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Influence of recession on the infiltration in open furrows on slopes, under constant flow

Influência da recessão na infiltração em sulcos aberto em declive, sob fluxo constante

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Abstract: During surface irrigation, some phases related to its hydraulics are produced. The monitoring of these phases allows determining dvance and recession curves. The recession phase occurs after the application of water to furrows. Hydraulically, it is the most complex phase and therefore difficult to predict in mathematical treatments. To obtain the recession phase, it is necessary to determine the time at which water advances over the soil surface to specific points, called stations, over the area and then record the time at which it disappears. Observing the passage of the recessive front through the measuring stations along the furrows as a function of time defines the recession curve. Using field data obtained by Ramsey (1976) and by the Department of Agriculture and Chemical Engineering, University of Colorado (1980), in three different farms: Horticulture, Stieben e Benson. This work aimed to study the effect of the recession time on the infiltrated profile in surface irrigation.

Key words: Furrow irrigation, shape factors, performance, Brazil

Resumo: Durante a execução da irrigação por superfície se produz uma série de fases, de forma simultânea ou sucessiva, relacionadas com sua hidráulica. O acompanhamento das diversas fases da irrigação superficial permite a determinação das curvas de avanço e de recessão. A fase de recessão ocorre após o encerramento da aplicação de água aos sulcos. Hidraulicamente, é a fase mais complexa e, portanto, difícil de ser prevista nos tratamentos matemáticos. Para obtê-las é necessário ir ao campo e determinar o tempo em que a água avança sobre a superfície do solo até pontos específicos, chamados estações, ao longo da área e em seguida anotar o tempo em que a mesma desaparece. A observação da passagem da frente recessiva através das estações de medição ao longo dos sulcos e em função do tempo define a curva de recessão. Utilizando dados de campo obtidos por Ramsey (1976) e pelo Departamento de Agricultura e Engenharia Química da Universidade do Estado do Colorado (1980) em três diferentes localidades (HORTICULTURE, STIEBEN e BENSON) estudou-se, neste trabalho, o efeito do tempo de recessão sobre o perfil infiltrado na irrigação por sulco aberto em declive.

Palavras-chave: irrigação por sulcos, fatores de forma, performance

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INTRODUCTION

The surface water flow can be characterized as non-permanent and spatially varied, showing gradual decrease due to water infiltration. According to Pordeus et al. (2001), furrows have different sizes in transversal and longitudinal sections, depending on soil texture and explored crop; therefore, requiring greater attention in their sizing. Due to the complexity of the mathematical formulation to represent non-permanent flows in the free surface, the solutions of equations involved require numerical treatment through computational models. With this approach, hydrodynamic and zero-inertia models stand out. According to Clemmens & Strelkoff (2011), the kinematic wave model produces a very short recession time at the upstream limit that can lead to incorrect calculation of the recession time when water continues to decrease on the surface. This problem becomes more severe for low slope values at the base of the furrow.

Several researchers have presented simplified solutions to solve the equations that govern surface flow. The basic assumptions are: the type of function represented by the water surface during the advance phase is the same for all time increments, and the irrigation water depth is the normal water depth at the head of the furrow, which is determined by a resistance equation for uniform flow. These assumptions provide the required means to compute the surface water volume.

Algebraic models have the advantage of involving simplified solutions which, in turn, are as closer to complex models as more representative are the values assigned to shape factors of surface and subsurface flow profiles, to the wetted perimeter and a good representation of the recession. According to Bautista et al. (2012), computations present special challenges when the equations are applied to surface irrigation due to the limits that move during advance and recession phases. According to Levien (1998), design and management of surface irrigation systems can be significantly improved by mathematical simulation of the hydraulic behavior of each irrigation operation without requiring large field experiments which are expensive and time consuming.

$$X_a = \frac{Q \cdot t}{A_o \cdot r_{yM} + A_{zo} \cdot r_{zM}} \tag{1}$$

where Xa - distance of water advance for a time interval t; r_{yM} and r_{zM} - surface and subsurface shape factors considering a weighted average of calibrated shape factors given by the following equation.

$$r_{yM} = r_{zM} = \bar{r}_i = \frac{\sum_{i=1}^{n} t_{ai} \cdot r_i}{\sum_{i=1}^{n} t_{ai}} \tag{2}$$

where r_i - shape factor that adjusts the model at each point i of the experimental advance curve; t_{ai} - advance time at each point i of the observed advance curve; A_o and A_{zo} - cross section of inlet and outlet flow, given by the following equations:

$$A_o = \frac{P_m \cdot Y_n}{M+1} \tag{3}$$

The horizontal recession phase begins when the depth of the surface water reduces to zero at the head of the furrow, which continues until no water remains on the field surface and irrigation is concluded (AMER & AMER, 2010). The recession phase is dependent on the water volume stored on the soil surface and on the advance rate of water on the plot. In the case of furrows of reduced flow section and depending on the magnitude of the surface slope gradient and infiltration rate, this phase can manifest quickly, and thus, its contribution to the infiltrated volume will be negligible.

Specifically, the aim of this work was to study the effect of the recession time on the infiltrated profile in surface irrigation systems of opened furrows in slopes, under a constant flow regime.

