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DESIGN OF BUBBLER IRRIGATION SYSTEM WITH EMITTERS AT GROUND LEVEL

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1 ABSTRACT

In the Brazilian semiarid region, sustainable growth rates and higher standards of living in society may be attained by the use of irrigation aiming at obtaining the best economic function without disregarding several factors, such as labor, soil, and water supply. The objective of this work is to present an alternative design procedure for low-head bubbler irrigation systems to make the technology more accessible to users. An electronic spreadsheet was developed and made available for sizing laterals and delivery hoses at a ground level based on the principles of mass conservation, energy conservation, and friction head loss. Nine combinations of spacings between plants and between rows were used with different lateral lengths, resulting in 22 designs operating at 9.8 kPa (1 m.wc). The designs were subjected to hydraulic and efficiency tests. Uniformities of water application were computed using Christiansen's uniformity coefficient and distribution uniformity coefficients. Designs were ranked according to the proposed classification of Mantovani. Irrigation uniformities, above the recommended limits and with low variability across designs, allow us to conclude that the design procedure for the proposed irrigation system is feasible.

Keywords: bubbler modified, uniformity, irrigation efficiency, semiarid

BOTELHO, M. V. B. L.; COELHO, E. F.; SANTOS, M. R. DIMENSIONAMENTO DE SISTEMA DE IRRIGAÇÃO BUBBLER COM EMISSORES AO NÍVEL DO SOLO

2 RESUMO

No semiárido brasileiro, o crescimento sustentável e o aumento do padrão de vida da sociedade podem ser proporcionados por projetos de irrigação que busquem à obtenção da melhor função econômica, sem desconsiderar os diversos fatores, como mão de obra, solo e suprimento de água. Objetivou-se com este trabalho apresentar um modelo de dimensionamento alternativo do sistema de irrigação bubbler, de baixa pressão, de forma a tornar a tecnologia mais acessível ao usuário. Foi desenvolvido e disponibilizado uma planilha eletrônica para o dimensionamento da linha lateral e emissores dispostos ao nível do solo, usando como base, os princípios da

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conservação de massa, da conservação de energia e da perda de energia por atrito. Escolhidos 9 combinações de espaçamentos entre plantas e linhas, em diferentes comprimentos de Linha Lateral, foram elaborados 22 projetos, operando com 9,8 kPa (1 mca), para realizar avaliação hidráulica e teste da eficiência do método. As uniformidades de aplicação da água foram calculadas pelos coeficientes de uniformidade de Christiansen e Uniformidade de Distribuição, e interpretados na classificação proposta por Mantovani. As uniformidades de irrigação, superiores aos limites recomendados, obtidas com baixa variabilidade entre os projetos, permitem concluir que a metodologia de dimensionamento do sistema de irrigação proposto é exequível.

Palavras-chave: bubbler adaptado, uniformidade, eficiência de irrigação, semiárido

3 INTRODUCTION

Bubbler irrigation is an easy system to install in the field and can be used in various horticultural crops involving greater spacing between plants and, similarly, in fruit trees. A total of 11.8% of the population of Brazil lives in semiarid regions, representing 22.6 million people, of which 38% are from rural areas (IBGE, 2010). Agriculture is feasible in these regions as irrigation is used (AGÊNCIA NACIONAL DE ÁGUAS, 2017). However, irrigated agriculture demands 70% of fresh water used worldwide and this natural resource has become scarcer in the 21st century (BRASIL, 2006; FAO, 2017).

Notwithstanding, sustainable development and a higher standard of living in society are achieved by increasing productivity (PINHEIRO *et al.*, 2015). In semiarid regions, higher productivities may be attained using efficient irrigation. Efficient irrigation systems are profitable for farmers and are beneficial for the environment by conserving soil and water (LEVIDOW *et al.*, 2014).

Localized irrigation systems exhibit greater water savings and higher irrigation efficiencies as long as they are both well designed and well managed. Bubbler irrigation is a relatively low-maintenance localized system (ABDEL-NABY, 2016). The cost of installing a bubbler system per unit area in a planting spacing of 4 x 4 m can reach half the cost of a microsprinkler system, and furthermore, bubble systems consume 30 times less energy (SILVA *et al.*, 2012). Andrade, Souza and Silva (2002) reported an average cost of installing a bubbler system with a planting spacing of 8 x 8 of US$ 455.00 ha^{-1}.

Bubbler systems can operate using only gravity as an energy source, conducting water through thin-walled tubes and applying it at high distribution uniformities (RAWLINS, 1977), including for wastewater irrigation (CARMO, 2013; MEDEIROS *et al.*, 2014). A low-pressure head makes emitters less likely to clog since their diameters are generally equal to or greater than 3 mm. This reduces overall cost as cheaper low-pressure pipes are often employed and, when filtration systems and mechanical pumping are necessary, low-power devices are used (WAHEED, 1990; REYNOLDS, 1993; ANDRADE; SOUZA; SILVA, 2002; SOUZA *et al.*, 2005; SILVA, 2013). Bubbler systems are fixed, which reduces labor requirements, and due to their higher water discharge rate, bubbler systems are well received by farmers of rural settlements in semiarid regions (COELHO *et al.*, 2012).

The system, similar to irrigation systems using microtubes, consists of a mainline, manifolds, laterals laid midway between two rows of plants, and delivery hoses inserted in the laterals to deliver water to the plants. However, for irrigation using microtubes, hoses are 0.5 to 2.0 mm in diameter, deliver small amounts of water, and are highly susceptible to clogging (PEREIRA; CORREIA; SALES, 2012; ALVES *et al.*, 2015).

