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Soil Surface Wetting Pattern under Trickle Source in Arid Lands: Badia Regions

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ABSTRACT

Arid regions are characterized by fragile soils that differ in behavior according to their physical and chemical compositions. In this study, the wetted soil surface area was measured for four different soil types to assess the impact of the individual soil particles (silt, sand and clay separates) on soil surface wetting area, under different application rates using point source trickle irrigation. Three flow rates were tested 4, 8 and 12 liters per hour (Lph) on four different soil types (silt loam, loam, sandy loam$_{\mathbf{58sand}}$ and sandy loam$_{\mathbf{77sand}}$). Soil surface wetted area increases as emitter flow rate increases. The results showed that increasing emitter flow rate from 4 to 8 and to 12 Lph, increased soil surface wetted area by about 60 and 160%, respectively. Soil surface wetted areas in loam soil and silt loam soils were 1.5 and 2.8 times that in sandy loam soils, respectively. Soil surface wetted area increases rapidly with time initially, but then increases at a decreasing rate, until the application rate became in equilibrium with soil infiltration rate. The surface wetted area had good correlation with the percentages of silt, sand and clay soil particles, with regression correlation ranging from 0.90 to 0.97. The trends were increased wetting with clay and silt and decreased wetting with sand. The expected losses on the form of evaporation in arid soils suffering from surface crust, therefore, would increase in soils dominated by silt or clay when compared with sand, indicating that cropping pattern in arid environments should be carefully selected in areas with scarce water resources.

Keywords: Drip irrigation, Wetting pattern, Infiltration, Aridity, Badia regions.

INTRODUCTION

Trickle irrigation is considered as one of the most efficient irrigation systems. The system usually makes use of the limited water supply to apply precise amounts of water to the root zone. This encouraged farmers in arid areas to adopt trickle system for irrigating a wide range of crops. From a technical point of view, a trickle irrigation system is designed to deliver light, frequent applications of water and partially wet the soil surface as water spreads over the soil surface and the wetted area expands gradually (Bresler et al., 1971). The wetted area in the vicinity of the trickle source is initially very small, but its radius becomes larger with time. The area through which water enters the soil will increase with the increase in time due to decrease in infiltration rate with time and constant emitter discharge (Subbaiah and Mashru, 2013).

The distance that water spreads horizontally from a drip line and the volume of soil wetted are limiting factors that determine the spacing and number of drip lines and emitters, the frequency of irrigation, and thus the cost of irrigation (Skaggs et al., 2010). The common trickle irrigation system used by the Jordanian farmers consists of laterals 1- 2 m apart, with emitters of 4-8 Lph discharge, spaced 0.3 - 0.5 m apart for vegetable crops. According to the crop type, each emitter is assumed to water an area of 0.3 m^2 (0.3 m by 1.0 m) for the close spacing and 1.0 m^2 (0.5 m by 2.0 m) for the wide spacing (Al-Qinna and Abu-Awwad, 2001).

The amount of evaporation with drip irrigation system

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is heavily dependent upon the percent of the soil surface that is both exposed and wetted, and the frequency of irrigation (Allen et al., 1998). The vast majority of drip irrigation systems are above ground, and the soil surface wetted areas may be quite large with some emitter designs and flow rates. Those continuously large wet soil surface regions will contribute to a high soil evaporation loss. (Bresler, 1975; Meshkat, et. al., 2000).

Soil wetting patterns under surface and subsurface micro irrigation have been measured and/or analyzed theoretically by several authors such as Gardenas et al., (2005), Singh et al., (2006), Wang et al., (2006), Siyal and Skaggs (2009), Subbaiah and Mashru (2013).

Reliable information about the wetted dimensions of soil under drip irrigation helps designers to determine optimal emitter flow rates and spacing to reduce system equipment cost and provide better soil water conditions for the most efficient and effective use of water (Malek and Peters, 2011). The shape and dimensions of the volume of wet soil below the emitter are some of the most influential variables in the optimal design and management of drip irrigation systems (Arbat et al., 2013).

Soil hydraulic properties and water content are the primary factors determining the soil capillary forces that drive horizontal water movement. It is not possible, for example, to use higher application rates to "push" water out through soils from drip lines. The soil wetting will be determined by the soil hydraulic properties and the antecedent soil water content and will not be significantly impacted by the discharge rate (Skaggs et al., 2010).