MATERIALS AND METHODS

The methodology used in this study aims to analyze the influence of the recession time on the infiltration profile distribution, as described below:

The advance calculation uses the volumetric balance equation for furrows presented by Souza (1981) and Pordeus et al. (2001). In the advance, a weighted average of calibrated shape factors is considered for shape factors of surface and subsurface profiles.

$$A_{z0} = P_m(y) \cdot Z(\tau) \tag{4}$$

where $Z(\tau)$ is the water infiltration as a function of t, given by equation of Kostiakov:

$$Z(\tau) = K \cdot \tau^a \tag{5}$$

where k and *a* are empirical constants for a given soil and a certain level of moisture and τ is the infiltration opportunity time;

The normal water depth y_n, that for a furrow is a function of flow rate (Q), i.e., $y_o = y_n (Q_o)$ is given by the following expression based on the Manning equation, proposed by (LEVIEN, 1985).

$$Y_n(Q_o) = \left[\frac{Q_o \cdot n}{C_u \cdot S_o^{1/2}} \cdot \frac{(M+1)^{5/3}}{C} \right]^{\frac{3}{(3M+5)}} \tag{6}$$

where Y_n (Q) - normal depth, m; Q_o - input flow, $m^3 s^{-1}$; n - Manning coefficient, $m^3 s^{-1}$; S_o – slope at the bottom of the furrow, m^{-1}; C_u - coefficient dependent on the system of units used: C_u = 1.0 $m^{1/2} s^{-1}$, in the metric system and C_u = 1.486 $ft^{1/2} s^{-1}$, in the English system.

The recession phase occurs after the application of water on furrows; and hydraulically, it is the most complex phase and therefore the most difficult to predict in mathematical treatments. The observation of the recessive front passage through the measuring stations along the furrows versus time curve defines the recession curve.

Levien & Souza (1987) developed an expression that determines the recession at the head of the furrow, i.e., the beginning of the curve plus another equation based on the first to determine a recessive curve that progressively increases up to the end of the plot.

The influence of the recession time on the surface and subsurface flow volume and on the efficiency parameters of furrow irrigation on free-flow slopes can be observed by comparing its results with those observed in field and obtained through equations presented by the three hypotheses used to calculate recession.

Hypothesis I - Recession curve - The following equation was developed by Levien & Souza (1987) to determine the recession curve. The authors state that the variation of the water depth with the distance is uniform and the average infiltration rate along the furrow is the arithmetic average of infiltration rates corresponding to the beginning and end of the furrow.

$$t = t_r + \frac{S_y}{(M+1)\cdot \bar{I} \cdot G^{3/2}} - \left\{ \left[3\cdot\left(G^{3/2}\cdot L\right)^{1/3} - 3\cdot ATN\left(G^{3/2}\cdot L\right)^{1/3}\right] - \left[3\cdot\left(G^{3/2}\cdot \ell\right)^{1/3} - 3\cdot ATN\left(G^{3/2}\cdot \ell\right)^{1/3}\right] \right\} \quad (7)$$

According to the authors, this expression allows calculating the recession curve in terms of the flooded length of the furrow (ℓ), with all other terms kept constant.

In which t - time during which the water disappears at point X_r; L - furrow length; tr - time of onset of recession; S_y - slope of the water surface; $\bar{I}$ - Average infiltration rate in the furrow; ℓ - flooded portion of the furrow; G – constant by the following equation.

$$\bar{I} = \frac{I(t_r) + I(t_r - t_{av})}{2} \quad (8)$$

$$G = \frac{C_u \cdot S_o^{1/2} \cdot S_y^{5/3}}{(M+1)^{5/3} \cdot n \cdot \bar{I}} \quad (9)$$

Equation (7) is used to calculate the recession curve - Hypothesis I of this work.

Hypothesis II - Recession time longer than the application time - At the head of the furrow, the water depth (y_o) decreases as the volume of surface water decreases to supply infiltration and surface flow. Based on these assumptions, Levien & Souza (1987) provide the means to estimate the time t_r, at which the water depth is reduced to zero at the head of the furrow and starts recession.

Considering the duration between the water cutting time (t_{co}) and the recession time (tr), the authors admit that this would be the time required to remove the ABCDE volume in Figure 1.

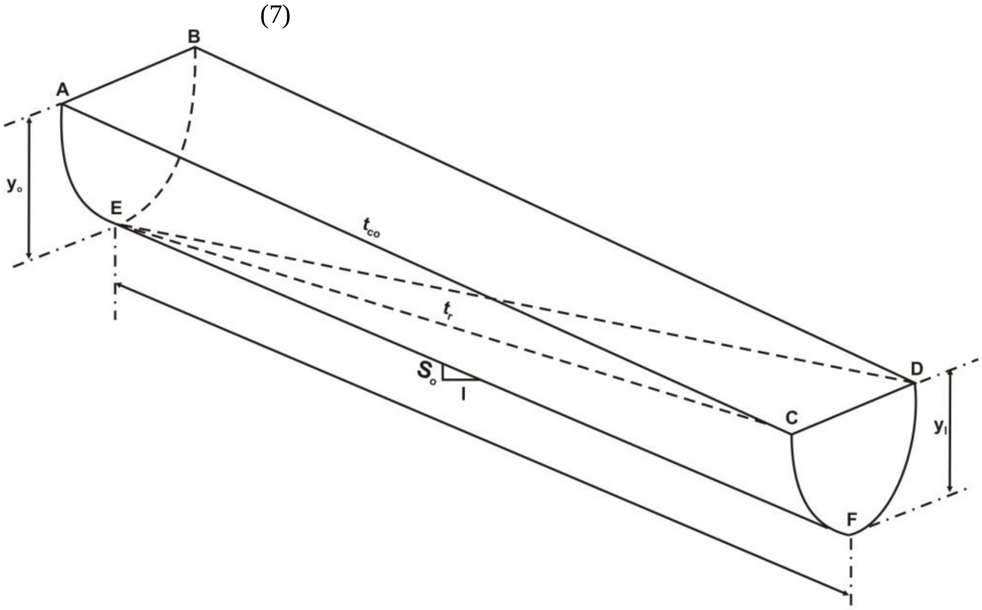

Figura 1. Schematic surface volume: depletion phase (AFTER LEVIEN, 1985)
where:

$$\forall = \frac{A_o \cdot L}{(M+2)} \quad (10)$$

Levien & Souza (1987) also consider that the volume (∀) is equal to the volume to be drained and infiltrated between the cutting time (tco) and time tr as follows:

$$\forall = Q_o(t_r - t_{co}) \quad (11)$$

Substituting (10) into (11), the following expression is obtained, which determines the onset of the recession curve in time *tr*:

$$t_r = t_{co} + \frac{A_o}{(M+2)} \cdot \frac{L}{Q_o} \quad (12)$$

The expression (12) is used to determine the recession curve - Hypothesis II, assuming that t = t_r , i.e., a constant curve and parallel to the abscissa axis.