Delivery hoses are anchored to wooden stakes so that water is delivered at different elevations, which are defined taking into account principles of conservation of energy and friction head loss. Nonetheless, stakes are occasionally knocked down, decreasing the uniformity flow in bubble systems (COELHO *et al.*, 2012). Therefore, the need estimate delivery hose heights and adjust these heights makes bubble systems less practical for farmers.

Since different delivery hop elevations ensure a uniform flow rate, it is possible to size components of the system so that delivery hoses with different lengths along laterals would lose head pressure to the same extent as elevated delivery hoses, even if emitters are located at ground level.

The objective of this work was to present an alternative design procedure for low-head bubble systems to make the system more accessible to farmers.

4 MATERIALS AND METHODS

This work consisted of three stages. In the first stage, a design procedure was developed based on a literature review. In the second stage, irrigation systems were designed with different spacings and lateral lengths. In the third stage, systems were installed in an area of Embrapa Cassava & Tropical Fruits located in Cruz das Almas, Bahia state (12° 48`S, 39° 06" W, 225 m) [s. l.] to assess flow rate uniformity across delivery hoses.

4.1 Alternative design procedure for bubble systems

We created an electronic spreadsheet to aid the sizing of laterals and delivery hoses.

Based on the principle of mass conservation, a continuity equation (eq. 1) was used to calculate the velocity of water within several portions of laterals and within delivery hoses.

$$Q = V \times A = \text{constant} \quad (1)$$

where

Q is the volumetric flow rate, $m^3\ s^{-1}$;
V is velocity, $m\ s^{-1}$; and
A is the cross-sectional area, m^2.

The Bernoulli equation (eq. 2) was used to compute head pressures at different points of the system and total friction head loss between these points.

$$\frac{P_1}{\gamma} + \frac{V_1^2}{2g} + Z_1 = \frac{P_2}{\gamma} + \frac{V_2^2}{2g} + Z_2 + Hf \quad (2)$$

where,

P is pressure, $kgf\ m^{-2}$;
γ is the specific weight of water, $kgf\ m^{-3}$;
V is the velocity of water, $m\ s^{-1}$;
G is gravitational acceleration, $m^2\ s^{-1}$;
Z is elevation with respect to a reference datum, m;
Hf is the total friction head loss, m.

Total friction head loss was termed allowable head loss (Hf_{all}). Hf_{all} is composed of head losses within laterals (Hf_l) and within delivery hoses (Hf_{dh}).

The Darcy-Weisbach equation (eq. 3) was used to calculate the friction head loss:

$$hf = f \times \frac{L}{D} \times \frac{V^2}{2g} \text{ or } hf = J \times L \rightarrow J = \frac{f}{D} \times \frac{V^2}{2g} \quad (3)$$

where
hf is the friction head loss, mm;
f is the friction factor, dimensionless;
L is the length of the pipe, m;
D is the diameter of the pipe, m;
V is the flow velocity in the pipe, m s^{-1};
G is gravitational acceleration, m^2 s^{-1}; and
J is the friction head loss per unit length, m m^{-1}.

The friction factor f is calculated by equations 4, 5, and 6 and depends on the Reynolds number (eq. 7).

Rn less than 2,000 $$f = 64\ Rn^{-1} \quad (4)$$

Rn between 2,000 and 100,000 $$f = 0.316\ Rn^{-0.25} \quad (5)$$

Rn greater than 100,000 $$f = 0.13\ Rn^{-0.172} \quad (6)$$

$$Rn = \frac{V \times D}{\upsilon} \quad (7)$$

where
Rn is the Reynolds number, dimensionless;
V is the water flow velocity in the pipe, m s^{-1};
D is the inside pipe diameter, m; and
υ is the kinematic viscosity of water, m^2 s^{-1}.

In systems using smooth pipes with roughness lower than the laminar boundary layer thickness and with small diameters, the Blasius equation (eq. 5) can estimate head losses with precision in the 2,000 to 10^5 range (WAHEED, 1990; REYNOLDS, 1993; WEBBER, 2014; ALMEIDA *et al.*, 2016).

In addition to head losses due to the friction of water against the walls of the pipe (major losses), there are also minor head losses due to the presence of fittings (delivery hoses). Hence, because of them, head losses were converted to an equivalent length (eq. 8) (BERNARDO *et al.*, 2019).

$$J' = J\ (Se + Le)\ Se^{-1} \quad (8)$$

where
J' is the adjusted total friction head loss, m m^{-1};
J is the major head loss, m m^{-1};
Se is the spacing between delivery hoses, m; and
Le is the length equivalent to friction head loss, m.

Equivalent length (Le) was estimated as a function of the inside diameter of the lateral and of delivery hose insertions in the lateral (KELLER; BLIESNER, 1990).

By inputting slope, spacing, number of plants per lateral (1 emitter $plant^{-1}$), pressure head at the lateral inlet, diameter of lateral, diameter of delivery hose and flow rate at the lateral inlet into the spreadsheet, calculations are performed instantaneously, displaying the lengths of each delivery hose in laterals. To facilitate understanding, calculations were split into two steps.

