type made of Teflon material. The feed wheel diameter is of (0.09m), thickness of (0.02m). The seeder width consists of three discs. Each disc case has two holes the top is used as entry seed from the hopper to the disc cells, while the bottom hole is used as the exit the seeds from the disc cells to the seeds planting tube which connected to chisel opener to sowing seeds on the ridges. The disc cells were equipped with the moving shaft in the iron case by means of a collecting unit. Transmission system was designed to transmit the motion from the ground wheel to the shaft of the feed disc through a sprocket gears to give the equivalent rotation number related to the peripheral speed of the ground wheel.

Figure (3): Elevation and side views for study machine.
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Figure (4): Study machine for installing discontinuous ridges and sowing crop seeds on it. 1) hitching points, 2) digger blade, 3) moldboard, 4) chisel opener, 5) seeds hopper, 6) cutting roller and 7) ground wheel.

Figure (5): Study machine in the field.

Sowing unit:

Sowing unit contains of seeds hopper made from iron sheet with a thickness of 0.002 m at the dimensions of 0.7m length x 0.7m width x 0.5m height as shown in Figure (4). Seed metering mechanism in this seeder gear wheel type made of Teflon material. The feed wheel diameter is of (0.09m), thickness of (0.02m). The seeder width consists of three discs. Each disc case has two holes the top is used as entry seed from the hopper to the disc cells, while the bottom hole is used as the exit the seeds from the disc cells to the seeds planting tube which connected to chisel opener to sowing seeds on the ridges. The disc cells were equipped with the moving shaft in the iron case by means of a collecting unit. Transmission system was designed to transmit the motion from the ground wheel to the shaft of the feed disc through a sprocket gears to give the equivalent rotation number related to the peripheral speed of the ground wheel.

Cutting unit:

Cutting unit cuts the ridges into short pieces as shown in Figure (6) consists of roller contained incisive tip. Whereas the roller changes according to the length of ridges requirements in study treatments. So that in this study was manufactured four rollers in different diameters and tips to install ridges at different length as shown in Table (2) and Figure (7). Treatment of continuous ridges (30m) installing by using machine without cutting unit.

Noting that all the ridges length equal 30m cutting into the lengths required for the study, and the distance between the pieces was equal in length, which is 0.2m. Where the number of pieces in each ridge, the number of distances between pieces, the total length of distances between pieces and the net length of cultivated ridges were shown in the Table (3).

Experimental design.

The experimental area about of one hectare. This experiment was established as split-split plots in three replicates, divided into three main plots involved three levels of irrigation rates (70%, 85%, and 100% from total water applied). Each main plot includes two sub-plots, which involved five levels of ridge length (0.5m, 1m, 1.5m, 2m and 30m) resulted in a total of 45 plots, each plot about of 225m$^2$ (30m x 7.5m). All study treatments were carried out at same tractor forward speed about of 3.5 km/h.

Irrigation system:

The irrigation system consists of the following components:

a- Control head.

Control head consists of centrifugal pump 5/5 inches (6 m lift and 140 m$^3$/h discharge), driven by diesel engine (50 Hp), pressure gauges, control valves, inflow gauge, water source was an open.
b- Line of gated irrigation pipes.

P.V.C pipeline, 6 bar, 110 mm nominal outside diameter, thickness of pipe is 4.7mm, 24 m long, 50cm spacing between holes, level of pipes is near to zero.

Millet seeds and planting method:

The millet crop was planted in April 2020 on the top of ridges using study machine, with a rate of 60 kg/ha.

Millet crop harvesting:

The millet crop was harvested in September 2020 as the fresh forage through three cuts and the three randomized samples were taken by hand from each plot using a wooden square frame (1m²) as a simpler to determine the millet yield (fresh forage) per hectare.

Table (2): Different diameter and tips for rollers to install ridges at different length.

