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REGULAR ARTICLE

Backpressure effects on emitters flow rate in subsurface drip irrigation

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Abstract

Subsurface drip irrigation success depends on surpassing the backpressure obstacle, a phenomenon which occurs when the water application intensity exceeds the infiltration rate of soil, which reduces the emitter flow rate. Thus, this study aimed to determine the flow rate variation, in relation to surface flow, of four drip emitters when buried at two depths in a loam soil (Yolo Loam soil), and the backpressure generated by the soil on subsurface condition. The cavity radius developed around the emitters outlet was also obtained. The experiment was conducted in a completely randomized design, in a strip-plot scheme, with three treatments: installation depth of driplines (two levels: 0.10 and 0.20 m); dripline type (four levels: D5000, JardiLine, TalDrip and and Hydro PCND) and irrigation time (three levels: 0.5, 1.0 and 3.0 h). The results showed that the flow rate variation between the surface and subsurface application on *Yolo Loam* soil, with inlet pressure of 145 kPa, was greater the higher was the emitter flow rate. For pressure-compensating emitters, even under backpressure influence, this was not enough to cancel the pressure-compensating device operation, of the emitters. The emitters installation depth, as well the irrigation time, did not affect the backpressure and, consequently, the flow rate variation.

Keywords

Irrigation engineering; Irrigation lateral lines hydraulics; Irrigation management; Trickle irrigation.

Introduction

The use of subsurface drip irrigation systems has been increasing due to its advantages over surface one, such as greater efficiency in water use and application, lower soil water evaporation and agricultural production improvements (Nogueira et al., 2021). However, in subsurface irrigation, soil physical and hydraulic properties can influence the hydraulic characteristics of the emitter (Wang et al., 2021) which contributes to the water distribution uniformity of this system can be lower than one for surface drip irrigation system (Cai et al, 2021).

Cavities in soil can develop around the buried emitter outlet, and the size of these cavities tends to affect the generated backpressure (Nogueira et al., 2021). Gil et al (2010) emphasized that the development of these cavities is related to the emitters discharge.

Saefuddin et al. (2019) explain that there is a relationship between soil pressure and emitter flow and, for this reason, soils with low infiltration capacity tend to decrease the buried emitters discharge, which causes variations in system flow rate. Thebaldi et al. (2021) present that this behavior is due to backpressure, a phenomenon that occurs when the buried emitter water application intensity exceeds soil infiltration rate, which, according to Shani et al. (1996), creates a positive pressure around the dripper and reduce the hydraulic potential gradient at the soil-emitter interface, consequently reducing the flow rate of this. Thus, the backpressure phenomenon can change the hydraulic characteristics of emitter in subsurface drip irrigation and may vary and reduce the drippers flow rate, resulting in poor irrigation uniformity (Ren et al., 2018; Thebaldi et al., 2016).

Shani et al. (1996) report that in fine-textured soils, the backpressure effects can be pronounced, resulting in a greater buried emitter flow rate reduction, however, in some cases, an opposite behavior can be found, as presented by Nogueira et al. (2021), in which, for a silty loam soil, with low saturated hydraulic conductivity, there was the smallest reduction in subsurface conditions flow rate, compared to other soils, since the resistance to flow was so great that there was the formation of preferred paths to the surface, as the emitters were buried at

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only 0.05 m. Yet, Wang et al. (2021) state that, in general, for the same emitter operating under a same type of soil, the greater its working flow rate, the greater is the backpressure around the dripper, and, consequently, the greater is the emitter's flow rate variation.

Thus, is clear that the success of subsurface drip irrigation is dependent on the understanding of the occurrence of the backpressure process. As shown, there is a lot of information at the literature regarding soil physical and hydraulic properties influence on the backpressure and the hydraulic responses, of different emitters, subject to the backpressure phenomenon, however, it is necessary to investigate the backpressure occurrence due to the emitter installation depth and water application time. Thus, with this study we aimed to determine the flow rate variation (relative to surface flow) of four emitters when buried in a loam soil, and the backpressure created by the soil on subsurface condition due to the installation depth of driplines, dripline type and irrigation time.