Zhang et al., (2012) showed that there was a positive linear correlation between saturated zone radius and application rate. The relationship between both the radial and vertical wetted distance and drip irrigation time can be described by a power function. Al-Qinna and Abu-Awwad (2001) indicated that increasing the application rate enhanced the horizontal water movement markedly due to the soil surface crust effect, thus reducing the infiltration rate; and the wetted volume that resulted formed a "V"-shaped cross-section. Goldberg et al., (1971) reported that it was possible to increase the surface lateral spread of the wetting front by increasing the emitter discharge rate or the amount of water applied.

In Jordan, land suitable for irrigated agriculture is estimated at around 840 thousand ha. However, taking into consideration available water resources, the irrigation potential is about 85 thousand ha (10.1%), including the area currently irrigated. In spite of the limited agricultural lands, many people adopted irrigation in less suitable lands located in the arid regions of the country. The total area equipped for irrigation is estimated at 78.9 thousand ha, of which 64 thousand ha (81.12%) is under localized drip irrigation (Water Report 34, 2009). More than half of the irrigated area in Jordan is located in the highlands, particularly in the Badia region. This arid region had witnessed an obvious shift in land use and nomadic life towards more settling patterns that included the intrusion of irrigated agriculture (Al-Bakri et al., 2001; Al-Bakri, 2015).

Although irrigation is expanding in the Badia region, however soils of this arid region are very sensitive to crust formation which put more challenges for farmers. The presence of the physical soil surface crust is a permanent feature, especially on untiled soils. Crusts strongly reduce infiltration capacity and control wetting patterns under trickle irrigation. Therefore, site specific information is required on wetting pattern or soil hydraulic properties to design efficient trickle irrigation systems (Thorburn et al., 2003). In many cases, broad soil texture ranges are usually the only information related to soil wetting used in trickle system designs. Unfortunately, this information is insufficient to predict wetting patterns, and to justify the use of different emitter spacing for different soil textures. Therefore, the objective of this research was to study the effect of the individual soil particles (separates) silt, sand and clay, by using different emitter discharges on soil surface wetting area under point source surface drip irrigation; in the prevailing soil types, including silt loam, loam and sandy loam, in the Badia region.

1. Materials and Methods

Field measurements were carried out during 2015 at four sites in the northeastern Badia (Figure 1). According to existing soil maps (MoA, 1993) the four sites were dominated by typic camborthids and calciorthids subgroups. Among the four sites, irrigation is practiced near the first (S1) and the third (S3) sites (Al-Bakri, 2015). The wetted soil surface area was estimated for four different soil types in the four sites using three different flow rates, corresponding to the ones used in trickle irrigation. The experimented soil textures covered silt loam (S1), loam (S2), sandy loam$_{58sand}$ (S3: sandy loam texture with 58% sand) and sandy loam$_{77sand}$ (S4: sandy loam texture with 77% sand) soil textures, representing the most dominant soil textural classes in Jordan Badia region.

Soil samples were collected from two soil layers (0-10 cm and 10-30 cm) to a depth of 30 cm and analyzed to determine physical properties such as soil water content at field capacity by using ceramic plates at 30 kPa and permanent wilting point at 1500 kPa, particle size distribution by using pipette method, bulk density by using undisturbed core method and infiltration rate by using double rings infiltrometer (Table 1). The soils had a considerable range of silt content (12% sandy loam$_{77sand}$ to 64%, silt loam), and sand content (13% silt loam to 77% sandy loam$_{77sand}$).

For each site, gravimetric soil samples were collected to calculate the initial volumetric soil water contents for the two soil layers. The initial volumetric soil water contents in the soil surface layer (0-10 cm), were almost the same at the four sites ranged from 29 to 34mm/m, with an average of 32mm/m. While for the subsurface soil layer (10-30 cm), volumetric soil water contents were varied from 66 to 94 mm/m. Soil infiltration rate measurements were carried out with double-ring infiltrometers. The infiltration rates were 3.7, 4.3, 8.0 and 9.0 mm/h for silt loam, loam, sandy loam$_{58sand}$ and sandy loam$_{77sand}$, respectively.Figure 1: Map showing the four experimented sites (S1, S2, S3 and S4).