Hypothesis III - Recession time equal to the application time – It is considered that the recession time (tr) is equal to the water application time (t_{co}), which means that the recession curve is constant and parallel to the abscissa axis.

$$t = t_r = t_{co} \quad (13)$$

The performance of recession curves simulated with three hypotheses are analyzed by determining the average deviations of simulated curves in relation to curves observed in field through expression (14).

$$\tau = \left[\frac{\sum_{i=1}^{n} (\hat{y}_{i-}\hat{y}_i)^2}{n} \right]^{1/2} \quad (14)$$

whare:

$\hat{y}_i$ = Ordinate of i points for recession curves simulated;

$\hat{y}_i$ = Ordinate of i points for recession curves observed in field;

n = Number of coordinate points for recession curves;

τ = Mean deviation of the simulated curves compared to curves observed in field.

To calculate the mean deviation, it is necessary to estimate the ordinates of the field recession curves as a function of the same distance of simulated curves. For this, it was decided to use linear interpolation to estimate the new ordinates of experimental points due to the difficulty of adjusting an algebraic expression that fairly represents the different shapes of recession curves, producing a corrected serie for recession time values (R_C). The same methodology was used to calculate the infiltration (Z_C).

The infiltration profile in furrow irrigation is directly related to the performance of advance and recession curves. The difference between the ordinates of each point of these curves defines the time intervals for infiltration.

In this work, it is considered that the wetted perimeter is equal to the width of the free water surface, which is a function of the normal water depth, and that the infiltrated sideband is equal to the spacing of furrows.

The time at which the water remains in contact with the soil is the time interval between the advance and recession curves. The following expression is used:

$$\tau_i = t_i - t_{ai} \quad (15)$$

where τ_i - Infiltration opportunity time at any point i; t_i - Time at which the water disappears at point i; t_{ai} - Time at which the water advances at point i.

The calculation of water depths infiltrated along the plot considers the two-dimensional case, that is, the water depth infiltrated in the vertical direction and infiltrated in the side band is here assumed as equal to the spacing between furrows. In turn, the areas infiltrated after irrigation are estimated by the following expression:

$$A_{zi} = Z_i \cdot E \quad (16)$$

Substituting equations (16) and (5) into equation (17) and assuming

$$P_m(y) = B(y_m) = Cy^M \quad (17)$$

then:

$$Z_i = \frac{B(y_n)}{E} \cdot k \cdot \tau^a \quad (18)$$

where Z_i - Water depth infiltrated at point i along the plot; E - Spacing between furrows; τ - Infiltration time for each recession case studied.

The geometric site of infiltrated water depths (Zi) along the plot represents the spatial distribution profile of the water in furrow irrigation.

In this study, the methodology that determines the distribution profile is used for simulated curves and those observed in field.

To analyze the performance of simulated infiltrated profiles in relation to the profiles computed using field data, the expression (14) is used analogously to the procedure above for recession curves.

The effect of recession on the distribution profile is analyzed based on the results of the average deviations, calculated for the recession curves for infiltrated profiles and based on observation of the graphs of these curves presented in Results and Discussion.

Furrow irrigation systems are designed and evaluated through prior knowledge of the water depth value or actual water volume required to refill the root zone.

To analyze the effect of recession on the infiltration of irrigation systems by furrows on slopes under constant flow, graphs and tables of results obtained with field data are presented, which were obtained in experiments carried out by Ramsey (1976) and by the Department of Agriculture and Chemical Engineering, University of Colorado (1980) at three different locations (HORTICULTURE, STIEBEN and BENSON, 1980). These data are used due to the accuracy with which they were obtained and represent extreme conditions in relation to various parameters. Table 1 shows data corresponding to flow (Q_o), slope (So), time of water application (t_{co}), furrow length (L), spacing between furrows (E), Manning hydraulic roughness (n), infiltration parameters (k and a) and the empirical constants of the furrow geometry equation (C and M) in the studied examples. Table 2 shows field data regarding the recession and advance time depending on the furrow length.

Table 1. Field data used in the furrow irrigation analysis

Input parameters	Examples (data)			
	# 1 Ramsey	# 2 Horticulture	# 3 Stieben	# 4 Benson
$Q_o(m^3\,s^{-1})$	0.00133	0.00081	0.000576	0.00161
$S_o(m\,m^{-1})$	0.001032	0.0036	0.0098	0.0045
$t_{co}(s)$	12,480	12,120	41,760	41,880
L(m)	100	175	350	625
E(m)	1.00	1.12	0.60	1.00
n $(m^3\,s^{-1})$	0.022	0.020	0.15	0.25
$k(m\,s^{-a})$	0.0012415	0.0008079	0.0000020192	0.00064369
a	0.50	0.55	0.8767	0.44
$C(m^{1-M})$	1.0915	0.61	1.9087	1.307
M	0.4539	0.22	0.5445	0.4498

RESULTS AND DISCUSSION

In the study of the influence of recession on the distribution profile of water in soil, three hypotheses are used, here treated as follows: R_1, recession is a curve according to equation 7, shown by Levien (1985), R_2 is recession at the head of the furrow given by equation 12, shown by Levien (1985), i.e., an instant curve in the recession time (t_r) and parallel to the abscissa axis; R_3 is the instant recession in the time of water application, where $t_r = t_{co}$, i.e., a curve parallel to the abscissa axis. According to Silva (2010), the recession curve of the surface flow is assumed to be horizontal, considering that it produces no significant effect on furrow irrigation parameters.

