Comparison of Inflow Cutback Determination Algorithms for Improving Furrow Irrigation Performance

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Abstract

Furrow irrigation systems are applied for their conservation of energy, but they are criticized for using large amounts of water inefficiently. To conserve such water, the furrow system needs to be designed properly and operated efficiently. One recommended avenue to improve system operation efficiency is to adopt the inflow cutback technique. The main aim of this study was to improve furrow irrigation system operational efficiency via selection of one operating algorithm based on performance evaluation parameters (application efficiency, runoff ratio, deep percolation ratio DPR and distribution efficiency). In this study, using mathematical algorithms these Clemmens algorithm "CLE", Walker-Skogerboe algorithm "SKO", and Muskingum-Cunge algorithm "MUS") to compare the proper cutback flow at inflow rate, furrow lengths and furrow spacing. The obtained results indicated that all the reported algorithms resulted in high distribution efficiency (96.29%, 95.50 %, and 95.25 % for CLE, MUS and SKO respectively), but they differ significantly ($p \leq 0.05$) with respect to application efficiency. The resulting application efficiencies in descending order are 86.25 %, 77.12, and 48.70 for MUS, CLE and SKO respectively. However, these high application efficiency values obtained by MUS and CLE algorithms support the selection of any one of them to improve furrow irrigation. This recommendation is supported by the low tail water losses, "runoff ratio" obtained as 1.98, 13.91 and 26.26% by MUS, CLE and SKO respectively, while the loss ratio is due to deep percolation, and are 11.77%, for MUS, 8.97% for CLE and 25.05% for SKO. The low DPR for all algorithms obtained is due to the low soil intake rate.

Keywords: Inflow cutback algorithms; improving furrow irrigation operation; performance evaluation.

مقارنة خوارزميات لتقدير الخفض الجزئي للتدفق لتحسين أداء الري بالاخاديد

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مستخلص الدراسة

تستخدم أنظمة الري بالاخاديد للحفاظ على الطاقة، ولكنها تتعرض لانتقادات بسبب استخدامها لكميات كبيرة من المياه بشكل غير فعال، وللحفاظ على هذه المياه يجب تصميم نظام الاخاديد بشكل صحيح، وتشغيله بكفاءة. أحد الطرق الموصى بها لتحسين كفاءة تشغيل النظام هو اعتماد تقنية خفض التدفق. كان الهدف الرئيسي من هذه الدراسة هو تحسين كفاءة تشغيل نظام الاخاديد من خلال اختيار إحدى خوارزميات التشغيل بناءً على مؤشرات تقييم الأداء(كفاءة التطبيق، ونسبة الجريان السطحي، ونسبة التسرب العميق وكفاءة التوزيع). في هذه الدراسة تم استخدام خوارزميات رياضية وهي خوارزمية كليمنس"CLE"، خوارزمية ووكر-سكوقربو"SKO "وخوارزمية مسكنجم-كونج"MUS" لمقارنة خفض التدفق المناسب عند معدلات تدفق، وأطوال الاخاديد وتباعد الاخدود. أشارت النتائج التي تم الحصول عليها إلى أن جميع الخوارزميات أدت إلى كفاءة توزيع عالية (96.29٪ ،95.50٪ و، 95.25٪ بواسطة SKO، MUS،CLE على التوالي)، ولكنها تختلف معنوياً (P≤0.05) فيما يتعلق بكفاءة التطبيق. كانت كفاءة التطبيق الناتجة بترتيب تنازلي كالآتي: 86.25٪ ، 77.12 ، 48.70 بواسطة SKO، CLE،MUS على التوالي. ومع ذلك، فإن قيم كفاءة التطبيق العالية التي تم الحصول عليها من خلال خوارزميات CLE، MUS تدعم اختيار أي منها لتحسين ري الاخدود، وتدعم هذه التوصية انخفاض فواقد مياه الجريان السطحي "نسبة الجريان السطحي" التي تم الحصول عليها بنسبة 1.98 ،13.91، 26.26٪ بواسطة SKO، CLE، MUS على التوالي، في حين أن نسبة فواقد التسرب العميق كانت 11.77٪ MUS، 8.97٪ CLE ، 25.05٪ SKO. يرجع انخفاض نسبة التسرب العميق لجميع الخوارزميات المستخدمة إلى انخفاض معدل تسرب التربة.