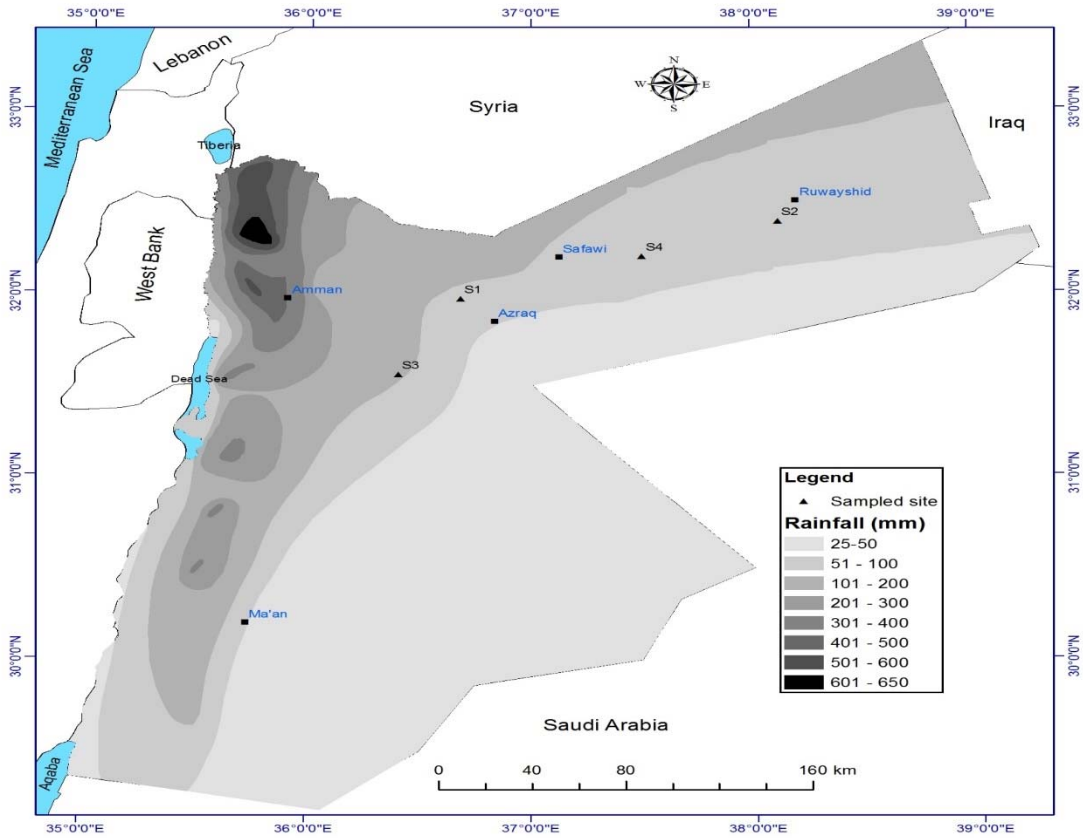

Figure 1: Map showing the four experimented sites (S1, S2, S3 and S4).

Table 1: Physical soil properties for the four sites.

Site	Coordinates	Soil depth cm	Bulk density gm/cm^3	Infiltration rate mm/h	Initial soil water content (mm/m)	Water holding capacity$^{(*)}$ (mm/m)	Clay %	Silt %	Sand %	Texture class
S1	N: 31°58'15'' E: 36°40'54''	0-10	1.20	3.7	33	166	23	64	13	Silt Loam
		10-30			94	146	16	61	23	
S2	N: 32°23'34'' E: 38°07'08''	0-10	1.20	4.3	34	222	17	41	42	Loam
		10-30			66	201	19	30	51	
S3	N: 31°33'21'' E:	0-10	1.32	8.0	32	134	13	29	58	Sandy Loam
		10-30			92	126	16	18	66	

Site	Coordinates	Soil depth cm	Bulk density gm/cm^3	Infiltration rate mm/h	Initial soil water content	Water holding capacity(*)	Clay %	Silt %	Sand %	Texture class
					mm/m					
	36°24'07''									
S4	N: 32°12'09''	0-10	1.36	9.0	29	102	11	12	77	Sandy Loam
	E: 37°30'08''	10-30			82	114	12	13	75	

A polyethylene drip pipeline with a length of 10 m, an outside diameter of 20 mm and a wall thickness of 1.5 mm was installed on the soil surface. A controlled Turbo key emitter type was used as a trickle point source with three different discharge rates; 4, 8 and 12 Lph at 10 kilopascals (kPa) operational pressure.