Tables 3, 4, 5 and 6 present the results of the recession times simulated by the model of Levien (1985) with the three assumptions R_1, R_2 and R_3. These results are used in the performance of irrigation systems of furrows opened in slopes, under a constant flow regime.

To evaluate the performance of simulated recession curves compared to those measured in field, Tables 3, 4, 5 and 6 show the results of recession times estimated based on the three assumptions R_1, R_2, R_3 and Table 2 shows the recession curves observed in field with the specified examples.

As shown in Table 3, when the recession time (Rc) at the head of the furrow is compared with the values obtained for the recession hypotheses R_1, R_2 and R_3, it is observed that R_1 and R_2 are underestimated only by 1.13 % while R_3 was underestimated by 3.25%. Considering the recession time at the end of the furrow, it was observed that R_1 was underestimated in less than 1%, whereas R_2 and R_3 were estimated by 9.2 and 11%, respectively. Individually analyzing the recession time measured in field and the hypotheses considered, it was found that for R_C, the recession value varied by 8.1% compared with the recession time measured at the beginning and end of the furrow, and similar value was found for hypothesis I (R_1), while the other hypotheses did not vary since they are considered constant. According to Schwank & Wallander (1988), for most irrigation conditions of furrows opened in slopes, the recession time is negligible compared to the advance and storage times, considering that the recession phase has negligible effect on the irrigation programming.

Table 3. Recession simulated by the algebraic model of Levien with adjusted data (R_C) of Ramsey

Distance (m)	Recession time (min)			
	(R_C)	(R_1)	(R_2)	(R_3)
0.00	215.00	212.56	212.56	208.00
9.61	225.28	213.55	212.56	208.00
17.56	229.66	214.42	212.56	208.00
24.70	230.00	215.24	212.56	208.00
31.30	230.00	216.04	212.56	208.00
37.48	230.12	216.84	212.56	208.00
43.34	230.76	217.63	212.56	208.00
48.92	231.38	218.44	212.56	208.00
54.26	231.97	219.25	212.56	208.00
59.41	232.53	220.09	212.56	208.00
64.37	233.08	220.96	212.56	208.00
69.18	233.61	221.86	212.56	208.00
73.85	233.88	222.81	212.56	208.00
78.38	233.38	223.83	212.56	208.00
82.80	233.00	224.92	212.56	208.00
87.11	233.00	226.13	212.56	208.00
91.32	233.04	227.51	212.56	208.00
95.44	233.50	229.17	212.56	208.00
99.47	233.94	231.47	212.56	208.00
103.43	234.00	231.91	212.56	208.00

Table 4 shows that comparing the recession time (R_C) adjusted at the head of the furrow with values obtained for the recession hypotheses considered R_1, R_2 and R_3, it was observed that R_1 and R_2 are overestimated by approximately 3.3%, while for R_3, no change was found in relation to the field data. When considering the recession time measured at the end of the furrow, R_1 was overestimated by 1.56% as R_2 and R_3 were underestimated by 5.94 and 9%, respectively. Individually assessing the recession time measured in the field and the hypotheses considered, it was found that for R_C, the recession value varied by 9% compared with the recession time measured at the beginning and end of the furrow; for R_1, this variation was 7.4% while the other hypotheses remained unchanged, since they were considered constant.

Table 4. Recession simulated by the algebraic model of Levien with adjusted data (Rc) of Horticulture

Distance (m)	Recession time (min)			
	(R_C)	(R_1)	(R_2)	(R_3)
0.00	202.00	208.81	208.81	202.00
23.93	208.70	210.35	208.81	202.00
39.40	210.90	211.41	208.81	202.00
51.87	212.50	212.30	208.81	202.00
62.59	213.66	213.10	208.81	202.00
72.13	214.69	213.84	208.81	202.00
80.79	215.35	214.54	208.81	202.00
88.78	215.83	215.21	208.81	202.00
96.21	216.27	215.86	208.81	202.00
103.20	216.82	216.49	208.81	202.00
109.82	217.48	217.11	208.81	202.00
116.07	218.11	217.71	208.81	202.00
122.06	218.71	218.32	208.81	202.00
127.79	219.22	218.92	208.81	202.00
133.30	219.66	219.52	208.81	202.00
138.60	220.09	220.13	208.81	202.00
143.73	220.50	220.74	208.81	202.00
148.69	220.90	221.36	208.81	202.00
153.49	221.14	222.00	208.81	202.00
158.16	221.33	222.65	208.81	202.00
162.70	221.50	223.33	208.81	202.00
167.12	221.68	224.04	208.81	202.00
171.42	221.86	224.79	208.81	202.00
175.63	222.00	225.51	208.81	202.00

According to Table 5, when the recession time (R_C) adjusted at the head of the furrow is compared with values obtained for R_1, R_2 and R_3, it is observed that R_1 and R_2 were overestimated by 4.89%, while the value found for R_3 was underestimated by only 0.3%. Based on the recession time, it appears that at the end of the furrow, R_1 was overestimated by 19.5%, whereas R_2 was overestimated by 0.4% and R_3 was underestimated by 4.8%. Individually analyzing all recession times, it was found that, for both values adjusted in the field as for the hypotheses considered, the recession value varied by 4.5% for R_C when compared to the recession time measured at the beginning and end of the furrow, while for R_1, the variation found was 19.15%. In relation to the other hypotheses, R_2 and R_3 showed no variation, since they are considered constant.