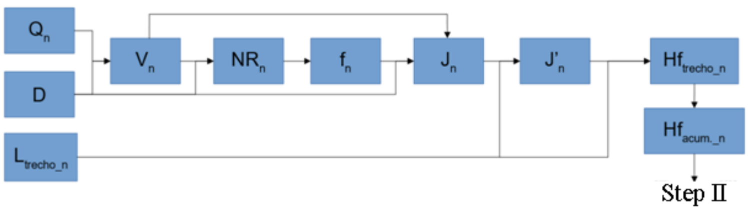
In step I, laterals were sized. Each connection along the lateral is considered a section due to the change in flow rate at it. Section 1 goes from the upstream end of the lateral to the connection point of the first delivery hose. The remaining sections are from the previous connection point to the next connection point of a given section. For instance, section 2 is from the connection point of the 1st delivery hose to the connection point of the 2nd delivery hose; section 3 is from the connection point of the 2nd delivery hose to the 3rd delivery hose, and so forth, up to the last delivery hose in the lateral. The lengths of the sections are equal to the spacing between delivery hoses, except for section 1, which is reduced by half.

Step I provides friction head losses within each section of the lateral (Hf_l) that will be used in Step II. Thus, on the spreadsheet, a line is sized for each section, then, lateral head losses are calculated from the first to the last section.

The flow rate within section n (Q_n) is estimated using the flow rate at the lateral inlet. In section 1, Q_1 is equal to the total flow rate, and in the following sections, Q_n is equal to the flow rate of the previous section minus the outlet flow rate at each connection point in the lateral. Using Q_n and the lateral inner diameter (D), the water velocity (V_n) was calculated, and then, the Reynolds number (Rn), friction factor (f_n), and friction head loss per unit length (J_n) were computed for each section. Therefore, using J_n and the length of section n (L_{sec}), the adjusted head loss per unit length (J'_n) due to minor losses was obtained, and then, the friction head loss within the section (Hf_{sec}) was calculated.

At the end of the step-by-step calculation (Figure 1), lateral friction head loss in each section (Hf_{l_n}) was calculated. In section 1, Hf_{l_n} is equal to Hf_{sec}. For the remaining sections, Hf_{l_n} is equal to the Hf of the previous section (Hf_{l_n-1}) plus the head loss of this section (Hf_{sec_n}).

Figure 1. Step-by-step calculations for laterals (Step I).



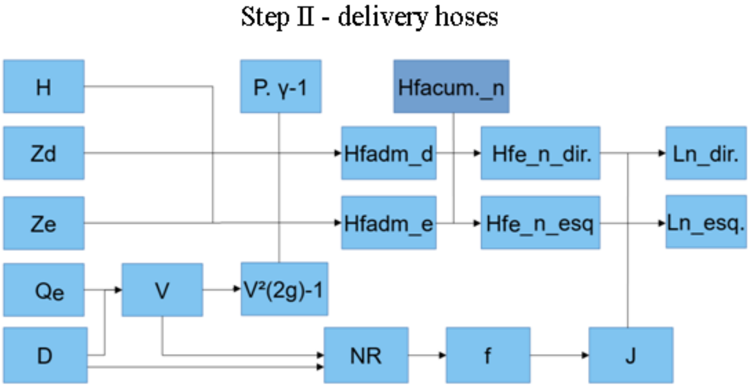
In Step II, calculations were used to size the length of delivery hoses for each section (or connection point) of the lateral. As in the previous step, on the spreadsheet, a line is used for each section of the lateral. It is assumed that the outlet of delivery hoses is under atmospheric pressure only, i.e., its piezometric head ($P\,\gamma^{-1}$) is zero, and the flow rate of every delivery hose is the same as the delivery hose flow rate (Q_{dh}) which is equal to the division of the flow rate at the lateral inlet by the number of delivery hoses in the lateral.

The area slope, number of plants per lateral, flow rate at the lateral inlet, and delivery hose diameter (D) are input into the spreadsheet to calculate the velocity head ($V^2(2\,g)^{-1}$), which will be the same for each delivery hose in the lateral, and the elevation head (Z_n) of each delivery hose. The elevation head equals zero in level areas. For uneven areas, elevation heads can vary from one section to another and in the section between the left and the right delivery hose in the lateral.

By subtracting delivery hose heads $V^2(2\,g)^{-1}$, Z_n, and $P\,\gamma^{-1}$ from the head pressure at the lateral inlet, the allowable friction head loss (Hf_{all_n}) of a given delivery hose is calculated. Afterwards, from the results of Step I, Hf_{l_n} of each section is subtracted from Hf_{all_n} to obtain the head loss of the delivery hose (Hf_{e_n}) in each section.

As shown in Figure 2, the Reynolds number (Rn) is calculated in parallel with the friction factor (f) and head loss per unit length (J) of delivery hoses. Finally, with Hf_{e_n} and J, delivery hose lengths (L_{n_r} or L_{n_l}) for each section and side (left or right) of the lateral are sized.