The radius of the soil surface wetted areas were measured using a 10cm x 10cm grid system and recorded at different predetermined times of 0, 15, 30, 45, 75, 105, 165, and 225 minutes from the start of the experiment. When the soil surface wetted area became almost constant, soil surface wetted area was calculated as follows:

$$WA = Q/I \qquad (1)$$

Where

WA = soil surface wetted area (m^2),

Q = emitter flow rate (m^3/h), and

I = infiltration rate at the time soil surface wetted area became almost constant (m/h).

2. Results and Discussion

Soil surface sealing is a common feature of most soils of arid lands in the Badia regions. Physical soil surface crust has been identified as a major factor decreasing water infiltration and increasing runoff, which could result in large surface wetted area even with low flow rate drip irrigation and increasing soil evaporation in most areas, in the Badia regions. The wetting pattern could be too large on soil surface compared to the typical subsurface bulb shape wetted area, at 15 to 30 cm soil depth, in most agricultural soils.

Results showed that for the same soil texture, soil surface wetted area increased as dripper flow rate increased (Figure 2). For the four soil types (silt loam, loam, sandy loam$_{58sand}$ and sandy loam$_{77sand}$), increasing emitter flow rate from 4 Lph to 8 Lph and to 12 Lph, increased soil surface wetted area by about 60% and 160%, respectively.

Loss of water from the soil profile through evaporation from the wet soil surface is an important contributor to inefficiency in irrigated crop production and the savings will increase as the wetted area on the soil surface decreases. Thus, since a decreased dripper flow rate can minimize the horizontal wetted surface area, reducing emitters flow rates in the arid lands and Badia region, where soils suffer from surface crust and high silt content, is expected to significantly reduce wet surface and consequently, water loss through evaporation. However, even with the inherent ability of drip irrigation to apply small irrigation amounts, and low emitters flow rates, deep crop root zones can make irrigation a critical issue to avoid water stress without significant water loss through surface evaporation and runoff. Water that ponds in flat, crusted areas is likely to evaporate, reducing the amount of water available to plants.

In general, the wetted pattern varies by emitter flow rate and soil type. Soil surface wetted area is larger in fine soil texture as compared with coarse soil texture. Regardless of drippers flow rates in this experiment (4 to 12 Lph), soil surface wetted area in loam soil was 1.6 to 1.8 times that in the sandy $loam_{77sand}$ soil; for silt loam soil it was 2.8 to 3.5 times that in sandy $loam_{77sand}$ soil; and it was 1.7 to 2.0 times that in the loam soil (Figure 2). Results revealed that soil surface wetted area is directly proportional with soil surface silt content, and approximately increased with the same ratio as silt content increase. As soil silt content increased from 29% in sandy $loam_{58sand}$ to 41% in loam soil (1.41 times), to 64% in silt loam (2.21 times) soil surface wetted area increased from 1.1 m^2 in sandy $loam_{58sand}$ to 1.4 m^2 in loam (1.27 times), to 2.6 m^2 in silt loam ((2.36 times). Also, as soil silt content increased from 41% in loam soil to 64% in silt loam (1.56 times), soil surface wetted area increased from 1.4 m^2 in loam to 2.6 m^2 in silt loam soil (1.86 times). Thus, soil surface silt content is a determinant factor that controls the soil surface wetted area in arid soils with surface crust.