Materials and methods

The experiment was conducted at the Campbell Tract Field Station of the University of California, Davis, USA, in an experimental area of Yolo Loam soil (15 x 48m) which was prepared with a harrow up to 0.30 m depth. It was used a completely randomized design, in a strip-plot scheme, with three treatments: installation depth of driplines (two levels: 0.10 and 0.20 m); dripline model (four levels: D5000, JardiLine, TalDrip and Hydro PCND) and irrigation times (three levels: 0.5, 1.0 and 3.0 h). The data means were compared by Scott-Knott test at 5% probability.

The driplines had the following technical features: a) Rivulis D5000, pressure-compensating (PC), nominal flow rate (NFR) of 2.0 L h^{-1}, nominal diameter (ND) of 0.016 m, inner diameter (IN) of 0.0138 m and operating pressure range between 50 and 350 kPa; b) NaanDanJain JardiLine, non-pressure-compensating (NPC), NFR of 3.6 L h^{-1}, maximum operation pressure of 350 kPa, ND of 0.016 m and ID of 0.0139 m; c) NaanDanJain TalDrip, NPC, NFR of 1.7 L h^{-1}, ND of 0.017 m and ID of 0.0158 m; and d) Rivulis Hydro PCND, PC and anti-draining, NFR of 2.35 L h^{-1}, ND of 0.016 m, ID of 0.0153 m, operating range between 75 and 350 kPa.

The irrigations were performed using a mobile system with a sub-mainline that included 6 buried lateral driplines. Irrigation manifold was constituted of a mobile water reservoir and a pump with a coupled filtration system. After the pumping system, we installed a pressure gauge and an Omega Engineering FL-46.302 flow meter. Before the transition to the sub-mainline, were installed a Senninger PRLG pressure regulator and another pressure gauge, on the downstream, which indicates an inlet pressure of 145 kPa. TalDrip and JardiLine driplines had 50 emitters while D5000 and Hydro PCND had 20 and 23, respectively, due to different spacing between drippers.

In each treatment, the emitter flow was measured immediately after the system start and immediately before the pumping system shut down, and at 1/3, 1/2 and 2/3 of irrigation time, what represented five repetitions in time. The obtained flow rate was divided by the number of emitters in each lateral dripline, thus making up the average flow per emitter. To determine the flow rate variation, was necessary to determine the flow of each studied emitters in surface condition. These were calculated by the flow-pressure equations presented by Thebaldi et al. 2016 (Table 1). With these values it was, then, possible to calculate the quotients between the difference of the average subsurface flow and the surface flow at an inlet pressure of 145 kPa; and the surface flow at an inlet pressure of 145 kPa.

Table 1. Flow-pressure models for the emitters at surface and subsurface conditions.

Emitter	Surface	Subsurface
D5000	$Q = 1.2739 \times h_0^{0.1053}$	$Q = 1.120 \times (h_0 - h_s)^{0.1320}$
JardiLine	$Q = 0.5062 \times h_0^{0.4331}$	$Q = 0.520 \times (h_0 - h_s)^{0.4250}$
Hydro PCND	$Q = 2.4038 \times h_0^{0.0044}$	$Q = 2.134 \times (h_0 - h_s)^{0.0269}$
TalDrip	$Q = 0.2470 \times h_0^{0.4154}$	$Q = 0.271 \times (h_0 - h_s)^{0.3940}$

Source: Thebaldi et al. (2016).

The backpressure values (hs) were estimated using the flow-pressure mathematical models of the emitters, in subsurface condition (Thebaldi et al., 2016), with the parameters "$k_{subsurface}$" and "$x_{subsurface}$". The physical and hydraulic characteristics and the constants of van Genuchten (1980) soil water retention curve are presented in Table 2. The average initial soil moisture was 0,15 $m^3\ m^{-3}$.

Table 2. Physical and hydraulic characteristics of the Yolo Loam soil.

Property	0 – 0.30 m layer	0.30 – 0.60 m layer
ρ_s (kg m^{-3})	1436	1407
K_{sat} (cm h^{-1})	1.7800	0.5500
α (cm^{-1})	0.0072	0.0064
n	1.5712	1.6020
m	0.3640	0.3760
θ_s (m^3 m^{-3})	0.4030	0.4070
θ_r (m^3 m^{-3})	0.0685	0.0683
Sand (%)	28.0000	26.0000
Silt (%)	49.0000	52.0000
Clay (%)	23.0000	22.0000

ρ_s – soil bulk density; k_{sat} – soil saturated hydraulic conductivity; θ_s – saturation water content; θ_r –residual water content, m calculated by Mualem restriction (m=1-1/n).