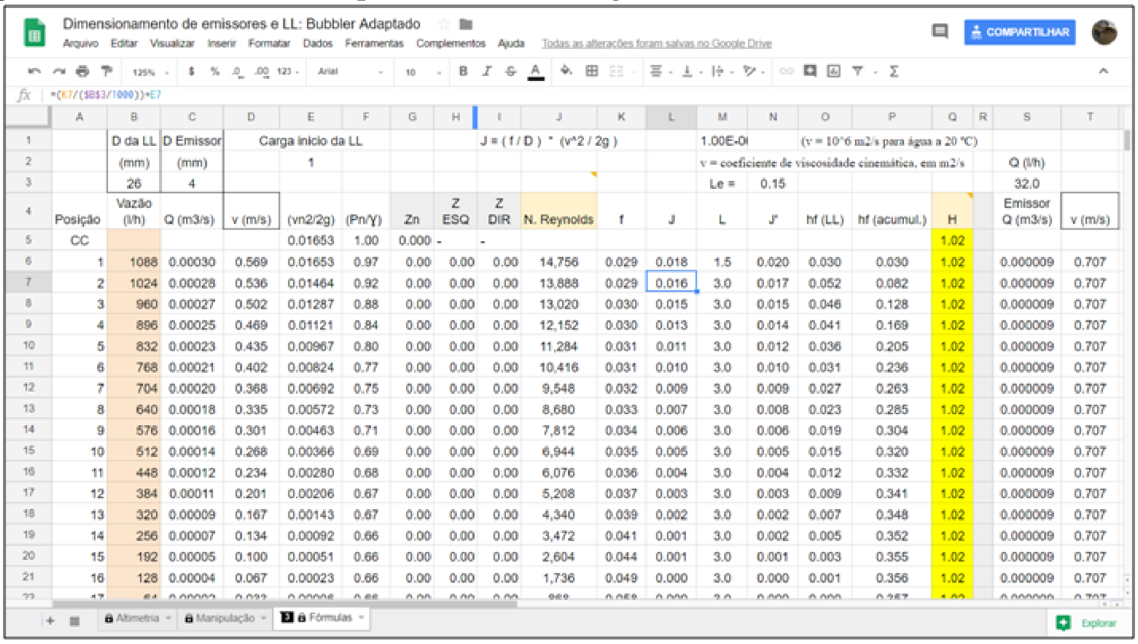
Figure 2. Step-by-step calculation for emitters (Step II).



A file with a detailed flow chart composed of three electronic spreadsheets is available at: https://docs.google.com/spreadsheets/d/1C2qrP_tVY3pRaIZdvjXcUaCoPKwmNgZsaWL9VqLqnxw/edit#gid=0.

To provide a simple interface and to facilitate use by the general public, spreadsheets contain the following: Formulas (Figure 3), section of the spreadsheet where calculations are done and equations are verified; Slope (Figure 4a), tab where elevations of different points in the area are inputted; and Manipulation (Figure 4 b), tab where the remaining system data (diameters, spacings, flow rates, etc.) are inputted and can be modified to find the best setup for the farmer.

Figure 3. Tab “Formulas” of spreadsheet for sizing emitters and laterals.


Dimensionamento de emissores e LL: Bubbler Adaptado

Arquivo Editar Visualizar Inserir Formatar Dados Ferramentas Complementos Ajuda Todas as alterações foram salvas no Google Drive