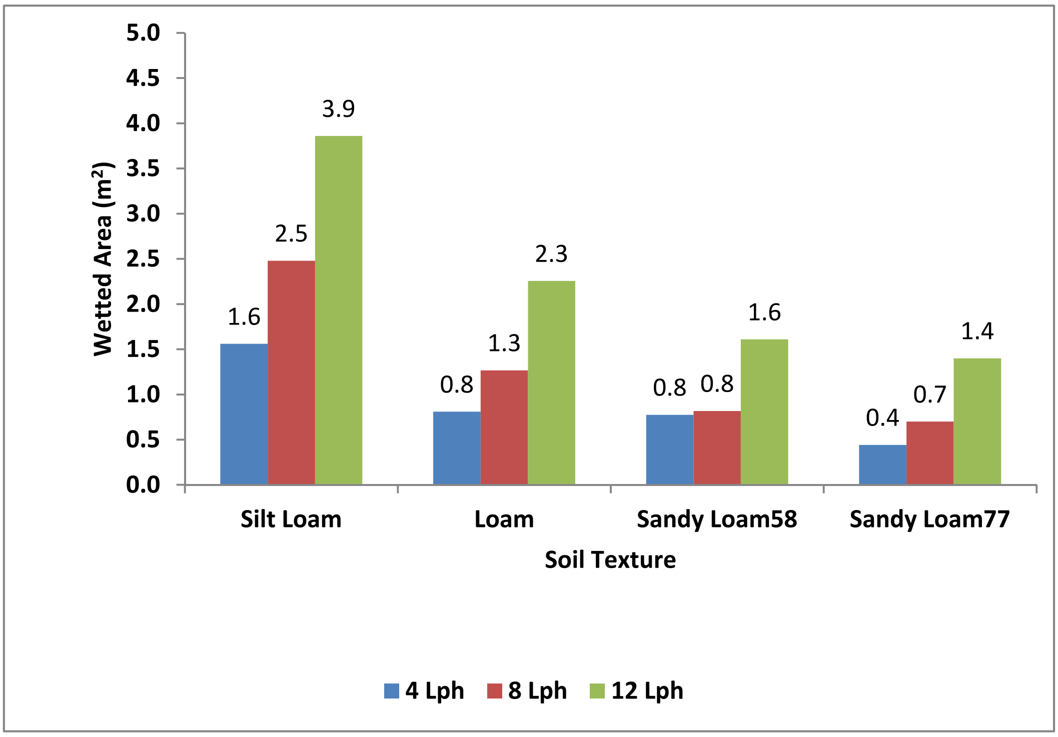

Figure 2: Soil surface wetted area as affected by soil texture under different emitters flow rates, at 105 minutes since the start of the infiltration process.

The results showed that the best correlation (R^2 = 0.85) between calculated and measured soil surface wetted area occurred at 105 minutes since the start of the infiltration for the different soil types and emitters flow rates. The relationship between the measured and calculated wetted area (Figure 3), was as follows:

$$CWA = 1.035\ MWA \qquad (2)$$

where CWA and MWA are calculated and measured soil surface wetted area, respectively.

The above relationship showed that the calculated wetted area would be slightly higher than the measured wetted area. Also, regardless of the soil type (silt loam,

loam, sandy loam$_{58sand}$ or sandy loam$_{77sand}$) and/or dripper flow rate (4, 8 or 12 Lph), soil surface wetted area would continue to increase, but in decreasing rate, as application time increased until the application rate would become in equilibrium with soil infiltration rate. At 105 minutes since the start of the infiltration process, infiltration rates were 3.7, 4.34, 8 and 9.0 mm/h for silt loam, loam, sandy loam$_{58sand}$ and sandy loam$_{77sand}$, respectively.

Results from the study provided specific empirical formulas that could predict soil surface wetted area around a drip irrigation emitter for the different soil separates under different point source drip irrigation flow rates, in the Badia regions where soils suffering from surface crust (Figure 4). Although four samples were implemented within regression analysis to derive the trend of soil wetting as influenced by soil separates, however the correlations were indicating the general trends and along a wide range of sand and silt percentages. In general, soil surface wetted area would be directly proportional with silt and/or clay soil particles percentage and inversely proportional with sand soil particles percentage. Water applied to the soil produces a wetting pattern, as it moves horizontally due to differential soil moisture potential and capillary suction. Wetting-pattern configurations depend on soil type; clay soils have fine particles that exert capillary forces greater than gravity, resulting in horizontal wetting patterns. Sandy soils on the other hand, have coarser particles that produce faster downward movement of water. Their bigger particles produce bigger voids, making it difficult for water to move horizontally. Results from this study confirmed those facts, with the effect of soil surface crust more pronounced, and therefore wetting area in sandy soils was inversely proportional to sand content. Furthermore, the slope of the regression line (Figure 4) was more negative when the application rate was increasing. Since, most soils comprise a combination of clay, silt and sand particles, the soil surface wetted area would be affected by trickle irrigation drippers flow rates, application time and infiltration rate. Increased application time would give more opportunity for horizontal movement of water, especially in clay soils (Harby, 2014) and soils suffering from surface crust (Al-Qinna and Abu-Awwad, 2001). This effect would be minimized for soils with high sand content, as indicated by the results of this study.