The spherical cavity radius developed around the emitter discharge outlet (r_0) was calculated by Philip's (1992) analytical expression. For this, it was necessary to adjust the Gardner (1958) parameter α_G for non-saturated hydraulic conductivity, which was obtained by equating the Kirchhoff's potential (Gardner, 1958) of Gardner and Mualem-van Genuchten hydraulic model (Genuchten, 1980), through the methodology proposed by Gil et al. (2011), presented by Equation 1.

$$\phi=\int_{-\infty}^{0} k(h)dh \tag{1}$$

where:

ϕ = Kirchhoff's potential;

k(h) = Non-saturated soil hydraulic conductivity, given by the Mualem – van Genuchten model, cm h^{-1}.

The non-saturated soil hydraulic conductivity model, as a function of soil water tension, is given by Equation 2.

$$k(h)=k_{sat}\frac{\left\{1-(|\alpha h|)^{n-1}\left[1+(|\alpha h|)^{n}\right]^{-m}\right\}^{2}}{\left[1+(|\alpha h|)^{n}\right]^{\frac{m}{2}}};\text{for }\left(m=1\,\frac{1}{n}\right) \tag{2}$$

where:

k(h) = non-saturated soil hydraulic conductivity, m s^{-1};

h = matric potential, given as a function of dimensionless water content, kPa;

α e n = fitted model parameters, related to soil.

By direct substitution, α_G may be obtained by Equation 3.

$$\alpha_G=\frac{k_{sat}}{\phi}$$

Considering the soil water retention curve parameters for 0 – 0.30 m layer and the soil saturated hydraulic conductivity (Table 2), the Gardner's alpha parameter was 2.8 m^{-1}. With the values of "$Q_{superficial}$" of each treatment, "α_G", "k_{sat}" and "h_s" and using Equation 4, the values of the radius of the spherical cavity formed at the discharge source point of the emitters (r_0) were obtained for the combinations of emitters, irrigation depths and times. Equation 4 is Philip's (1992) analytical solution to relate the soil cavity pressure (h_s) with the physical and hydraulic properties and the emitter flow rate.

$$h_s=\left(\frac{2-\alpha_G r_0}{8\pi k_{sat} r_0}\right)Q_{superficial}\frac{1}{\alpha_G}$$

where:

$Q_{superficial}$ = emitter flow rate at superficial condition, m³ s-^{1};

r_0 = spherical cavity radius, m.

The backpressure values (h_s) were calculated using the models presented in Table 1, suitable for each emitter evaluated in submerged condition. Isolating "r_0" in Equation 4, Equation 5 is obtained, used to estimate the values of the cavities radius formed around the water source points, for each treatment.

$$r_0=\frac{2\ Q_{superficial}\alpha_G}{8\pi\ k_{sat}(\alpha_G h_s+1)+\alpha_G^2 Q_{superficial}}$$

Results and discussion

Both in flow rate variation and backpressure evaluation, it was found statistically significant differences only for the "Emitter" source of variation (Table 3). Thus, the driplines installation depth as well the irrigation time, do not affect flow rate variation in relation to surface application and backpressure generated. It should be noted that the soil in the experimental area was plowed up to a 0.3 m depth, and the emitters were buried at 0.10 and 0.20 m, so, it is expected uniformity or, at least, a tendency to uniformity, of the soil physical and hydraulic characteristics, which influences on the backpressure phenomenon and eventual flow rate variation.

Table 3. Summary of ANOVA performed on the evaluation of variation between surface and subsurface flow rate of emitters (ΔQ) and backpressure (h_s) due to the applied treatments.

Source of Variation	DF	Mean Square and F significance	
		ΔQ	h_s
Depth (D)	1	1.5623^{ns}	26.5903^{ns}
Error a	8	5.0141	78.4802
Emitter (E)	3	1294.0489*	1832.1631*
D x E	3	0.2066^{ns}	0.4853^{ns}
Error b	24	2.5776	38.3193
Irrigation Time (T)	2	0.0773^{ns}	2.3326^{ns}
T x E	6	0.4659^{ns}	9.8375^{ns}
T x D	2	0.2492^{ns}	3.5477^{ns}
T x D x E	6	0.3453^{ns}	5.1297^{ns}
Error c	64	0.7790	25.2173
cv a		19.70	41.62
cv b		14.12	29.08
cv c		7.76	23.59

DF: degrees of freedom. ns: not significant at 5% probability. *: significant by the F test at 5% probability. cv: coefficient of variation (%).