<table>
<thead>
<tr>
<th>Roller diameter, cm</th>
<th>67</th>
<th>76</th>
<th>54</th>
<th>70</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of tips</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Ridge length, cm</td>
<td>50</td>
<td>100</td>
<td>150</td>
<td>200</td>
</tr>
</tbody>
</table>

Table (3): Specifications of study ridges.

<table>
<thead>
<tr>
<th>Continuous ridge length, m</th>
<th>Piece length, m</th>
<th>Distances between pieces, m</th>
<th>Number of pieces in each ridge</th>
<th>Number of distances between pieces</th>
<th>Total length of distances between pieces, m</th>
<th>Net length of cultivated ridges, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0.5</td>
<td>0.2</td>
<td>43</td>
<td>42</td>
<td>8.4</td>
<td>21.6</td>
</tr>
<tr>
<td>30</td>
<td>1</td>
<td>0.2</td>
<td>25</td>
<td>24</td>
<td>4.8</td>
<td>25.2</td>
</tr>
<tr>
<td>30</td>
<td>1.5</td>
<td>0.2</td>
<td>17</td>
<td>16</td>
<td>3.2</td>
<td>26.8</td>
</tr>
<tr>
<td>30</td>
<td>2</td>
<td>0.2</td>
<td>13</td>
<td>12</td>
<td>2.4</td>
<td>27.6</td>
</tr>
<tr>
<td>30</td>
<td>30</td>
<td>0.2</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>30</td>
</tr>
</tbody>
</table>

Figure (6): Cutting ridges by the roller of machine. a) continuous ridges, b) and c) the roller during cutting process.
Crop water requirement was calculated using the Reference Evapotranspiration (ETo) and the Crop coefficients (Kc) by the following equation:

\[ ETc = ETo \times Kc \]

Where: \( ETc \) = Crop Evapotranspiration, (mm/day), \( ETo \) = Reference Evapotranspiration, (mm/day), and \( Kc \) = Crop coefficients.

Represent the Reference Evapotranspiration (ETref) according to (Center Laboratory for Agricultural Climate, CLAC.), the average crop coefficients (Kc) for Millet according to Andreas P. (2002).

**Table (4): Growth stages, Reference evapotranspiration, and crop coefficient of millet.**

<table>
<thead>
<tr>
<th>Growth stage</th>
<th>from</th>
<th>to</th>
<th>ETo mm/day</th>
<th>Kc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>15 April</td>
<td>6 May</td>
<td>4</td>
<td>0.51</td>
</tr>
<tr>
<td>Dev.</td>
<td>7 May</td>
<td>6 June</td>
<td>6</td>
<td>0.81</td>
</tr>
<tr>
<td>Mid-season</td>
<td>7 June</td>
<td>7 July</td>
<td>6</td>
<td>1.1</td>
</tr>
<tr>
<td>Season end</td>
<td>8 July</td>
<td>8 Aug.</td>
<td>7</td>
<td>0.83</td>
</tr>
<tr>
<td>Total</td>
<td>112 days</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Net irrigation requirement (IRn) is derived from the field balance equation:

\[ IRn = \left( \frac{ETc \times A}{10^7 \times E_a} \right) \times (1 + LR) - P_{eff} \]

Leaching requirement (LR) estimated according to Rhoades and Merrill (1976) as the following:

\[ LR = \frac{EC_w}{[5 \times (EC_e) - EC_w]} \]

Where: \( IRn \) = Net irrigation requirement, (mm/day), \( ETc \) = Crop evapotranspiration, (mm/day), \( A \) = Irrigated area, (m²), \( E_a \) = Application efficiency, (%), \( P_{eff} \) = Effective dependable rainfall, (mm), \( LR \) = Leaching requirement, (mm), \( EC_w \) = Electric conductivity of irrigation water, (ds/m), and \( EC_e \) = Electric conductivity of soil paste, (ds/m).