Table 5. Recession simulated by the algebraic model of Levien with adjusted data (R_C) of Stieben

Distance	Recession time (min)			
(m)	(R_C)	(R_1)	(R_2)	(R_3)
0.00	698.00	733.91	733.91	696.00
22.10	702.42	739.56	733.91	696.00
43.82	704.50	745.34	733.91	696.00
65.18	706.82	751.27	733.91	696.00
86.23	709.80	757.38	733.91	696.00
106.97	713.11	763.69	733.91	696.00
127.43	716.20	770.24	733.91	696.00
147.61	717.81	777.05	733.91	696.00
167.53	719.75	784.17	733.91	696.00
187.19	721.47	791.66	733.91	696.00
206.61	722.76	799.59	733.91	696.00
225.79	723.53	808.03	733.91	696.00
244.74	724.29	817.12	733.91	696.00
263.47	725.04	827.03	733.91	696.00
281.98	725.92	838.02	733.91	696.00
300.27	727.02	850.53	733.91	696.00
318.36	728.47	865.36	733.91	696.00
336.25	730.00	884.49	733.91	696.00
353.95	731.00	907.74	733.91	696.00

As shown in Table 6, when the recession time at the head of furrow (R_C) is compared with values obtained for the hypotheses considered R_1, R_2 and R_3, it is observed that R_1 and R_2 have also been overestimated by 12.22%; therefore, it is noteworthy that the value found for R_3 was underestimated by only 0.09%. Considering the recession time measured at the end of the furrow, the value found for R_1 was overestimated by approximately 36% and this difference is probably due to the high furrow length. In contrast, for R_2 and R_3, the differences were not high when compared to R_1 but R_2 was overestimated by 5.4% and R3 by 6.5%. Individually analyzing all recession times, Rc showed variation of only 6.4% when compared to the recession time measured at the beginning and end of the furrow; for hypothesis R_2 and R_3, the recession value along the furrow was assumed to be constant, while R_1 showed high variation, 31.26%, being possibly related to the high furrow length. The Recession Time (Tr) is the most affected by the flow rate, furrow length, form and slope (NEBRASKA AMENDMENT, 1983). Rota (2003) evaluated furrow irrigation in soils with impediment layer and observed that in soils where the infiltration rate is low and the water volume stored in the furrow at the cutting moment is fairly large due to the small slope of the furrow, the depletion and recession phases become very significant.

Table 6. Recession simulated by the algebraic model of Levien with adjusted data (R_C) of Benson

Distance (m)	Recession time (min)			
	(R_C)	(R_1)	(R_2)	(R_3)
0.00	698.60	789.05	789.05	698.00
27.72	703.26	797.83	789.05	698.00
53.20	707.38	806.12	789.05	698.00
77.47	710.30	814.21	789.05	698.00
100.87	713.08	822.21	789.05	698.00
123.56	715.26	830.17	789.05	698.00
145.67	717.38	838.13	789.05	698.00
167.27	719.42	846.10	789.05	698.00
188.43	721.41	854.13	789.05	698.00
209.19	723.05	862.22	789.05	698.00
229.60	724.28	870.39	789.05	698.00
249.67	725.48	878.67	789.05	698.00
269.45	726.67	887.07	789.05	698.00
288.94	727.84	895.60	789.05	698.00
308.17	729.07	904.30	789.05	698.00
327.16	730.40	913.16	789.05	698.00
345.92	731.71	922.23	789.05	698.00
364.46	732.72	931.52	789.05	698.00
382.80	733.64	941.06	789.05	698.00
400.94	734.55	950.88	789.05	698.00
418.90	735.44	961.02	789.05	698.00
436.68	736.33	971.52	789.05	698.00
454.30	737.25	982.43	789.05	698.00
471.75	738.26	993.80	789.05	698.00
489.05	739.26	1.005.7	789.05	698.00
506.20	740.07	1.018.2	789.05	698.00
523.20	740.55	1.031.6	789.05	698.00
540.07	741.02	1.045.8	789.05	698.00
556.81	741.73	1.061.2	789.05	698.00
573.41	742.80	1.078.2	789.05	698.00
589.90	743.85	1.097.2	789.05	698.00
606.26	745.02	1.119.4	789.05	698.00
622.51	746.40	1.147.9	789.05	698.00

To facilitate the evaluation in the performance of recession curves R_1, R_2 and R_3 in relation to the field results, the recession times are estimated with field data corresponding to the same advance distance simulated with form factors r_{yM} and r_{zM} through linear interpolation considering two pairs of points of the experimental curve, located at the neighborhood of each value to be estimated. This methodology is used due to the existence of indefinite trajectories in recession curves observed as simulated and due to the difficulty of adjusting specific models to these curves; however, this decision allows estimating points in the ordinate in the experimental recession curves that are coincident with simulated curves and enables the adoption of a more consistent comparative criterion in the performance of curves simulated by the model.

a

Tables 3, 4, 5 and 6 also show the results of experimental recession time estimated by linear interpolation with the specified examples. These tables allow plotting the graphs of Figure 2.