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Ren et al. (2018) evaluated the hydraulic performance of a subsurface drip irrigation system and concluded that the spatial variability of soil physical properties might influence on emitters discharge due to backpressure phenomenon. But, according to the results obtained in this study the elapsed irrigation time did not statistically influence the emitter flow rate variation and the backpressure generated. Such behavior can be explained by the fact that backpressure and the saturated cavity development are a local phenomenon, which occurs around a discharge point source, that is, around the emitter outlet (Gil et al., 2010). Furthermore, we emphasize, that the difference between the emitters installation depths was low, 0.10 m, so that it was possible to minimize the influences of the spatial variability of soil hydraulic and physical properties on the obtained results.

Gil et al. (2011) state that, as soon as the water flows through the emitter, there is a fast soil pressure increase in the first operation minutes and then the pressure stabilizes, as can be seen in this study, because we did not find for the statistically significant variation for the variable "Depth" (Table 3). Cai et al. (2021) claim that when starting irrigation in a low moisture soil, the total soil water potential is too negative due to the matric potential prevalence: at this moment, the soil water potential gradient would promote a fast water flow rate through the dripper and the emitter discharge in soil would be greater than in the air. As the water content in the soil increases, the matric potential also increases and the soil energy becomes less negative and the infiltration rate decrease, which normally tends to also decrease the emitter flow rate. When the soil water content reaches saturation, there is a pressure potential dominance, with positive values, which will hinder or even inhibit the water flow rate trough the emitter. So, according to the authors, the higher soil water content, the lower the buried emitter discharge.

The different emitter models represent, in its essence, different flows associated to the pressure-compensating characteristic or not (Table 4). At an inlet pressure of 145 kPa, the JardiLine emitter, which superficial flow rate was 4.37 L h^{-1}, was the one that suffered the higher flow rate variation (11.42%), while the TalDrip dripper, with a superficial flow rate of 1.91 L h^{-1}, was the second one (5.52%). In contrast, the D5000 and Hydro PCND drip emitters, which have surface flow rate at 145 kPa of 2.15 and 2.46 L h^{-1}, showed a statistically equal flow variation of 1.21 and 1.12%, respectively. The smaller variation between the surface and subsurface flow rate to the latter, is due the fact that they are pressure-compensating. The result also implies that, statistically, the value of the pressure-compensating emitters discharge exponent (Table 1) did not influence on these emitters flow rate variation.

Table 4. Flow rate variation (ΔQ) of the evaluated emitters buried in the Yolo Loam soil with a lateral dripline inlet pressure of 145 kPa.

Emitter	Flow rate variation (decimal)
Hydro PCND	0.0112a
D5000	0.0121a
TalDrip	0.0552b
JardiLine	0.1142c

Different letters on the columns indicate statistical differences by the Scott-Knott test with 5% probability level.

Similarly, Elamin et al. (2017) evaluated the hydraulic performance of two pressure-compensating buried emitters (4.0 L h^{-1}) and one non-pressure-compensating emitter (8.0 L h^{-1}) under different operating pressures and found a major flow rate variation at the non-pressure-compensating emitter. According to Alabas (2013), it occurs because pressure-compensating emitters are designed to discharge water at a uniform rate over a wide pressure range, while to the non-pressure-compensating emitters, the pressure variation must remain constant, so that, there is no large flow rate variation. In contrast, Nogueira et al. (2021) evaluated the behavior of a pressure-compensating emitter (2.3 L h^{-1}) and a non-pressure-compensating one (4.0 L h^{-1}) on 4 different soil types (sandy loam, clay loam, silty loam, and clay) and noticed that, except for sandy loam soil application, the pressure-compensating dripper was the one that presented the major percentage variation between the subsurface and surface flow.