الكلمات المفتاحية: خوارزمية خفض التدفق؛ تحسين تشغيل الري بالاخاديد؛ تقييم الاداء

1. Introduction

Furrow irrigation is used in dry areas for storing harvested rain water. In the furrow irrigation system application efficiency is reported to be low and runoff rates are high especially in low intake soils. To improve furrow performance, it is essential to design the system with proper combination of design variables of inflow rate, furrow length, soil infiltration rate and field slope for specific depth of application. In addition, improvements of performance require proper field operation and system implementation. For predicting furrow performance with these design variables advanced simulation models have been used for predicting irrigation processes (advance, storage and recession) as cheap substitute to direct field measurements (Nie *et, al* , 2018).

During operation phases inflow rate is unsteady and non-uniform and function to infiltration and surface storage affected by discharge (Bahrami *et, al*, 2010). However, use of high inflow rate leads to high tail water losses while using low inflow rate results in accumulation of water deeply in furrow head resulting in poor water distribution efficiency. One method to reach a compromise between the two is to employ inflow cutback technique. To apply such technique requires prediction of state of advance and recession. Forecast of advance and recession can be made using two approaches. The first approach is based on hydrodynamic equations of mass and energy (or momentum) conservation with some approximations thereof. The second approach is the volume balance normal depth approach which is based on the principle of mass conservation and assumption of storage-discharge relation to replace the energy equation.

James (1988) reported that the cutback irrigation involves decreasing (cutting back) the rate of inflow when water approach graded furrow tail during an irrigation event to reduce runoff losses to improve application efficiency. Cutback basic strategy of controlling runoff by matching the rate at which water enters the soil to the average infiltration capacity of the soil along the length of the furrow and by reducing water accumulation during the storage phase. Usually, inflow is reduced in discrete steps as opposed to continually.

Merriam and Keller (1978) described a case study where water use efficiency was improved from 48-71% by using a single cut-back flow. The technique requires a high labour in-put unless a system of auto-irrigation is used.

Clemmens (2007) stated that after advance has been completed to the end of the field the efficiency of furrow irrigation systems may often be improved, reducing the inflow rate. (One step) to reduce high labour demand. Rapid advancement and more consistent opportunity time can be achieved with a high beginning flow rate, whereas stream reduction will lessen the amount of stored water leading to reduced runoff. If the cutback in flow is insufficient to offset infiltration, downstream recession may occur and progress back across the field. Instead of stopping immediately after advancing, the cutoff is usually postponed until the infiltration is slightly diminished. This will also serve to ensure that the downstream end receives sufficient flow depth and wetted perimeter. A common practice is to cut back to 50% of the inflow. Dividing the cutback inflow rate by the wetted field area gives the average infiltration rate that matches the cutback inflow. There exist different mathematical algorithms to estimate inflow reduction rate.

This includes the first and pioneer work of Walker-Skogerboe (1978) which is based on reducing the initial inflow by the soil basic intake rate and thus, runoff is eliminated when the rate at which inflow decreases over time precisely matches the rate at which the average infiltration rate decreases over time for the entire length of field.

The second approach is Clemmens algorithm (2007) which is calculation procedures are based on continuity, but include some empirical expressions for convenience. These calculations are used to determine advance and application times and the resulting distribution of infiltrated water for a specific set of conditions. And the third algorithm is given by Muskingum-Cunge (1969) and assumed that uses the bottom slope in the expression for hydraulic diffusivity, defined as one-half of the unit-width discharge divided by the water surface slope. The Muskingum - Cunge algorithm relies on the continuity, or storage, equation. However, the Muskingum - Cunge algorithm relates reach storage, at any time, to a linear combination of inflow and outflow. This arises the question which approach to adopt to improve operating efficiently of furrow system.

Objectives

The main aim of this study was to present and discuss how to improve the operational efficiency of furrow irrigation via choosing one operating algorithm of performance evaluation for furrow irrigation. The specific aim is to present simple algorithms and easy -use operations based on Excel sheets.

2. Materials and Methods

2.1Clemmens (CLE)

The Clemmens model that was proposed by Walker and Albert Clemmens in 2007, the model depends on the volume balance model.

$$A_o = y(Wb + Z \times y) = yWb + y^2Z \qquad (1)$$

$$P = Wb + 2y\sqrt{1 + Z^2} \qquad (2)$$

$$Q_f = \frac{1}{n} AR^{2/3} {S_o}^{1/2} \qquad (3)$$

Where A_o: furrow cross-sectional area, (m^2); y: depth, (m); Wb: bottom width, (m);Z: side slope (1_{Vert}:Z_{Hor}). P: wetted perimeter, (m); R: hydraulic radius of flow, (m); S_o: slope, (m/m); n: Manning roughness coefficient.