An important factor that could be indicated from the relationships between percentages of silt and clay was the larger wetted area when compared with the soils with high contents of sand. This wetted area would contribute to direct evaporation from the soil and would result in significant water loss in high-frequent micro-irrigation systems. Increasing soil surface wetted area would increase the wet soil surface evaporation from the saturated zone developed under drippers, especially in an arid area like Jordan Badia, where soils would suffer from water loss resulted from high contents of silt combined with a low permeability resulting from the soil surface crust. Soil surface sealing is a common feature of most soils of arid lands in the Badia regions. The high evaporation from soil surface would be a major problem for farms of fruit trees and olives when compared with farms of vegetables, as black plastic mulch would not be used in the former. This would imply that cropping patterns in this area and in similar arid environments should be revised according to soil type.

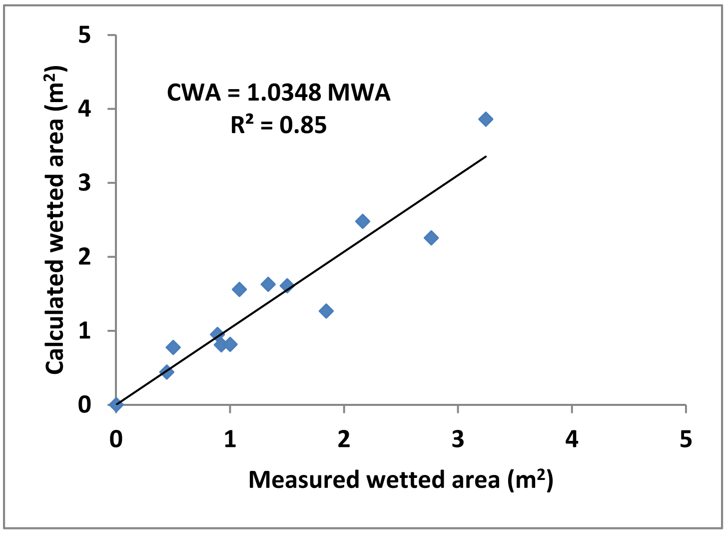

Figure 3: Soil surface calculated wetted area (CWA) versus measured wetted area (MWA).