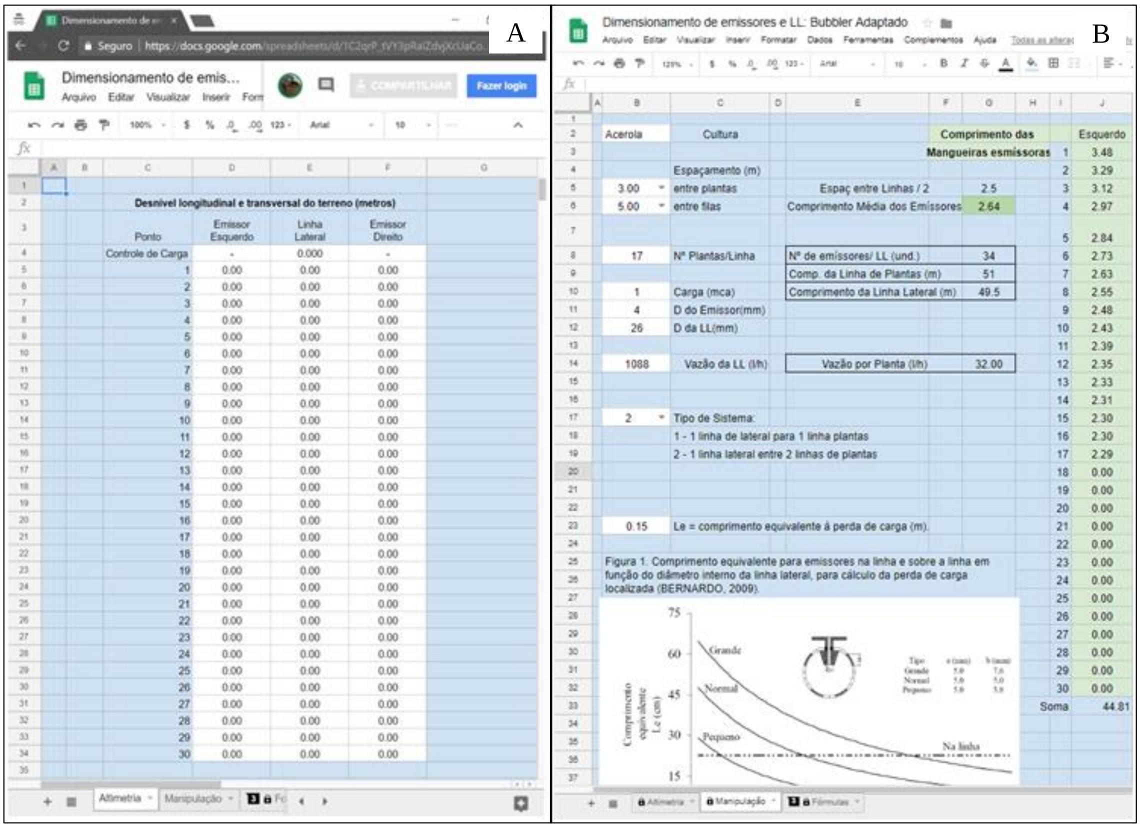
COMPARTILHAR

fx =(K7/(B3/1000))*E7

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1		D da LL	D Emissor		Carga início da LL				J = (f / D) * (v^2 / 2g)				1.00E-0		(ν = 10^6 m2/s para água a 20 °C)					
2		(mm)	(mm)		1								ν = coeficiente de viscosidade cinemática, em m2/s						Q (l/h)	
3		26	4										Le =	0.15					32.0	
4	Posição	Vazão (l/h)	Q (m3/s)	v (m/s)	(vn2/2g)	(Pn/γ)	Zn	Z ESQ	Z DIR	N. Reynolds	f	J	L	J'	hf (LL)	hf (acumul.)	H		Emissor Q (m3/s)	v (m/s)
5	CC				0.01653	1.00	0.000	-	-								1.02			
6	1	1088	0.00030	0.569	0.01653	0.97	0.00	0.00	0.00	14,756	0.029	0.018	1.5	0.020	0.030	0.030	1.02		0.000009	0.707
7	2	1024	0.00028	0.536	0.01464	0.92	0.00	0.00	0.00	13,888	0.029	0.016	3.0	0.017	0.052	0.082	1.02		0.000009	0.707
8	3	960	0.00027	0.502	0.01287	0.88	0.00	0.00	0.00	13,020	0.030	0.015	3.0	0.015	0.046	0.128	1.02		0.000009	0.707
9	4	896	0.00025	0.469	0.01121	0.84	0.00	0.00	0.00	12,152	0.030	0.013	3.0	0.014	0.041	0.169	1.02		0.000009	0.707
10	5	832	0.00023	0.435	0.00967	0.80	0.00	0.00	0.00	11,284	0.031	0.011	3.0	0.012	0.036	0.205	1.02		0.000009	0.707
11	6	768	0.00021	0.402	0.00824	0.77	0.00	0.00	0.00	10,416	0.031	0.010	3.0	0.010	0.031	0.236	1.02		0.000009	0.707
12	7	704	0.00020	0.368	0.00692	0.75	0.00	0.00	0.00	9,548	0.032	0.009	3.0	0.009	0.027	0.263	1.02		0.000009	0.707
13	8	640	0.00018	0.335	0.00572	0.73	0.00	0.00	0.00	8,680	0.033	0.007	3.0	0.008	0.023	0.285	1.02		0.000009	0.707
14	9	576	0.00016	0.301	0.00463	0.71	0.00	0.00	0.00	7,812	0.034	0.006	3.0	0.006	0.019	0.304	1.02		0.000009	0.707
15	10	512	0.00014	0.268	0.00366	0.69	0.00	0.00	0.00	6,944	0.035	0.005	3.0	0.005	0.015	0.320	1.02		0.000009	0.707
16	11	448	0.00012	0.234	0.00280	0.68	0.00	0.00	0.00	6,076	0.036	0.004	3.0	0.004	0.012	0.332	1.02		0.000009	0.707
17	12	384	0.00011	0.201	0.00206	0.67	0.00	0.00	0.00	5,208	0.037	0.003	3.0	0.003	0.009	0.341	1.02		0.000009	0.707
18	13	320	0.00009	0.167	0.00143	0.67	0.00	0.00	0.00	4,340	0.039	0.002	3.0	0.002	0.007	0.348	1.02		0.000009	0.707
19	14	256	0.00007	0.134	0.00092	0.66	0.00	0.00	0.00	3,472	0.041	0.001	3.0	0.002	0.005	0.352	1.02		0.000009	0.707
20	15	192	0.00005	0.100	0.00051	0.66	0.00	0.00	0.00	2,604	0.044	0.001	3.0	0.001	0.003	0.355	1.02		0.000009	0.707
21	16	128	0.00004	0.067	0.00023	0.66	0.00	0.00	0.00	1,736	0.049	0.000	3.0	0.000	0.001	0.356	1.02		0.000009	0.707

Altimetria Manipulação Fórmulas Explorar

Figure 4. Tabs “Slope” (A) and “Manipulation” (B) of spreadsheet for sizing emitter and laterals.



4.2 Simulation of bubbler system design using alternative procedure

In the second stage of the work, irrigation designs were simulated for further hydraulic evaluation. To simulate different situations that might occur in the field, 9 combinations of spacings between plants and between rows and different lateral lengths were field-tested, which resulted in 22 irrigation designs (Table 1). As in any irrigation system, previous knowledge of the crop and information of the area are essential, such as water source location, available flow rate, size, slope of the area, and other factors that might influence the design.

Table 1. Characteristics of irrigation: spacing between plants (SBP) and plant rows (SPR), number of delivery hoses per lateral (NDHL), lateral length (LL), flow rate at the lateral inlet (FRDH), and flow rate of delivery hoses (FRL) for a given design.