Gross irrigation requirements account for losses of water incurred during conveyance and application to the field.

\[ IRg = IRn/Ea \]

Where: \( IRg \) = Gross irrigation requirements, (mm/day), \( IRn \) = Net irrigation requirement, (mm/day), and \( E_a \) = Overall irrigation efficiency, (%), for pressure piped network surface methods = (65 - 75%) (Phocaides, 2000).
### Table (5): Total water applied with leaching Requirement (LR).

<table>
<thead>
<tr>
<th>Crop</th>
<th>Irrigation system</th>
<th>Total water applied (m³/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>100% from total water applied</td>
</tr>
<tr>
<td>Millet</td>
<td>Modern Surface Irrigation</td>
<td>10157</td>
</tr>
</tbody>
</table>

Total water stored in the effective root zone:

Water stored in the root zone was determined according to James (1988) as follows:

\[
TWS = \sum_{i=1}^{4} \left( \frac{\theta_{fc} - \theta_{wp}}{100} \right) D_r \times \rho_b
\]

Where: TWS = Water stored in the root zone, (mm), \( \theta_{fc} \) = Soil moisture content at field capacity, (%), \( \theta_{wp} \) = Soil moisture content at permanent wilting point, (%), \( D_r \) = Effective root depth, (mm), \( \rho_b \) = Soil bulk density, (g/cm³) for depth and \( i \) = Number of soil layers (1-4).

Water consumptive use in effective root zone:

Water consumptive use by growing plants was calculated based on soil moisture depletion (SMD) according to Hansen et al. (1979).

\[
WCU = \sum_{i=1}^{4} \left( \frac{\theta_{fc} - \theta_i}{100} \right) D_r \times \rho_b
\]

Where: WCU = Water consumptive use in the effective root zone, (mm), \( \theta_{fc} \) = Soil moisture content at field capacity, (%), \( \theta_i \) = Soil moisture content before next irrigation, (%), \( D_r \) = Effective root depth, (mm), \( \rho_b \) = Soil bulk density, (g/cm³) for depth and \( i \) = Number of soil layers (1-4).

Water stored efficiency:

Water stored efficiency was calculated according to Israelsen and Hansen (1962) as follows:

\[
WAE = \left( \frac{TWS}{TWA} \right) \times 100
\]

Where: WAE = Water stored efficiency, (%), TWS = Total water stored in the effective root zone, (m³/ha) and TWA = Total water applied, (m³/ha).

Water consumptive use efficiency:

Water consumptive efficiency was calculated according to Israelsen and Hansen (1962) as follows:

\[
ECU = \left( \frac{TCU}{TWA} \right) \times 100
\]

Where: ECU = Water consumptive efficiency, (%), TCU = Total water consumptive use in the effective root zone, (m³/ha) and TWA = Total water applied, (m³/ha).

Productivity of irrigation water:

Productivity of irrigation water (PIW) was calculated according to Ali et al. (2007) as kg yield/m³ water applied.

\[
PIW = \frac{Y}{I}
\]

Where: \( Y \) = Crop yield, (kg/ha) and \( I \) = Total water applied, (m³/ha).

Soil moisture content and soil salinity:

Moisture measurement (TDR 300 soil moisture meter) Soil salinity (Direct soil EC probe).

Irrigation distribution uniformity:

Comparison between the irrigation methods was made on basis of the infiltration distribution uniformity. The soil samples were taken at a depth of 0-20 and 20-40cm before irrigation and after irrigation from all plots. The tool used to evaluate irrigation distribution uniformity was Christian's Uniformity Coefficient, which is given according to James (1988):

\[
UCC = \left[ 1 - \frac{\sum_{i=1}^{n} |\theta_i - \bar{\theta}|}{n \bar{\theta}} \right] \times 100
\]

Where: UCC = Christian’s uniformity coefficient, (%), \( \theta_i \) = The observed water content for the \( i \)th point, in cm³ (from gravimetric moisture determination). It is the moisture content after oven dry of each of the soil sample from a plot, (%), \( \bar{\theta} \) = The mean water contents, (%) mean water content is determined by:

\[
\bar{\theta} = \frac{\sum_{i=1}^{n} \theta_i}{N}
\]

and \( N \) = Number of points where samples were taken. \( N \) is 1, 2, 3 ... 36, because uniformity was computed for each treatment.