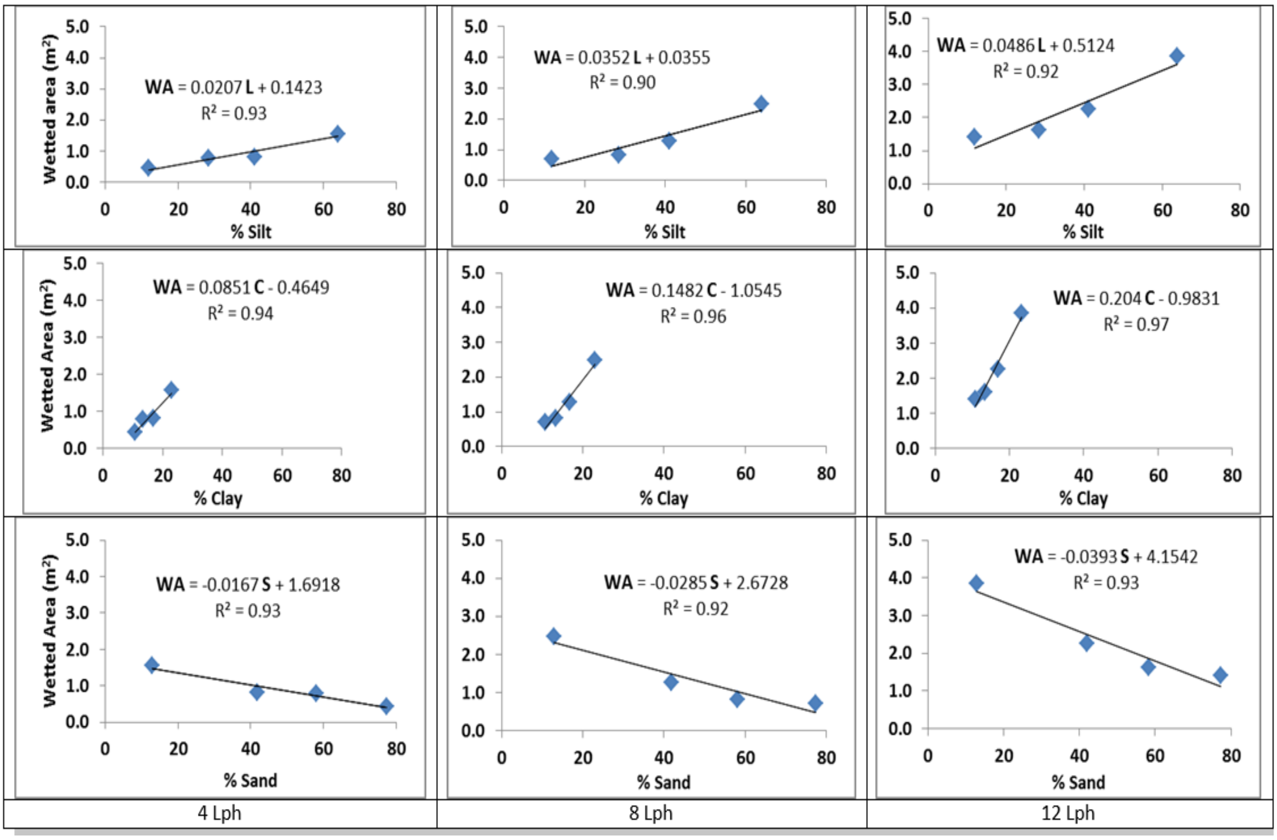

Figure 4: Soil surface wetted area as affected by silt (L), sand (S) and clay (C) soil particles percentage under different application rates.

Results revealed that, regardless of the drippers flow rates, as silt percentage increases from about 12% to 41% (≈ 3.4 times) and/or clay percentage increases from 11% to 17% (≈ 1.6 times), wetted surface area increased by about 61 to 83%, with an average of 72%; however, as silt percentage increases from 41% to 64% (≈ 1.6 times) and/or clay percentage increases from 17% to 23% (≈ 1.4 times), wetted surface area increased by 71% to 96%, with an average of 83.5%. Also, results indicate that with the 4 Lph and 8 Lph emitters flow rates, the increase in the wetted surface area, as silt percentages increases from 12% to 41% and from 41% to 64% were almost the same being 82% and 94%, respectively; while, with the 12 Lph emitter flow rate the increase in the wetted surface area was less, being 61% and 71%, respectively. Thus, the effect of the silt soil particles content on the surface area wetted becomes clearer at its high percentage, and even stronger under trickle irrigation with low emitter flow rate.

On the other hand, as sand soil particles decreased from 58% to 13% (≈ 4.5 times), wetted surface area increased by 2.0, 3.0 and 2.4 times with 4, 8 and 12 Lph emitter flow rate, respectively; while, for both 4 and 8 Lph emitter flow rates, as sand percentage decreased from 77% to 13%, wetted surface area increased by the same percentage, being 3.5 times. However, for the same decrease in sand percentage (from 58% to 13% and from 77% to 13%) with the 12 Lph emitter flow rate, the increase in the wetted surface area was less being 2.4 and 2.8 times, respectively. Thus, as sand soil particles content decrease, surface area wetted is expected to increase, but in decreased rates; and for the same increase in sand soil particles content, the surface area wetted is expected to decrease, but in a decreased rate as emitter flow rate increases.

Table 2: Soil surface wetted area as influenced by soil particles percentage and emitters flow rates.