Infiltration is one of the most important factors affecting the design and performance of surface irrigation systems. Unfortunately, estimating infiltration conditions is one of the most difficult aspects to do in the field. Irrigation engineers have tended to use the Kostiakov Equation, or a variation thereof, defined by

$$d(\tau) = c + k\tau^a + b\tau \qquad (4)$$

$$i(\tau) = ak^{a-1} + b \qquad (5)$$

Where d: depth of infiltration, (mm); i: rate of infiltration, (mm/hr); τ: opportunity time for infiltration, (hr); a,b: mm/hr c mm, and k mm/hr^a there are four empirical constants.

Typically, based design assumes that one side of the field will have a lower infiltrated depth than the other. Next, the inflow rate and cutoff time are than adjusted to ensure the necessary infiltration at that point. The time available for infiltration at any point along the field is known as the infiltration opportunity time, defined by

$$\tau_{opp}(x) = t_R(x) - t_A(x) \quad (6)$$

The opportunity time and the recession time are equal at the beginning of the field (x = 0).

$$\tau_{opp}(0) = t_R(0) = t_{co} + t_{lag} \quad (7)$$

Where $\tau_{opp}(x)$: infiltration opportunity time, (min); $t_R(x)$: recession time, (min); t_A: advance time ,(min). t_{co}: Cut-off time, (min); t_{lag}: recession lag time, (min) or required time for the upstream end's water depth to reach zero following cutoff.

Computing advances and recession curves are not necessary for design based that prioritize achieving requirement upstream end. But in addition to estimating the recession lag time, an estimate of PE min is needed (USDA, 1974). The minimum depth for well-designed systems is usually found at the downstream end of the field, furthest distance from the source of water(x = L). When computing a recession and advance curves, estimating the inflow rate and required time to realize τ_{req} becomes the biggest challenge.

$$t_R(L) = t_A(L) + \tau_{req} \quad (8)$$

The St.Venant equations of continuity and momentum can be solved if possible to obtain precise solutions for advance and recession. Nevertheless, this approach is on a case-by-case basis and necessitates numerical analysis. It doesn't immediately yield general formulas for advance and recession. The cutoff time can be computed by the following equation.

$$t_{co} = t_A(L) + t_{req} - [t_R(L) - t_R(0) + t_{lag}] \quad (9)$$

The period between the cut-off time and the recession for sloping furrow is usually taken to be zero. They provide design techniques in this model that are based on meeting the downstream end minimum for depth.

$$V_{in}(t) = V_y(t) + V_z(t) \qquad (10)$$

Where V_{in} (t): represents the volume of water entering at time t, (m^3); $V_y(t)$: indicates the volume of water stored on the surface at time t, (m^3); and $V_z(t)$: shows the volume of water infiltrated at time t, (m^3).

By having information on both the surface and subsurface volumes beforehand, you can be utilized this connection to calculate the time, tx, needed to travel a distance x.

$$Q_{in}(t) = \sigma_y A_o(t)x + \sigma_z WZ(t)x \qquad (11)$$

Where σ_y: surface storage shape factor; W: width, (m); Z: infiltrated depth, (m) and σ_z: subsurface shape factor. The surface shape factor is the ratio between the average cross-sectional flow area and that at the head of the field. For furrows, it is typically between 0.70 and 0.80. The subsurface shape factor is the ratio between the average infiltrated cross sectional area (infiltrated depth times width), and the infiltrated cross-sectional area (depth times width) at the head of the field. When infiltration is defined by equation 5, the subsurface volume is rewritten as below in equation (12):

$$V_z = Wx\left(c + \sigma_z k t_x^a + \frac{h}{1+h} b t_x\right) \qquad (12)$$

Where h: exponent on the advance equation

$$t_x = sx^h \qquad (13)$$

Where: s: constant. From (ASAE, 1991), σ_z can then be determined.

$$\sigma_z = \frac{h + a((h-1)) + 1}{(a+1)(h+1)} \qquad (14)$$

The initial step in the design process involves computing the advance time for the progressing stream access to half and the full length of the field. One can compute the advanced exponent can be computed from these two equations.

$$h = \frac{\log(t_{l/2}/t_l)}{\log(1/2)} \qquad (15)$$

Recession curve adjustment can be achieved by deducting the total applied volume from the volume of water on the surface of cutoff. Therefore, the application time can be found from the equation.

$$t_{co} = t_A(L) + t_{req} - \left(\frac{V_y(Q_{in})}{Q_{in}}\right) \qquad (16)$$

Whereas: $V_y(Q_{in})$: Stable state surface volume for the inflow rate following the completion of the advance.