b

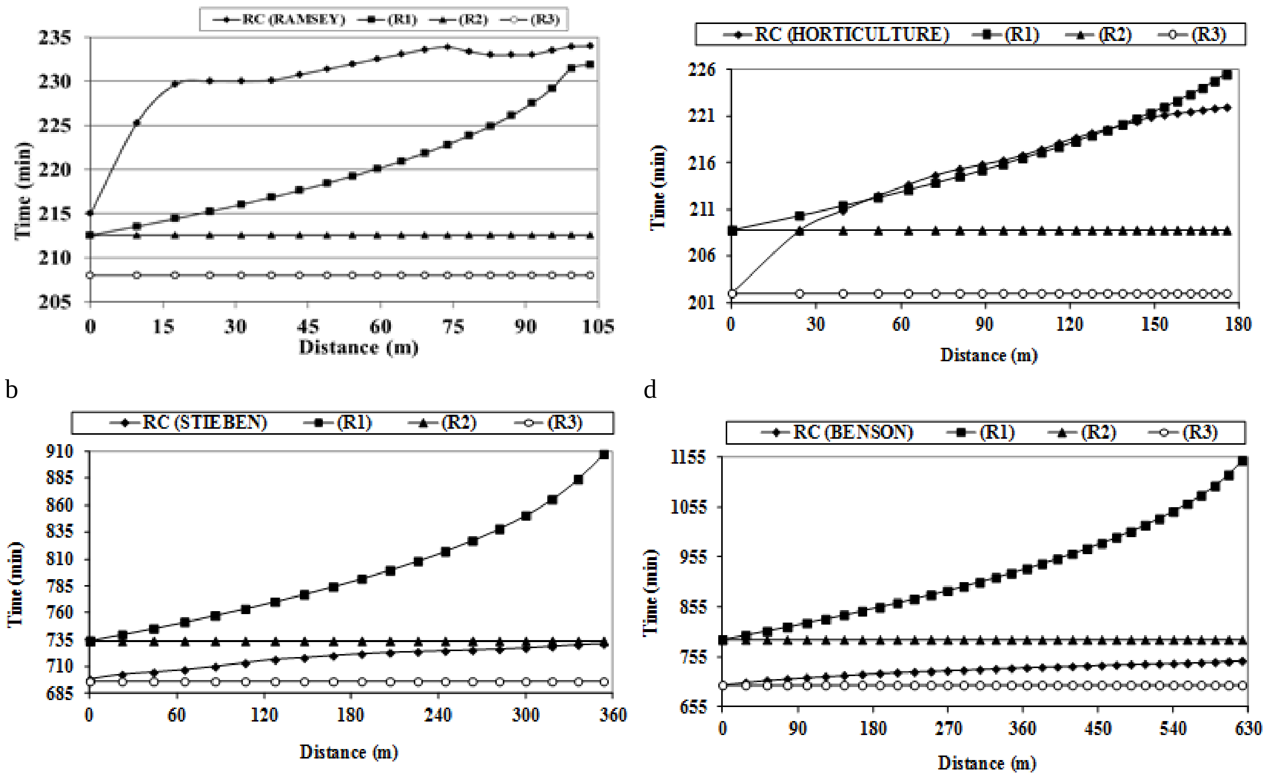

Figura 2. Recession curves R_1, R_2 and R_3 simulated by the algebraic model of Levien compared with field data.

The simulated infiltrated water depths are called Z_1, Z_2 and Z_3 and correspond to the simulated recession curves R_1, R_2 and R_3. Tables 7, 8, 9 and 10 show the results of the infiltrated water depths simulated by the model of Levien (1985) and water depths adjusted with field data, determined by expression 19 by assuming that the advance phase is represented by curves simulated with form factors r_{yM} and r_{zM}.

According to Table 7 and evaluating variable infiltrated water depth by comparing the infiltrated water depth at the head of the furrow (Zc) adjusted with values obtained for simulated infiltrated water depths Z_1, Z_2 and Z_3, it is observed that, virtually, they did not vary significant in relation to Z_C. When the infiltrated water depth measured at the end of the furrow was considered, the water depths showed behavior similar to that of the beginning of the furrow. This behavior is due to the small variation in the water infiltration opportunity time, either at the beginning or end of the furrow. Figure 2a shows that the simulation model for the infiltrated water depth of hypothesis I had higher efficiency with less variation in the value of the infiltrated water depth measured in field, while all models have shown small variation both at the beginning and end of the furrow.

Table 7. Infiltrated water depths simulated by the algebraic model of Levien corresponding to the effect of the three recession cases, with adjusted data (Z_C) of Ramsey

Distance (m)	Infiltrated water depth (mm)			
	(Z_C)	(Z_1)	(Z_2)	(Z_3)
0.00	38.62	38.40	38.40	37.90
9.61	39.44	38.40	38.30	37.80
17.56	39.74	38.30	38.20	37.80
24.70	39.68	38.30	38.10	37.70
31.30	39.59	38.30	38.00	37.60
37.48	39.52	38.30	37.90	37.50
43.34	39.49	38.30	37.80	37.40
48.92	39.45	38.30	37.70	37.30
54.26	39.42	38.20	37.60	37.20
59.41	39.38	38.20	37.50	37.10
64.37	39.34	38.20	37.40	37.00
69.18	39.30	38.20	37.30	36.90
73.85	39.23	38.20	37.30	36.80
78.38	39.10	38.20	37.20	36.70
82.80	38.98	38.20	37.10	36.60
87.11	38.89	38.20	37.00	36.50
91.32	38.80	38.30	36.90	36.50
95.44	38.75	38.30	36.80	36.40
99.47	38.70	38.40	36.70	36.30
103.43	38.62	38.40	36.60	36.20

Table 8 shows that when analyzing the water depth infiltrated at the head of the furrow (Z_C) adjusted with values obtained for simulated infiltrated water depths Z_1, Z_2 and Z_3, Z_1 and Z_2 were also overestimated by 1.8%, while the value found for Z_3 did not vary in relation to value measured in field. Considering the infiltrated water depth measured at the end of the furrow, the value found for Z_1 was overestimate by 1.23%, whereas Z_2 and Z_3 have been underestimated by 4.8 and 7.3%, respectively. Individually analyzing simulated infiltrated water depths and field measurement (Z_C) along the furrow, it was verified that Z_C, Z_1, Z_2 and Z_3 showed variation between the infiltrated water depth at the beginning and end of the furrow of 14.14, 14.67, 19.76 and 20.43%, respectively, and the variation of Z_1 approaches that obtained in field, while in Z_2 and Z_3, this variation was greater because Z_2 and Z_3 were estimated considering the recession as a constant straight line. Figure 2b shows that the simulation model with the highest efficiency in simulating the infiltrated water depth at the beginning of the furrow was hypothesis III, while for the simulation referring to the end of the furrow, hypothesis I stood out.