Theoretical and actual field capacity and field efficiency:

Theoretical and actual field capacity and field efficiency were calculated by using equations mentioned by kepner et al, (1978).

Pulling force:

Pulling force for machine was measured by hydraulic dynamometer which, coupled between
the two tractors with the attaching machine to estimate its draught force. A considerable number of readings were taken at a time interval 10 seconds to obtain an accurate average of draught force.

**Fuel consumption rate.**

Fuel consumption per unit time was determined by measuring the volume of fuel consumed during operation time. It was measured using the fuel meter equipment as shown in Figure (8) the length of line which marked by the marker tool on the paper sheet represents the fuel consumption. The fuel meter was calibrated prior and the volume of fuel was determined accurately.

![Figure (8): Fuel meter for measuring fuel consumption.](image)

**RESULT AND DISCUSSION**

**Performance evaluation of prototype machine:**

The results as shown in Figure (9) showed a significant effect of ridges cutting process on performance of prototype machine. The actual field capacity and field efficiency of study machine decreased about 10% and 9% respectively, when cutting irrigation ridges in short lengths compared to continuous ridges. This may be due to the fact that, the ridges cutting process caused decreasing in the distance covered by the machine per unit time as a result, actual field capacity and field efficiency decreased. On the other hand, fuel consumption rate and pulling force of study machine increased about 19% and 37% respectively, when cutting irrigation ridges in short length compared to continuous ridges. This may be due to the fact that, the ridges cutting process caused resistance for cutting roller rotating as a result, fuel consumption rate and pulling force increased. In general, the ridge length 0.5 m achieved the lowest values of actual field capacity and field efficiency in addition achieved the highest values of fuel consumption rate and pulling force compared to others study ridges length.

![Figure (9): Effect of ridge length (0.5m, 1m, 1.5m, 2m and 30m) on actual field capacity (ha/h), field efficiency (%), fuel consumption rate (l/h) and pulling force (kN). Values followed by different letters are significantly different at p < 0.05 according to the LSD test. Error bar s show the standard deviation among the repetitions (n = 3). LSD for actual field capacity = 0.0105, field efficiency = 2.0625, fuel consumption rate = 0.2146 and pulling force = 0.1517.](image)
and water consumptive use efficiency:

Figure (10) showed a significant effect of different ridges length and water application levels on water stored, water consumptive, water stored efficiency and water consumptive use efficiency. The water stored, water consumptive, water stored efficiency and water consumptive use efficiency increased when increasing water application level from 70% to 85% and from 70% to 100% about (24% and 52%), (21% and 51%), (4% and 8%) and (5% and 7%) respectively. Also, the water stored, water consumptive, water stored efficiency and water consumptive use efficiency increased about 17%, 19%, 18% and 19% respectively, when using discontinuous ridges system compared to continuous ridges system. This may be due to the fact that, when using discontinuous ridge system in irrigation, the contact surface area between the ridges and irrigation water increases, causing an increase in the water stored, water consumptive, water stored efficiency and water consumptive use efficiency. In addition, the highest values of the water stored, water consumptive, water stored efficiency and water consumptive use efficiency were 6818 m$^3$/ha, 4989 m$^3$/ha, 67% and 49% respectively, achieved at water application level 100% and ridge length one-meter treatment. But the lowest values of the water stored, water consumptive, water stored efficiency and water consumptive use efficiency were 3413 m$^3$/ha, 2589 m$^3$/ha, 48% and 36% respectively, achieved at water application level 70% and ridge length 30m treatment. This may be due to the fact that, when the ridge length is 0.5 m, the surface contact area of the ridge with irrigation water increases, but the size of the ridge is small, which reduces the volume of water stored, but when the ridge length increased to one meter, there are ideal conditions for the contact surface between the ridge and water in addition the size of the ridge is greater so that it is allowed to increase the volume of water stored in it. But when the ridge length increased more than one meter, the store irrigation water decreases due to decreasing the contact area between the ridge and the water despite the increase in the ridge size.