Dividing the cutback inflow rate by the wetted field area gives the average infiltration rate that matches the cutback inflow

$$.\bar{i_{cb}} \leq \frac{Q_{cb}}{WL} \qquad (17)$$

The infiltration rate, the obtained on the field length is averaged by equation below (18).

$$\bar{i_{cb}} = b + \frac{akt_{cb}^{(a-1)}}{ah}\left[\left(\left\{\frac{t_{cb}}{t_L}\right\} - 1 + h\right)^a - \left(\left\{\frac{t_{cb}}{t_L}\right\} - 1\right)^a\right] \qquad (18)$$

A conservative estimate of the correction in cutoff time can be found by dividing the change in surface volume by the cutback flow rate, which is related to the distance averaged infiltration rate through Equation 17. The adjusted cutback time is simply as in equation (19).

$$t_{cbadj} = \frac{V_y(Q_{in}) - V_y(Q_{cb})}{Q_{cb}} \qquad (19)$$

The cutoff time is determined by using Equation 16, with $V_y(Q_{Cb})$ instead of $V_y(Q_{in})$, due to a smaller volume being stored on the soil surface during cutback.

2.2 Skogerboe model (SKO)

The volume balance model assumes that at any time, t, water entering the field will progress a distance, X, toward the lower end of the field. The furrow inflow at the inlet of the field, Qo, is assumed steady, so that at time, t, the product of Qo and t equals the volume of water on the soil surface, Vy(t), plus the volume infiltrated, Vz(t), which are both time dependent**.**

$$Q_o t = \sigma_y A_o X + \sigma_z Zx \qquad (20)$$

The trajectory of the advance of the waterfront in a furrow can be described as a simple power function:

$$X = P(t_A)^r \qquad (21)$$

Where: X: the distance the front has advanced at time t_A, r, and P are empirically fitted parameters.

The infiltration function has a Kostiakov-Lewis characteristic form (Walker and Skogerboe, 1987):

$$Z = k\tau^a + f_o\tau \qquad (22)$$

Where: Z is the volume of infiltrated water per unit length m^3/m, τ is the opportunity time min, f_o: the basic intake rate in units of volume per unit length per unit time (m^3/min/min), and (k)(m^3/min^a /m) and (a) values are empirically fitted parameter. Utilizing these two assumptions in the Lewis-Milne equation, the volume balance model can be written as follows (Walker and Skogerboe, 1987).

$$Q_o t = \sigma_y A_o X + \sigma_z k t^a X + \frac{f_o t X}{r+1} \qquad (23)$$

$$\sigma_z = \frac{a + r(1-a) + 1}{(1+a)(1+r)} \qquad (24)$$

Where: σ_z: the subsurface water profile shape factor and σ_y is the surface water profile shape factor. The cross-sectional flow area at the field inlet, A_o, can be calculated using the Manning equation as follows:

$$A_o = \left(\frac{Q_o^2 n^2}{3600 S_o \rho_1}\right)^{1/\rho_2} \qquad (25)$$

Where Ao: Furrow cross-sectional area, (m^2); Q_o: inflow rate (m^3/min); n: manning coefficient; S_o: field slope,(m/m)and p_1 and p_2: empirical shape coefficients.

The Newton-Raphson procedure can be used to get the advance time (t_L) using the following equation:

$$(t_L)_{i+1} = (t_L)_i - \frac{Q_o (t_L)_i - \sigma_y A_o L - \sigma_z k (t_L^a)_i L - \frac{f_o (t_L)_i L}{(1+r_i)}}{Q_o - \frac{\sigma_z a k L}{(t_L^{1-a})_i} - \frac{f_o L}{(1+r_i)}} \qquad (26)$$

Assume an initial estimate of $(t_L)_{i+1}$ as: $(t_L)_i$

$$(t_L)_i = 5 A_o L / Q_o \qquad (27)$$

Compare the initial $(t_L)_i$ and revised $(t_L)_{i+1}$estimates of t_L. If they are approximately 0.5 minutes or closer, the design moves on to the next stage. If they are unequal, assign $(t_L)_i$ the value of $(t_L)_{i+1}$ and repeat the step in equation 26.

Determine the advance time to reach the midpoint of the field, 0.5L, by substituting 0.5L for L and t_L for $t_{0.5L}$, just as you would when be calculating t_L. The midpoint length and inlet area replaced for level field condition. The values of t_L and $t_{0.5L}$ are determined A_o must be replaced level field condition. The values of t_L and using equation 27 with L and 0.5L, respectively. Using approximations to compute the time intake for moving stream to reach half and entire length of the field. A revise estimate of the advanced exponent can be compute for these two.

$$.r_{i+1} = \frac{\log(2)}{\log(t_l/t_{l/2})} \qquad (28)$$

Compare the initial estimate with the retouch estimate. If they are same, then the process of determining t_L is finished. If not, then retouch r_i to r_{i+1} in equation 26.