Table 8. Infiltrated water depths simulated by the algebraic model of Levien, corresponding to the effect of the three cases of recession, with adjusted data (Z_C) of Horticulture

Distance (m)	Infiltrated water depth (mm)			
	(Z_C)	(Z_1)	(Z_2)	(Z_3)
0.00	32.80	33.40	33.40	32.80
23.93	33.12	33.30	33.10	32.50
39.40	33.05	33.10	32.90	32.30
51.87	32.93	32.90	32.60	32.00
62.59	32.77	32.70	32.30	31.70
72.13	32.59	32.50	32.10	31.40
80.79	32.38	32.30	31.80	31.20
88.78	32.15	32.10	31.50	30.90
96.21	31.92	31.90	31.20	30.60
103.20	31.69	31.70	31.00	30.30
109.80	31.48	31.40	30.70	30.00
116.07	31.26	31.20	30.40	29.70
122.06	31.04	31.00	30.10	29.40
127.79	30.80	30.80	29.80	29.10
133.30	30.56	30.50	29.50	28.90
138.60	30.32	30.30	29.20	28.60
143.73	30.07	30.10	28.90	28.30
148.69	29.82	29.90	28.60	27.90
153.49	29.55	29.60	28.30	27.60
158.16	29.28	29.40	28.00	27.30
162.70	29.00	29.20	27.70	27.00
167.12	28.72	29.00	27.40	26.70
171.42	28.44	28.70	27.10	26.40
175.63	28.15	28.50	26.80	26.10

According to Table 9 and evaluating variable infiltrated water depth at the head of the furrow, adjusted (Z_C) with values obtained for simulated infiltrated water depths Z_1, Z_2 and Z_3, it was observed that Z_1 and Z_2 have also been overestimated by 4.34%, while Z_3 was underestimated by only 0.08% and can be considered equal to Z_C; however, considering the infiltrated water depth measured at the end of the furrow, the value found for Z_1 was overestimated by 19.47% in relation to Z_C, and this disparity may be checked by the increasing curve shown in Figure 2c; on the other hand, Z_2 resembled Z_C, while Z_3 was underestimated by 4.8% in relation to the value measured in field (Z_C). Analyzing each infiltrated water depth, both adjusted in field (Z_C) as simulated, it was found, regarding infiltration variations along the furrow length, that Z_C varied 7.14% between the beginning and end of the furrow, while Z_1 varied 9.33%; for Z_2 and Z_3, such variation was 11.03 and 11.54%, respectively. According to Figure 2c, the simulation model of the infiltrated water depth of hypothesis III resembled field data from the beginning of the furrow up to the first half of its length, while in the remaining of the furrow length, the closest to field data was simulation of hypothesis II.

Table 9. Infiltrated water depths simulated by the algebraic model of Levien corresponding to the effect of the three cases of recession, with adjusted data (Z_C) of Stieben

Distance (m)	Infiltrated water depth (mm)			
	(Z_C)	(Z_1)	(Z_2)	(Z_3)
0.00	13.01	13.60	13.60	13.00
22.10	13.00	13.60	13.50	12.90
43.82	12.96	13.60	13.50	12.80
65.18	12.91	13.70	13.40	12.80
86.23	12.88	13.70	13.30	12.70
106.97	12.85	13.70	13.20	12.60
127.43	12.82	13.70	13.10	12.50
147.61	12.77	13.70	13.00	12.40
167.53	12.71	13.80	13.00	12.30
187.19	12.66	13.80	12.90	12.30
206.61	12.60	13.90	12.80	12.20
225.79	12.53	13.90	12.70	12.10
244.74	12.46	14.00	12.60	12.00
263.47	12.39	14.10	12.60	11.90
281.98	12.32	14.20	12.50	11.80
300.27	12.26	14.30	12.40	11.80
318.36	12.20	14.40	12.30	11.70
336.25	12.14	14.70	12.20	11.60
353.95	12.08	15.00	12.10	11.50

The data shown in Table 10 refer to the variable infiltrated water depth simulated to Benson farm measured for furrows with 650 m in length. Comparing the water depth infiltrated in the head of the furrow adjusted (Z_C) with values obtained for the simulated infiltrated water depths Z_1, Z_2 and Z_3 obtained for the three recession time hypotheses, it was observed that Z_1 and Z_2 have also been overestimated by 5.21%; in turn, Z_3 was underestimated by 0.24% compared Z_C, whereas when considering the infiltrated water depth measured at the end of the furrow, Z_1 was overestimated by 23.07% as compared to Z_C, while Z_2 was overestimated by 3.88% and Z_3 was underestimated by 4.63%. When we analyzed the variation between water depths infiltrated at the beginning and end of the furrow, the following was observed: Z_C varied 14.42% while Z_1 varied 5.44%, and Z_2 and Z_3 varied 16.04 and 18.18%, respectively. Figure 2d shows that, for the beginning of the furrow, hypothesis III showed values similar to those observed in field, while at the end of the furrow, the hypothesis that most resembled field data was hypothesis II; however, hypothesis III also showed small variation throughout the furrow length, being the one closest to field data.