Figure (10): Effect of ridge length (0.5m, 1m, 1.5m, 2m and 30m) and water application level (70%, 85% and 100%) on water stored (m$^3$/ha), water consumptive (m$^3$/ha), water stored efficiency (%) and water consumptive use efficiency (%). Values followed by different
letters are significantly different at p < 0.05 according to the LSD test. Error bars show the standard deviation among the repetitions (n = 3). LSD for water stored = 70, water consumptive = 102, water stored efficiency = 2.1316 and water consumptive use efficiency = 1.5262.

Effect of study treatments on irrigation distribution uniformity, soil salinity, millet yield and productivity of irrigation water:

The data presented by Figure (10) showed a significant effect of different ridges length and water application levels on irrigation distribution uniformity, soil salinity, millet yield and productivity of irrigation water. The irrigation distribution uniformity, millet yield and productivity of irrigation water increased when increasing water application level from 70% to 85% and from 70% to 100% about (2% and 6%), (30% and 45%) and (8% and 2%) respectively. Also, the irrigation distribution uniformity, millet yield and productivity of irrigation water increased about 12%, 19% and 19% respectively, when using discontinuous ridges system compared to continuous ridges system. In addition, the highest values of the millet yield and productivity of irrigation water were 100 Mg/ha and 10.5 kg/m³ respectively, achieved at water application level 100% and ridge length one-meter treatment. But the highest value of irrigation distribution uniformity was 87% achieved at water application level 100% and ridge length 0.5m treatment. While, the lowest values of the irrigation distribution uniformity, millet yield and productivity of irrigation water were 71%, 51 Mg/ha and 7.2 kg/m³ respectively, achieved at water application level 70% and ridge length 30m treatment. On the other hand, the soil salinity decreased when increasing water application level from 70% to 85% and from 70% to 100% about 8% and 16% respectively. The lowest value of soil salinity was 5.4 ds/m achieved at water application level 100% and ridge length 0.5 m treatment. But the highest value of soil salinity was 8.9 ds/m achieved at water application level 70% and ridge length 30m treatment. This may be due to the fact that, when the length of the ridge decreases, the contact surface area with the irrigation water increases, and with the small size of the ridge, the ridge wetting increases, which causes an increasing in the irrigation distribution uniformity and decreasing in soil salinity due to the small size of the ridge with increase in the volume of the surrounding water. The opposite effect occurs when the ridge length increases.

Figure (11): Effect of ridge length (0.5m, 1m, 1.5m, 2m and 30m) and water application level (70%, 85% and 100%) on distribution uniformity (%), soil salinity (ds/m), millet yield (fresh forage) (first + second + third) cuts (Mg/ha) and productivity of irrigation water, (kg/m³). Values followed by different letters are significantly different at p < 0.05 according to the LSD test. Error bars show the standard deviation among the repetitions (n = 3). LSD for distribution uniformity = 1.5073, soil salinity = 0.2236, millet yield = 3.3139 and productivity of irrigation water = 0.2151.
Estimating optimum ridge length and water application level:

Regression equations were calculated for the relationship between the productivity of irrigation water as a dependent variable and the ridges length as an independent variable as shown in Figure (12). Also, regression equations were calculated for the relationship between the productivity of irrigation water as a dependent variable and the water application levels as an independent variable as shown in Figure (13). These equations were differentiated to obtain the optimum ridge length and water application levels, which achieved the highest productivity of irrigation water. The results in Table (6) indicated that the highest productivity of irrigation water at different levels of water application levels 100%, 85% and 70% were achieved when the ridge lengths were about 1.25m, 1.28m and 1.23m, respectively. So that the average value of optimum ridge length was about 1.25m. Also, the results in Table (7) indicated that the highest productivity of irrigation water at different levels of ridges length 0.5m, 1m, 1.5m and 2m were achieved when the water application levels were about 90.3%, 89%, 89.3 and 91.5, respectively. So that the average value of water application level was about 90%.