The intake opportunity time τ_{req} related to Z_{req} needs to be determined, representing a specific instance that requiring a nonlinear solution for equation 22. The Netwoton-Raphson procedure is used, beginning with an initial estimate τ_{req}, which is labeled as $(\tau_{req})_i$ for convenience. To refine the estimate, compute an updated approximation, $(\tau_{req})_{i+1}$ using the given equation.

$$\left(\tau_{req}\right)_{i+1} = \left(\tau_{req}\right)_i + \frac{Z_{req} - k\left(\tau_{req}^{a}\right)_i - f_o\left(\tau_{req}\right)_i}{\frac{ak}{(\tau_{req}^{1-a})_i} + f_o} \qquad (29)$$

Compare the values of the initial and revised estimates. If they are equal to each other, or within an acceptable tolerance, the value of τ_{req} is determined. If they are not sufficiently equal in value, replace the initial value of τ_{req} with the revised value, $(\tau_{req},)_i$ = $(\tau_{req})_{i+1}$ in equation 29.

Following the advanced stage, it is important to ensure that the reduction in flow is enough to maintain the continuous flow of water along the entire length of the furrow.

Tailwater's presence is unavoidable, but effort should be made to reduce it as much as possible. Knowing that infiltration rates will decrease during the wetting period to values similar to the basic intake rate con help determine how to size up the cutback flow.

$$\mathrm{Q_{cb} = bf_o L} \quad . \tag{30}$$

Where: b: factor requiring some judgment to apply. It should probably be in the range of 1.1 to 1.5.

Thus, the application efficiency of the cutback system can be described as

$$\mathrm{E_a = \frac{Z_{req}L}{Q_o t_L Q_{cb} \tau_{req}} = \frac{Z_{req}L}{\tau_{req}(Q_o + Q_{cb})}} \tag{31}$$

2.3 Muskingum-Cunge model (MUS)

The Muskingum-Cunge method enhances the classical Muskingum method for flood routing by incorporating physical-numerical principles from Cunge to calculate the routing parameters. Comparatively, it can be stated that the classical Muskingum method is hydrologic, whereas the Muskingum-Cunge method is distinctly hydraulic. The equations that govern the model include Manning's equation, the volume balance equation, Lewis-Kostiakov equation, and the mass conservation equation. The Muskingum-Cunge model includes the same component equations as the Muskingum model, but routing parameters are determined based on hydraulic parameters. The Muskingum-Cunge model is solved by applying the continuity and momentum equations (Bahrami, *et,al* 2010). The continuity equation can be expressed in the following manner:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \tag{32}$$

Where: A: cross sectional area (m^2); Q: discharge (m^3/s); t: time (s); and x: space (m).

When there is lateral inflow contribution to the system, equation 32 becomes:

$$\frac{\partial \mathrm{A}}{\partial \mathrm{t}} + \frac{\partial \mathrm{Q}}{\partial \mathrm{x}} = \mathrm{q_L} \tag{33}$$

Where q_L is the lateral inflow (m^3/s)

The diffusion form of the momentum equation is written as follows:

$$S_f = S_o - \frac{\partial y}{\partial x} \quad (34)$$

Where S_f: is friction slope (m/m) and S_o: is channel bed slope (m/m).

After combining these two equations and after a linearization process, a convective diffusion equation is derived as

$$\frac{\partial Q}{\partial t} + c\frac{\partial Q}{\partial x} = u\frac{\partial^2 Q}{\partial x^2} + cq_L \quad (35)$$

Where c: is wave celerity (m/s), μ: hydraulic diffusivity (m^2/s). They are expressed as follows:

$$c = \frac{dQ}{dA} \quad (36)$$

$$\mu = \frac{Q}{2BS_o} \quad (37)$$

The downstream outflow can be predicted by using the following equation.

$$Q_{j+1}^{i+1} = C_1 I_j^{i+1} + C_2 I_j^i + C_3 Q_{j+1}^i \quad (38)$$

Where as

$$C_1 = \frac{\Delta t - 2K\theta}{2k(1-\theta)+\Delta t} \quad (39)$$

$$C_2 = \frac{\Delta t + 2K\theta}{2k(1-\theta)+\Delta t} \quad (40)$$

$$C_3 = \frac{2k(1-\theta) - \Delta t}{2k(1-\theta)+\Delta t} \quad (41)$$

Where:Q_{j+1}^{i+1}: downstream outflow at time (j+1) (m^3/sec). Q_{j+1}^{i}: Downstream outflow at time (j+1) (m^3/sec). I_j^{i+1}: Upstream inflow at time (j) (m^3/sec). I_j^i: Upstream inflow at time