Design number	Characteristics					
	SBP (m)	SPR (m)	NDHL	LL (m)	FRDH (L h^{-1})	FRL (L h^{-1})
1	4	8	36	70	25	900
2	4	8	26	50	28.6	744
3	4	8	16	30	31.1	498
4	4	6	36	70	27.5	990
5	4	6	26	50	32.3	841
6	4	6	16	30	35.9	575
7	4	2	36	70	35.1	1265
8	4	2	26	50	46.2	1200
9	4	2	16	30	57.2	915
10	3	7	48	70.5	22.7	1090
11	3	7	34	49.5	28	952
12	3	7	20	28.5	32	640
13	3	5	48	70.5	24.8	1190
14	3	5	34	49.5	32	1088
15	3	5	20	28.5	38	760
16	2	6	40	39	29.5	1180
17	2	6	30	29	33	990
18	2	4	40	39	35	1400
19	2	4	30	29	41	1230
20	2	2.5	40	39	39	1560
21	2	2.5	30	29	47.5	1425
22	1.5	2.5	40	29.3	41	1640

To meet the variety of spacings and lateral lengths found in the designs, several common characteristics were chosen. The designs had only a mainline and a lateral, both of which were made of polyethylene with an inner diameter of 26 mm and delivery hoses with an inner diameter of 4 mm, for the purpose of delivering water to plants, at ground level.

At the upstream end of the lateral, a gate valve and a piezometer were installed to control the head pressure at the first delivery hose inlet, always at a distance equal to half the spacing between plants. The water source maintained its level at approximately 1.8 m high in relation to the irrigated area. The water supply was regulated to have a constant head of 9.8 kPa (1 m.wc) at the lateral inlet. 22 L h^{-1} was the lowest flow rate recorded, so all delivery hoses had a Reynolds number greater than 2,000.

Actual design began by filling out the spreadsheet following the steps:

1 – Input slope. In this work, the area is flat as every elevation point is zero;

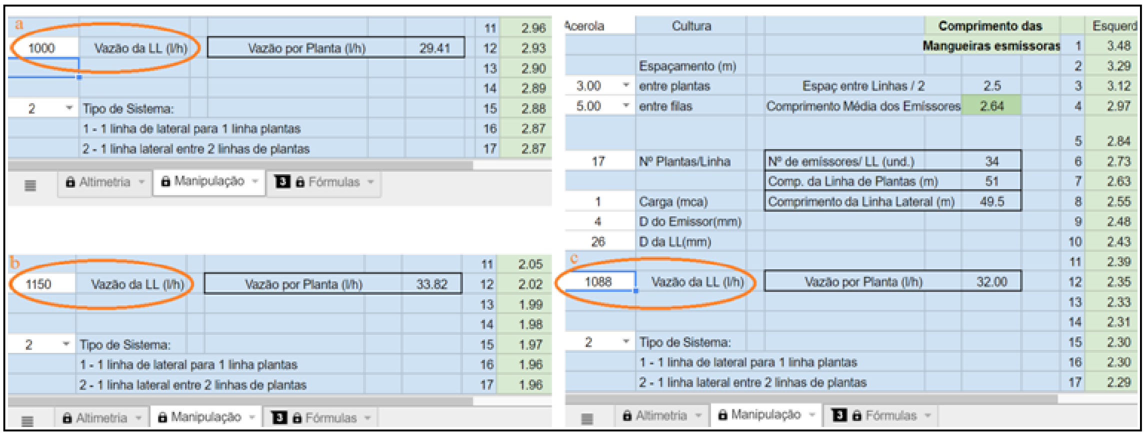
2 – Input previously defined common characteristics: pressure head, 1 m.wc; delivery hose diameter, 4 mm; and lateral diameter, 26 mm;

3 – Input individual characteristics of each design: spacing between plants, spacing between plant rows, and number of plants per row for lengths sized on the spreadsheet;

4 – Input flow rate at the lateral inlet of each design.

After inputting the lateral flow rate, the sizing procedure for delivery hoses starts. The spreadsheet provides the length of delivery hoses to even the flow rates across outlets. However, a given flow rate may result in delivery hoses that are too long or too short, thereby making the system unfeasible. Therefore, flow rates were either increased or decreased on the spreadsheet (Figure 5) to size the average length of delivery hoses which is approximately half the spacing between rows. For example, for design 14 with a spacing of 5 m between rows, the average length of delivery roses was 2.64 m, so from the ninth delivery hose on, delivery hoses were shorter than half the spacing between rows although long enough to deliver water to plants.

Figure 5. Screenshot of the spreadsheet for pipe sizing and the tab for manipulation. The cell "lateral flow rates" are highlighted on the images: **a** – 1000 L h^{-1}; **b** – 1150 L h^{-1}; and **c** – 1088 L h^{-1}.



4.3 Validation of the procedure in the field

After sizing pipe and delivery hoses, the designs were field-tested in an area belonging to Embrapa Cassava & Tropical Fruits, located in Cruz das Almas, Bahia state (12° 48`S, 39° 06" W, 225 m) to assess the flow rate of delivery hoses and uniformity of flow. Flow rates were measured by the direct volumetric method performed three times using a 500-ml graduated container and a chronometer. Flow rates were measured at eight points distributed uniformly along the lateral.

The uniformity of water application was computed using Christiansen's uniformity coefficients (UC), as they provide reliable results (BERNARDO *et al.*, 2019), and using distribution uniformity (DU) expressed as the ratio of the low quarter depth of application to the overall average depth of application, which allows a more restrictive measurement as plants receiving less water weigh more in irrigation uniformity calculations (LÓPEZ *et al.*, 1992). Interpretations of UC and DU were based on the classification presented by Mantovani (2001) (Table 2).

Table 2. Classification of UC and DU uniformity coefficients.