Regarding the backpressure (Table 5), the results showed that the different flow rate of each emitter caused different backpressure values, except for TalDrip and D5000 emitters, which showed equal backpressure values when buried in Yolo Loam soil with an inlet pressure of 145 kPa. The JardiLine emitter had the highest backpressure acting on its discharge point, 32.41 kPa, while the TalDrip and D5000 emitters were those which caused the smallest backpressures on the soil. Amer et al. (2017) studied the flow rate variation of superficial and subsuperficial drippers, with 4.0 and 8.0 L h^{-1} flow rates, under an inlet pressure of 100 and 150 kPa, and noticed to the buried emitters, as higher was the emitter flow, the greater was the cavity formed around the emitter discharge point, because of specific soil characteristics and, due this, the lower was the soil backpressure; and for the same emitter flow, the greater the inlet pressure at the lateral driplines, the greater was the backpressure generated.

Table 5. Surface flow rate at 145 kPa inlet pressure and calculated backpressure acting on buried emitters.

Emitter	Surface flow at 145 kPa (L h^{-1})	Backpressure (kPa)
TalDrip	1.91	14.99a
D5000	2.15	16.86a
Hydro PCND	2.45	20.88b
JardiLine	4.37	32.41c

Different letters on the columns indicate statistical differences by the Scott-Knott test with 5% probability level.

Thus, at Table 6, then, are presented the spherical cavity radius (r_0) that were calculated for each emitter, depths, and irrigation time combinations. The results showed that the greater values obtained for r_0, in general, were obtained for the JardiLine emitter, which had greater superficial flow rate among the others and greater acting backpressure. Gil et al. (2010) obtained similar results and reported that in case of low flow rate, the cavity radius increase tends to be linear

Table 6. Cavity radius developed around the emitter outlet, r_0 (m), at a lateral dripline inlet pressure of 145 kPa for the various Yolo Loam soil treatments.

Emitter	Depth (m)	Irrigation Time (hours)		
		0.5	1.0	3.0
TalDrip	0.10	0.004908	0.004680	0.004627
	0.20	0.004716	0.004250	0.004625
JardiLine	0.10	0.005593	0.005260	0.005426
	0.20	0.005216	0.00531	0.005198
D5000	0.10	0.004548	0.005220	0.004550
	0.20	0.004239	0.004636	0.004710
Hydro PCND	0.10	0.004415	0.004396	0.004650
	0.20	0.004563	0.004025	0.004530

For two and three-way interaction among the sources of variation, there were found no-statistically differences for the dependent variables (Table 3). Due it, with the analysis of individual means of flow rate variation by treatments combination (Table 7), were observed similar values as a function of installation depth and irrigation time within each emitter model. Likewise, for the mean calculated backpressure in all combinations of treatments, minor differences were noted between the individual backpressure values for the treatments. These differences, even if not statistically significant, are associated with the different subsurface flow rate obtained in the field tests for each emitter.

Table 7. Variation between superficial and subsuperficial flow rate and backpressure at an inlet pressure of 145 kPa for the various treatments.

		Irrigation Time (hours)					
Emitter	Depth (m)	0.5	1	3	0.5	1	3
		Flow rate variation			Backpressure (kPa)		
TalDrip	0.1	0.0522	0.0547	0.0554	13.9300	14.7700	14.9800
	0.2	0.0541	0.0596	0.0550	14.6400	16.6100	14.9900
JardiLine	0.1	0.1086	0.1157	0.1121	30.7200	32.8700	31.7800
	0.2	0.1167	0.1146	0.1171	33.2000	32.5700	33.3200
D5000	0.1	0.0126	0.0098	0.0126	17.2300	14.5600	17.2300
	0.2	0.0139	0.0122	0.0117	18.7500	16.8400	16.5300
Hydro PCND	0.1	0.0113	0.0111	0.0109	20.9000	21.0000	19.6700
	0.2	0.0110	0.0118	0.0110	20.1100	23.2600	20.2500

Conclusions

The flow rate variation between the surface and subsurface application in the Yolo Loam soil, with inlet pressure of 145 kPa, was greater as higher was the emitter flow rate. For pressure-compensating emitters, D5000 and Hydro PCND, the backpressure influence was not enough to cancel the devices' pressure-compensating effect, which is interesting, so that the system performs in field as similar as possible to the designed. The emitters installation depth, as well the irrigation time, did not affect the backpressure and, consequently, the flow rate variation.

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