(j) (m^3/sec), K: storage constant (sec). X: weighting factor (show the relative importance of inflow and outflow in computing storage) (dimensionless) Δt: time interval (sec).

$$\theta = 0.5 - \frac{Q}{2BS_oC\Delta x}\left(1 - \frac{4}{9}F^2\right) \quad (42)$$

$$F = \frac{c}{\sqrt{gR}} = \frac{c}{\sqrt{g\frac{A}{B}}} \quad (43)$$

Where: θ: weighting factor, non-dimensional, Q: discharge (m^3/sec), B: is the width of the water surface(m). So: bed slope (dimensionless), c: celerity corresponding to Q and B (m/sec), Δx: is the increment in space (m) A: cross-sectional area (m^2).

$$S = K[\theta I + (1-\theta)Q] \quad (44)$$

Where: S: reach storage m^3, I: inflow discharge, m^3 /sec, O: outflow discharge, m^3 /sec.

Bahrami, *et, al*, (2010) stated that an important difference between furrow irrigation and river conditions is due to infiltration phenomenon in the field. Infiltration can affect this cycle as an outflow similar to lateral channels pour to or branch from major channels or rivers. With spotting this assumption which can be an accurate assumption, following applied relation is presented:

$$Q_{j+1}^{i+1} = C_1 I_j^{i+1} + C_2 I_j^i + C_3 Q_{j+1}^i + C_4(q_L \Delta x) \quad (45)$$

Where as

$$C_4 = \frac{2\left(\frac{\Delta t}{k}\right)}{2k(1-\theta)+\Delta t} \quad (46)$$

$$Q_{j+1}^{i+1} = C_1 I_j^{i+1} + C_2 I_j^i + C_3 Q_{j+1}^i - C_4\left(\frac{G^i + G^{i+1}}{2}\right) \quad (47)$$

G^i and G^{i+1}: infiltration rate at two consecutive infiltration opportunity times. Duration of advance phase in each place segment is determined by using volume balance as

$$\Delta x = \frac{\left[\frac{Q^{i+1}+Q^i}{2}\right]\Delta T}{\sigma_y A_o + \sigma_z Z_o} \quad (48)$$

Q^{i+1} and Q^{i}: outflow in advance phases at beginning and ending of time step ΔT.

The infiltration rate, over the field length, is averaged by the equation below.

$$\bar{i}_{cb} = \frac{f_o L}{r+1} + \frac{akL}{t_{cb}^{(1-a)}}\left[\left(\left\{\frac{t_{cb}}{t_L}\right\} - 1 + r\right)^{a} - \left(\left\{\frac{t_{cb}}{t_L}\right\} - 1\right)^{a}\right] \qquad (49)$$

Compute the adjusted cutback time using equation 19. Equation 16 is used to compute the cutoff time, However $Vy(Q_{in})$ is replaced with $Vy(Q_{cb})$.

2.2 Input Data

It includes design inputs, furrow length, spacing, and slope, furrow shape coefficients, manning coefficient, infiltration parameters, irrigation requirement and surface shape factor. While for the Clemmens algorithm, there are inputs specific to the Clemmens algorithm that include bottom width, water depth, water depth cutback, side slope and infiltration parameters. The input design parameters can be summarized by running the all algorithms are given in tables 1.0.

Table 1: Input data for all algorithms.

<table>
<tr><td>Inlet discharge; Qo (L/s)</td><td>1.8</td><td>2.2</td><td colspan="2">2.5</td><td colspan="2">2.9</td></tr>
<tr><td>Field length; L (m)</td><td>130</td><td>180</td><td colspan="2">230</td><td colspan="2">270</td></tr>
<tr><td>Field spacing; W ((m)</td><td>0.75</td><td>1.0</td><td colspan="2">1.2</td><td colspan="2"></td></tr>
<tr><td>slope; S_o (m/ m)</td><td colspan="6">0.002</td></tr>
<tr><td>irrigation requirement, Z_{req} (mm)</td><td colspan="6">100</td></tr>
<tr><td>surface shape factor σ_y</td><td colspan="6">0.77</td></tr>
<tr><td>Manning coefficient; n</td><td colspan="6">0.04</td></tr>
<tr><td>Shape coefficient; p_1</td><td colspan="6">0.325</td></tr>
<tr><td>Shape coefficient; p_2</td><td colspan="6">2.734</td></tr>
<tr><td></td><td colspan="2">Skogerboe</td><td colspan="4">Clemmens</td></tr>
<tr><td rowspan="3">Infiltration parameters</td><td>a</td><td>0.303</td><td colspan="2">a</td><td colspan="2">0.62</td></tr>
<tr><td>K; (m^3/min^a.m)</td><td>0.0063</td><td colspan="2">k mm/hr^a</td><td colspan="2">39.7</td></tr>
<tr><td>fo ;(m^3/min .m)</td><td>0.00032</td><td colspan="2">b mm/hr</td><td colspan="2">0.0</td></tr>
<tr><td>water depth; y (m)</td><td colspan="2">-</td><td>0.063</td><td>0.070</td><td>0.074</td><td>0.079</td></tr>
<tr><td>water depth cutback y_{cb} (m)</td><td colspan="2">-</td><td>0.045</td><td>0.050</td><td>0.053</td><td>0.057</td></tr>
<tr><td>bottom width; Wb (mm)</td><td colspan="2">-</td><td colspan="4">100</td></tr>
<tr><td>side slope z</td><td colspan="2">-</td><td colspan="4">2:1</td></tr>
</table>