Table 10. Infiltrated water depths simulated by the algebraic model of Levien corresponding to the effect of the three cases of recession with adjusted data (Z_C) of Benson

Distance (m)	Infiltrated water depth (mm)			
	(Z_C)	(Z_1)	(Z_2)	(Z_3)
0.00	33.08	34.90	34.90	33.00
27.72	33.01	34.90	34.70	32.90
53.20	32.93	34.90	34.50	32.70
77.47	32.82	34.90	34.40	32.50
100.87	32.71	34.90	34.20	32.40
123.56	32.58	34.90	34.10	32.20
145.67	32.46	34.90	33.90	32.00
167.27	32.34	34.90	33.70	31.80
188.43	32.21	34.90	33.60	31.70
209.19	32.07	34.90	33.40	31.50
229.60	31.92	34.90	33.30	31.30
249.67	31.77	34.90	33.10	31.10
269.45	31.62	34.90	32.90	30.90
288.94	31.47	34.90	32.80	30.80
308.17	31.32	34.90	32.60	30.60
327.16	31.17	34.90	32.40	30.40
345.92	31.02	35.00	32.20	30.20
364.46	30.86	35.00	32.10	30.00
382.80	30.70	35.00	31.90	29.80
400.94	30.54	35.00	31.70	29.60
418.90	30.37	35.10	31.50	29.50
436.68	30.21	35.10	31.40	29.30
454.30	30.04	35.20	31.20	29.10
471.75	29.88	35.30	31.00	28.90
489.05	29.71	35.30	30.80	28.70
506.20	29.54	35.40	30.70	28.50
523.20	29.35	35.50	30.50	28.30
540.07	29.17	35.60	30.3	28.10
556.81	28.99	35.80	30.10	27.90
573.41	28.82	35.90	29.90	27.60
589.90	28.65	36.20	29.70	27.40
606.26	28.48	36.40	29.50	27.20
622.51	28.31	36.80	29.30	27.00

The results of simulated recession curves R_1, R_2 and R_3, of curves observed in field, of simulated infiltration profiles Z_1, Z_2 and Z_3 and of infiltration profiles estimated by data observed in the four examples studied, allowed the use of expression 14, which determines the calculation of average deviations of simulated data in relation to field data.

This study not only allowed a more representative analysis of the performance of recession curves and infiltration profiles but also facilitated assessing the influence of the recession on the infiltration profile in furrow irrigation.

Table 11 shows the recession curves and corresponding infiltration profiles simulated by the algebraic model of Levien, considering the effect of the three cases of recession R_1, R_2 and R_3 on the infiltration profiles.

Table 11 shows the smallest average deviation, around 1.87, obtained with Horticulture data for recession curve R_1, whose effect is quite significant for the infiltrated profile Z_1, with average deviation of 0.19, which means that both the simulated recession curve R_1 as the corresponding infiltration profile Z_1, are simulated curves that are the closest to the curves obtained with observational Horticulture data.

In contrast, the simulated curves that most deviated from the curves obtained with field data are recession R_1 and the infiltration profile $Z_1$with Benson data, which is the case in which the average deviations are respectively 231, 48 and 4.79.

The best performance was observed for recession curve R_1, with Ramsey and Horticulture data; for Stieben data, the recession curve R_2 and for Benson data, the best performance is the recession curve R_3.

Table 11 shows that all the mean deviation results of infiltration profile Z_1, Z_2 and Z_3 with the examples studied are proportionally related to the effects of the three hypotheses of recession curves R_1, R_2 and R_3.

Table 11. Recession curves and corresponding infiltration profiles simulated by the algebraic model of Levien, considering the three cases of recession, compared to field data using the specified examples

Examples	Mean deviation					
	R_1	R_2	R_3	Z_1	Z_2	Z_3
Ramsey	10.71	8.98	23.44	0.97	1.74	2.15
Horticulture	1.87	9.60	15.86	0.19	1.09	1.67
Stieben	91.36	18.34	24.30	1.51	0.29	0.39
Benson	231.80	60.97	33.88	4.79	1.32	0.93

CONCLUSION

For the data analyzed, the simulation of the infiltrated water depth for Ransey and Horticulture was best shown for the recession time with hypothesis I; however, when working with Stieben and Benson data, there was great disparity with respect to field values for infiltrated water depths to this hypothesis, this occurred probably due to the fragility of equation that simulated the recession time of this hypothesis for furrows considered long.

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Table 2. Field data regarding the recession and advance time depending on the furrow length

Ramsey farm			Horticulture farm			Stieben farm			Benson farm		
Distance (m)	Advance (min)	Recession (min)	Distance (m)	Advance (min)	Recession (min)	Distance (m)	Advance (min)	Recession (min)	Distance (m)	Advance (min)	Recession (min)
0.00	0.00	215.0	0.0	0.0	202.0	0.0	0.0	698.0	0,0	0.0	698.6
9.09	1.05	225.0	25.0	4.7	209.0	25.0	5.0	703.0	25.0	9.0	0.0
18.18	2.35	230.0	50.0	10.2	212.3	50.0	10.0	705.0	50.0	18.3	707.0
27.27	3.60	230.0	75.0	17.3	215.0	75.0	16.0	708.0	75.0	27.6	0.0
36.36	5.00	230.0	100.0	26.2	216.5	100.0	21.0	712.0	100.0	36.3	713.0
45.45	6.50	231.0	125.0	38.0	219.0	125.0	27.0	716.0	125.0	45.0	0.0
54.54	8.05	232.0	150.0	50.4	221.0	150.0	33.0	718.0	150.0	53.3	717.8
63.64	9.65	233.0	175.0	61.5	222.0	175.0	40.0	720.5	175.0	62.6	0.0
72.73	11.55	234.0				200.0	48.0	722.5	200.0	73.5	722.5
81.82	13.60	233.0				225.0	55.0	723.5	225.0	83.2	0.0
90.91	15.65	233.0				250.0	61.0	724.5	250.0	93.3	725.5
100.00	17.95	234.0				275.0	70.0	725.5	275.0	103.7	0.0
						300.0	77.0	727.0	300.0	115.0	728.5
						325.0	85.0	729.0	325.0	125.4	0.0
						350.0	94.0	731.0	350.0	135.3	732.0
									375.0	144.0	0.0
									400.0	153.3	734.5
									425.0	162.0	0.0
									450.0	171.1	737.0
									475.0	179.3	0.0
									500.0	188.8	739.9
									525.0	199.2	0.0
									550.0	208.5	741.3
									575.0	218.4	0.0
									600.0	229.3	744.5
									625.0	243.5	746.6