Soil Particle		**Silt, %**			
		64.0	41.1	28.5	11.9
Wetted Area, m^2	4 Lph	1.56	0.81	0.78	0.44
	8 Lph	2.48	1.27	0.82	0.70
	12 Lph	3.86	2.26	1.61	1.40
Soil Particle		Sand, %			
		12.9	41.9	58.2	77.4
Wetted Area, m^2	4 Lph	1.56	0.81	0.78	0.44
	8 Lph	2.48	1.27	0.82	0.70
	12 Lph	3.86	2.26	1.61	1.40
Soil Particle		Clay, %			
		23.1	16.9	13.3	10.7
Wetted Area, m^2	4 Lph	1.56	0.81	0.78	0.44
	8 Lph	2.48	1.27	0.82	0.70
	12 Lph	3.86	2.26	1.61	1.40

Conclusions

This study concluded that soil surface wetted area would increase in decreasing rates as application time increased until the application rate became in equilibrium with soil infiltration rate. The effect of the silt soil particles content on the surface area wetted became clearer at its high percentage, and even stronger under trickle irrigation with low emitter flow rate. While, as sand soil particles content decreased, surface area wetted was expected to increase, but in decreased rates; and for the same increase in sand soil particles content, the surface area wetted was expected to decrease, but in a decreased rate as emitter flow rate increases.

Thus, even with the inherent ability of drip irrigation to apply small irrigation amounts, and low emitters flow rates, deep crop root zones can make irrigation a critical issue to avoid water stress without significant water loss through surface evaporation and runoff. Consequently, water that ponds in flat, crusted areas is likely to evaporate, reducing the amount of water available to plants. Therefore, the expected trends of soil surface wetting should be considered in irrigation system design in arid lands, where soils suffer from surface crust. Also, the impacts of these patterns on water losses on the form of evaporation from soil surface should be considered when selecting certain cropping pattern.

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نمط ابتلال سطح التربة باستخدام الري بالتنقيط في الترب الصحراوية للمناطق الجافة

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ملخص

تمتاز المناطق الجافة بتربتها الهشة، التي تختلف في سلوكها وفقا لخصائصها الكيميائية والفيزيائية. في هذه الدراسة تم قياس مساحة سطح التربة المبتلة، لأربعة أنواع من الترب، لتقييم تأثير توزيع حجم حبيبات (جسيمات) التربة على المساحة المبتلة لسطح التربة، باستخدام نظام الري بالتنقيط. تم اختبار ثلاث معدلات (تصريف) تدفق (4، 8 و 12 لتر/ساعة)، للأنواع ألاربعة من الترب. بينت الدراسة أن المساحة المبتلة لسطح التربة تزداد بزيادة معدل تصريف المنقط. حيث ازدادت المساحة المبتلة بنسبة 60% بزيادة تصريف المنقط من 4 لتر/ساعة الى 8 لتر/ساعة، وبنسبة 160% عند زيادة تصريف المنقط من 4لتر/ساعة إلى 12لتر/ساعة. و كانت المساحة المبتلة في التربة الطميية (Loam) والطميية الغرينية (Silty Loam) 1.5 و2.8 أضعاف المساحة المبتلة للتربة الطميية الرملية (Sandy Loam)، على التوالي. وبينت الدراسة أن المساحة المبتلة تزداد مع زمن اضافة ماء الري ولكن بنسبة متناقصة لوحدة الزمن، حتى يصبح معدل الاضافة مساويا للتوصيل المائي (الهيدروليكي) للتربة. كما بينت الدراسة أن علاقة المساحة المبتلة وحبيبات التربة المختلفة كالغرين (silt) والرمل (sand) والطين (clay) هي علاقة خطية. حيث تزداد المساحة المبتلة بزيادة نسبة حبيبات الغرين والطين في التربة، وتقل بزيادة نسبة حبيبات الرمل. بناءً على ذلك فإنه من المتوقع أن يزداد فقد الماء بالتبخر في الترب التي تحتوي على نسبة عالية من الغرين والطين عند مقارنتها بالرملية، نتيجة زيادة المساحة المبتلة على سطح التربة، مما يتطلب اختيار نمط زراعي مناسب في المناطق الجافة والتي تعاني من شح المصادر المائية.

الكلمات الدالة: استخدام الري بالتنقيط، لواء البادية.

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