2.3 Statistical analysis

A one way analysis of variance test, standard error (SE) and the multiple comparison tests were (LSD) using Statistix 8.0 model to analyses the significance of the means and their comparison with each other. The values sharing at least one same latter are significantly different.

3 . Results and Discussion

3.1 Application Efficiency (E_a)

The analysis of variance for application efficiency results is shown that in Table 2. The impacts of algorithms were significant ($p \leq 0.05$) on application efficiency. All three means are significantly different from one another and the mean values of E_a for SKO, CLE and MUS were of 48.70, 77.12 and 86.25% respectively. The impact of the inflow rate on E_a was significant ($p \leq 0.05$). There are no significant pair wise differences among the means and the mean values of E_a were 72.09, 71.55, 70.5 and 68.62% for 1.8, 2.2, 2.5 and 2.9 L/s, respectively. E_a showed an increasing trend as inflow rate decreased. The impact of the furrow length on E_a was significant ($p \leq 0.05$). There are no significant pair wise differences among the means and the mean values of E_a were 65.47, 71.76, 73.4 and 72.1% for 130, 180, 230 and 270 m, respectively. E_a showed an increased trend as the furrow length increased except furrow length 270 m. The impact of the furrow spacing on E_a was significant ($p \leq 0.05$). There are no significant pair wise differences among the means and the mean values of E_a were 69.1, 71.45 and 71.52 % for 0.75, 1 and 1.2 m, respectively. E_a showed an increasing trend as the furrow spacing increased. This is in agreement with the result of Assefa *et al*. (2017) who stated highest efficacies achieved for small furrow lengths with relatively low discharges and larger flow rates are needed as furrow length increases to obtain high efficacies.

Table 2: Statistical comparison of the models (SKO, MUS and CLE), furrow length and furrow spacing for application efficiency.

	Algorithms			**Inflow rate l/s**			
	MUS	**CLE**	**SKO**	**1.8**	**2.2**	**2.5**	**2.9**
E_a %	86.25A	77.12B	48.70C	72.09A	71.55A	70.50A	68.62A
SE	2.09			4.51			
LSD (0.05)	4.12			8.92			
	Furrow spacing m			**Furrow length m**			
	0.75	1	1.2	130	180	230	270
E_a %	69.10A	71.45A	71.52A	65.47A	71.76A	73.40A	72.13A
SE	3.90			4.46			
LSD (0.05)	7.70			8.82			

3.2 Surface runoff ratio (RO)

Results from the Surface runoff ratio show in table 3, the effect of the models significant difference (p≤0.05). All three means are significantly different from one another and the mean values of RO were of 1.98, 13.91and 26.26% for MUS, CLE and SKO respectively. The results for RO show that there was significant (p≤0.05) variation in effect of the inflow rate on RO. There are two groups in which the means are not significantly different from one another. The RO increased as the inflow rate increased and the mean values of RO were of 8.47, 12.76, 15.62 and 19.34 for inflow rates 1.8, 2.2, 2.5and 2.9l/s respectively. The results for RO show that there was significant (p≤0.05) variation in effect of the furrow length on RO and there are three groups in which the means are not significantly different from one another. The mean values of RO were of 25.42, 14.64, 8.93 and 7.2 for furrow length 130,180,230 and 270 m respectively.RO show decreasing trend with increasing furrow length. This is in agreement with the result of Assefa *et al*. (2017) who stated surface runoff ratio showed decreasing trend with increasing furrow length. The effect of the furrow spacing on RO was significant (p≤0.05) There are no significant pair wise differences among the means and the mean values of RO were 16.8, 13.1and 12.16 % for furrow spacing 0.75, 1and 1.2 m, respectively. RO trend decreasing with increasing furrow spacing**.**

Table 3: Statistical comparison of the models (SKO, MUS and CLE), furrow length and furrow spacing for Surface runoff ratio.