![Figure (12): Optimum ridge length at different water application levels (70%, 85% and 100%).](image1)

![Figure (13): Optimum water application level at different ridges length (0.5m, 1m, 1.5m and 2m).](image2)

### Table (6): Optimum ridge length at different water application levels.

<table>
<thead>
<tr>
<th>Water application levels, %</th>
<th>Ridges length, m</th>
<th>Regression equations</th>
<th>R²</th>
<th>Optimum ridge length, m</th>
<th>Average of ridges length, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>0.5</td>
<td>y = - 4.5 x² + 11.1 x + 4</td>
<td>0.98</td>
<td>1.23</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>30</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>85</td>
<td>0.5</td>
<td>y = - 4.2 x² + 10.8 x + 4.2</td>
<td>0.98</td>
<td>1.28</td>
<td>1.25</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td></td>
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<td></td>
<td>2</td>
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<tr>
<td></td>
<td>30</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>0.5</td>
<td>y = - 5 x² + 12.5 x + 3.9</td>
<td>0.99</td>
<td>1.25</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>1.5</td>
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</tr>
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</tr>
<tr>
<td></td>
<td>30</td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

$y$ = dependent variable (productivity of irrigation water).

$x$ = independent variable (ridges length).
Table (7): Optimum water application levels at different ridges length.

<table>
<thead>
<tr>
<th>Ridges length, m</th>
<th>Water application levels, %</th>
<th>Regression equations</th>
<th>$R^2$</th>
<th>Optimum water application levels, %</th>
<th>Average of water application levels, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>70</td>
<td>$y = -0.0019x^2 + 0.3433x - 6.0333$</td>
<td>0.98</td>
<td>90.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>85</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>70</td>
<td>$y = -0.0032x^2 + 0.57x - 13.867$</td>
<td>0.99</td>
<td>89</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>85</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>70</td>
<td>$y = -0.003x^2 + 0.5356x - 13.744$</td>
<td>0.98</td>
<td>89.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>85</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td></td>
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</tr>
<tr>
<td>2</td>
<td>70</td>
<td>$y = -0.0021x^2 + 0.3844x - 8.5222$</td>
<td>0.98</td>
<td>91.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>85</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td></td>
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</tr>
</tbody>
</table>

$y =$ dependent variable (productivity of irrigation water).

$x =$ independent variable (water application levels).

CONCLUSION

The evaluations of discontinuous ridges system (DRS) compared to continuous ridges system (CRS) under different water application levels concluded as the following:

1- The actual field capacity and field efficiency of study machine decreased about 10% and 9% respectively, also fuel consumption rate and pulling force of study machine increased about 19% and 37% respectively, when using DRS compared to CRS.

2- The water stored, water consumptive, water stored efficiency, water consumptive use efficiency, irrigation distribution uniformity and millet yield achieved the highest increasing about 52%, 51%, 8%, 7%, 6% and 45% respectively, when increasing water application level from 70% to 100%. While, the productivity of irrigation water achieved the highest increasing about 8% when increasing water application level from 70% to 85%.

3- The highest increasing of water stored, water consumptive, water stored efficiency, water consumptive use efficiency, irrigation distribution uniformity, millet yield and productivity of irrigation water were 17%, 19%, 18%, 19%, 12%, 19% and 19% respectively, achieved when using DRS compared to CRS.

4- The soil salinity decreased about 16% when increasing water application level from 70% to 100% and decreased about 22% when using DRS compared to CRS.

5- The optimum ridge length and water application level under study conditions were 1.25m and 90% respectively, which achieved the highest value of productivity of irrigation water.

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