Classification	UC	DU
Excellent	> 90%	> 84%
Good	80% - 90%	68% e 84%
Moderate	70% e 80%	52% e 68%
Poor	60% e 70%	36% e 52%
Inacceptable	< 60%	< 36%

Source: Mantovani (2001).

5 RESULTS AND DISCUSSION

The characteristics of the systems and the results of the field tests are shown in Figure 6. None of the designs had application uniformity calculated with either method below 80%. The DU coefficients of 21 out of 22 designs were classified as excellent. Design number 13 was classified as good (DU of 82.4%). By using UC as an indicator, 19 system designs were classified as excellent. Design numbers 10, 13, and 20 had 88.4%, 86.9%, and 89.4%, respectively (good). Design numbers 6, 12, and 15 had the best performances with DUs of 98.3%, 97.7%, and 97.7% and UCs of 98.8%, 98.7%, and 98.6%, respectively. The spreadsheet was able to design systems with different spacings and lateral lengths. The standard deviation and coefficient of variation show the low variability of the results (Table 3). The satisfying results demonstrate the technical feasibility of low-head continuous-flow localized irrigation systems using microtubes as delivery hoses of 4 mm in diameter at ground level.

Figure 6. Uniformities of field-tested systems: coefficients of distribution uniformity (DU) and Christiansen's uniformity coefficient (UC) for classification by Mantovani (2001).

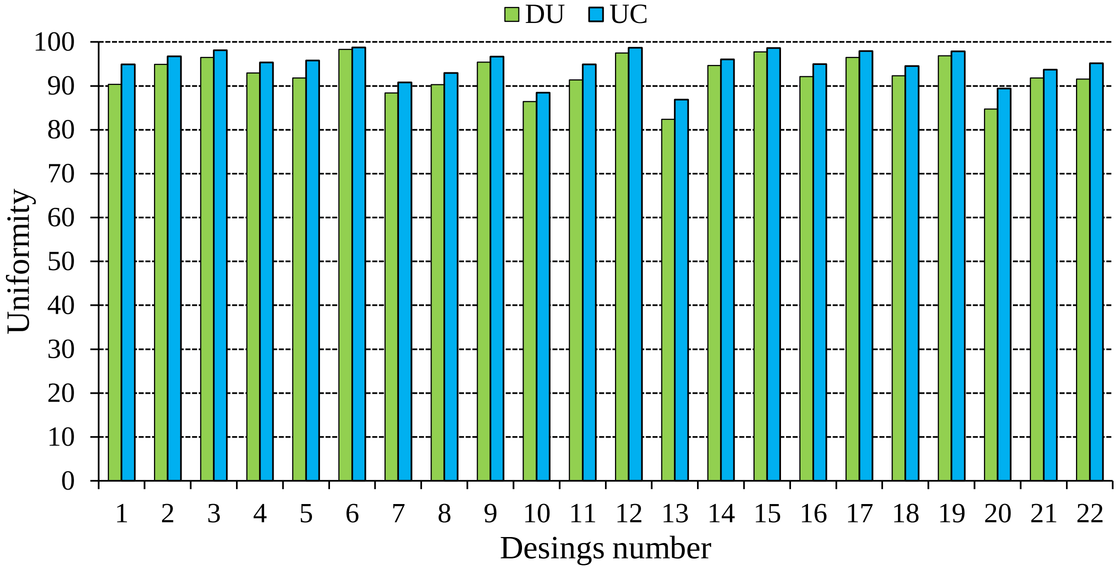


Table 3. Mean, standard deviation and coefficient of variation of results of UC and DU referring to field tests to validate systems.

Parameter	**DU**	**UC**
Mean	92.5%	94.9%
SD	4.3	3.4
CV	4.6%	3.6%

High application uniformities have been reported in bubble systems, but in the 80 to 97% range (RAWLINS, 1977; SILVA, 2013; MEDEIROS *et al.*, 2014; CARMO *et al.*, 2016; XAVIER, 2016; SOOTHAR, 2016), the range in which the results found herein are. The results show that the proposed procedure maintains one of the main advantages of bubble systems: good uniformity of water application.

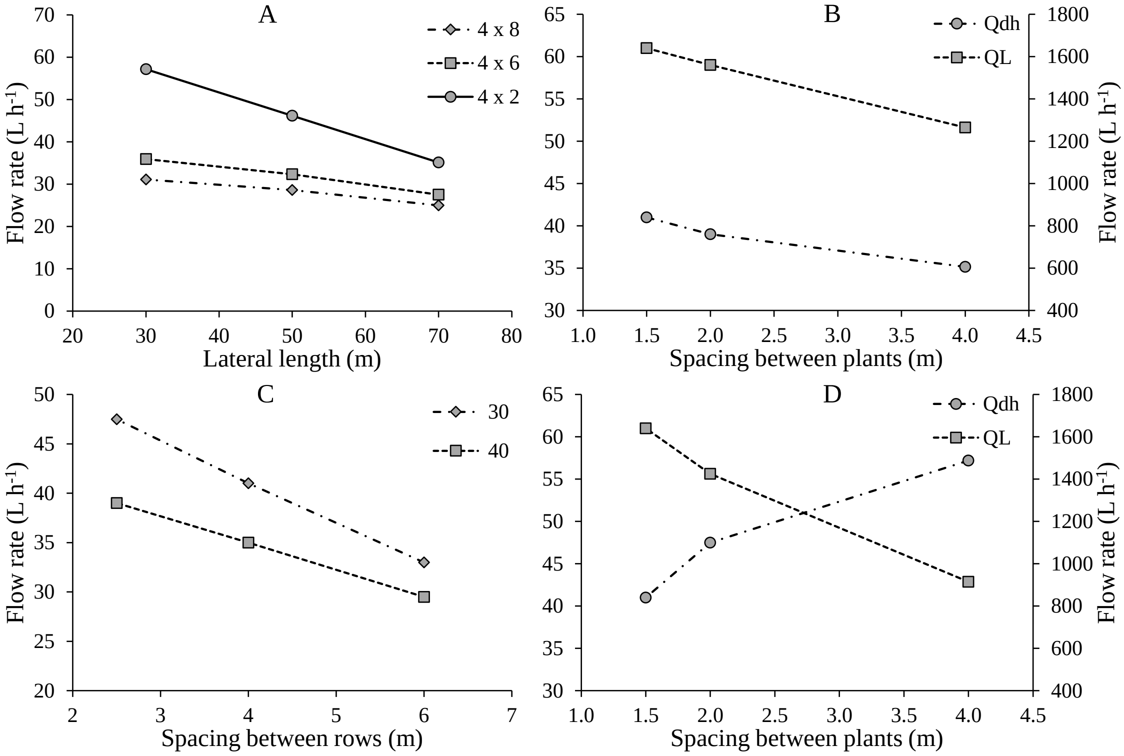
Localized irrigation systems typically have DUs varying from 65% to 90% for drip irrigation and up to 85% for micro sprinkler irrigation. Nonetheless, systems exhibiting uniformities below 50% are commonly found in the field on account of inadequate sizing, low-quality equipment, lack of maintenance, and, mainly, clogging (MAROUELLI *et al.*, 2011). Low uniformities of water application, approximately 50%, are also reported in bubbler systems as a result of poor sizing (AL-AMOUD, 2008) and operation without following the established design (COELHO *et al.*, 2012). By increasing the run time, a decrease in uniformity in a bubble system was reported by Carmo *et al.* (2016), but the performance was still acceptable. Causes for that could be: lacking or insufficient system maintenance; animals chewing and insects entering the delivery hoses; and incorrect resetting of falling delivery hoses.

The results of the present work corroborate Souza, Andrade and Silva (2005), who, when working with a bubbler irrigation system, found 96.64% and 95.85% for CUC and UD, respectively, demonstrating that the performance of the system can be classified within an excellent degree of acceptability.

In the proposed procedure, with some variation in coefficients, water distribution performance does not depend on spacing between plants, spacing between rows, or flow rates of laterals and delivery hoses. Systems with numerous, longer delivery hoses per lateral had lower uniformity, although one cannot affirm that the performance of the system decreased as a function of these characteristics. What occurs in the field is that systems with numerous, longer delivery hoses per lateral are more susceptible to manufacturing defective fittings and pipers, to water leaks at fittings, and to small undulations on the area, which have a strong influence on the system due to its low-head operation.

Flow rates within laterals and delivery hoses varied with the system design. Across designs, when the diameter of laterals and delivery hoses, head pressure at the lateral inlet, and field layout are kept the same, defining the spacing and sizing of laterals directly influence the flow rate of laterals and delivery hoses. For example, maintaining spacings between plants and rows when increasing the length of laterals results in lower flow rate per delivery hose (Figure 7A); however, if the number of delivery hoses is increased in the lateral, an increase in the total flow rate is needed.

Figure 7. Flow rate of delivery hoses as a function of the lateral length in designs with spacing of 4 x 8 (systems 1 to 3), 4 x 6 (systems 4 to 6) and 4 x 2 (systems 7 to 9) (A), Flow rate of delivery hoses - Qdh and laterals - QL of designs 22, 21 and 9 as a function of spacing between plants (B), as a function of spacing between rows in system designs with 30 delivery hoses in the lateral (designs 17, 19 and 21) and 40 delivery hoses in the lateral (designs 16, 18 and 20) (C) and Flow rates of delivery hoses and laterals of designs 22, 20 and 7 as a function of spacing between plants (D).



The increase in planting density, i.e., a higher number of plants per unit area, is achieved by decreasing the spacing between rows, between plants, or both. When increasing the planting density by decreasing the spacing between plants (Figure 7C), the flow rate per delivery hose increases while the spacing between plants, lateral length, and number of delivery hoses are maintained.

The increase in planting density by decreasing spacing between plants occurred in two cases. In designs 9, 21 and 22, the spacing between plants was reduced from 4 m to 2 and to 1.5 m, and the number of delivery hoses per lateral was increased from 16 to 30 and to 40, respectively, maintaining the length of 30 m for laterals. In this case, the increase in planting density requires a reduction in flow rate per delivery hose and an increase in flow rate in the lateral (Figure 7B). In the second case, for designs 7, 20 and 22, the spacing between plants is reduced from 4 m to 2 and to 1.5 m, and the lateral spacing is reduced from 70 m to 39 and to 29.3 m, respectively. Increases in planting density require increases in flow rate in both delivery hoses and laterals (Figure 7D).

6 CONCLUSIONS

Bubbler irrigation systems using delivery hoses at ground level are technically feasible.

The proposed design procedure for a continuous-flow localized irrigation system with 4-mm delivery hoses (microtubes), head pressure within laterals of 9.8 kPa (1 m.wc), and high uniformity of water application can be used when designing systems with different lateral lengths and different spacings between both plants and plant rows.

The electronic spreadsheet allows sizing lengths of microtubes with Reynolds numbers greater than 2,000.

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