	Algorithms			**Inflow rate l/s**			
	MUS	**CLE**	**SKO**	**1.8**	**2.2**	**2.5**	**2.9**
RO %	1.98C	13.91B	26.26A	8.47B	12.76AB	15.62A	19.34A
SE	2.30			3.43			
LSD (0.05)	4.54			6.79			
	Furrow spacing m			**Furrow length m**			
	0.75	1	1.2	130	180	230	270
RO%	16.8A	13.18A	12.16A	25.42A	14.64B	8.93BC	7.20C
SE	3.05			3.13			
LSD (0.05)	6.02			6.19			

3.3 Deep percolation ratio (DP)

The differences in DP values between models were significant (p≤0.05). There are two groups in which the means are not significantly different from one another. The mean values of DP for CLE, MUS and SKO were 8.97, 11.77 and 25.05%, respectively. The analysis variation on DP indicated that there was significant (p≤0.05) variation in effect of the inflow rate on DP and there are two groups in which the means are not significantly different from one another. The mean values of DP were of 19.43, 15.74, 13.88 and 12.04% for inflow rates 1.8,2 .2, 2.5 and 2.9 l/s, respectively. The DP decreased as the inflow rate increased. The results for DP show that there was significant (p≤0.05) variation in effect of the furrow length on DP and there are three groups in which the means are not significantly different from one another. The mean values of DP were 9.11, 13.6, 17.67 and 20.67 for 130, 180, 230 and 270 m, respectively. The DP increased as the furrow length increased. The effect of the furrow spacing on DP was not significant (p≤0.05) there are no significant pairwise differences among the means. The mean values of DP were 14.10, 15.37 and 16.33% for 0.75, 1and 1.2 m, respectively. The DP increased as the furrow spacing increased.

Table 4: Statistical comparison of the models (SKO, MUS and CLE), furrow length and furrow spacing for deep percolation ratio.

	Algorithms			Inflow rate l/s			
	MUS	CLE	SKO	1.8	2.2	2.5	2.9
DP %	11.77B	8.97B	25.05A	19.43A	15.70AB	13.88B	12.04B
SE	1.44			2.27			
LSD (0.05)	2.84			4.49			
	Furrow spacing m			Furrow length m			
	0.75	1	1.2	130	180	230	270
DP %	14.10A	15.37A	16.33A	9.11C	13.60B	17.67AB	20.67A
SE	2.03			2.12			
LSD (0.05)	4.01			4.19			

3.4 Distribution Uniformity (DU)

The analysis of variance (ANOVA) of distribution uniformity results shows that in table 5. The inflow rate had a not significant impact on the DU (p≤0.05). There are three groups in which the means are not significantly different from one another. As DU increased as the inflow rate increased and the mean values of DU were 93.15,95.66 and 97.34 for inflow rates 1.8, 2.2, 2.5 and 2.9 l/s, respectively. The effect of the models on DU was not significant ($p \leq 0.05$). There are no significant pairwise differences among the means and the mean values of DU were 96.29,95.5 and 95.25 for CLE, MUS and SKO, respectively. The effect of the furrow length on DU was significant ($p \leq 0.05$), all four means are significantly different from one another. The DU decreased as the furrow length increased and the mean values of DU were 98.71,97.00,94.77 and 92.24% for furrow lengths 130, 180, 230 and 270 m, respectively. This is similar to the reports of Holzaphel *et al.* (2010) which stated that uniformity is an increasing function of flow rate and a decreasing function furrow length. Increase in flow rates reduces the difference in wetting time between the head and tail of the furrow the effect of the furrow spacing on DU was not significant ($p \leq 0.05$) there are no significant pairwise differences among the means and the mean values of DU were 95.06, 95.89 and 96.09% for furrow spacing 0.75, 1and1.2 respectively.

Table 5: Statistical comparison of the models (SKO, MUS and CLE), furrow length and furrow spacing for distribution uniformity.

	Algorithms			Inflow rate l/s			
	MUS	CLE	SKO	1.8	2.2	2.5	2.9
DP %	95.5A	96.29A	95.25A	93.15C	95.66B	96.58AB	97.34A
SE	0.73			0.76			
LSD (0.05)	1.44			1.50			
	Furrow spacing m			Furrow length m			
	0.75	1	1.2	130	180	230	270
	95.06A	95.89A	96.09A	98.71A	97.00B	94.77C	92.24D
SE	0.73			0.62			
LSD (0.05)	1.44			1.23			

4. Conclusions

The proposed algorithms are flexible in that they allow the user the freedom to choose input for different types of soils. In this study, three cutback flow algorithms were proposed, chosen for their simplicity and ease use, with the aim of improving furrow irrigation performance. These algorithms differ slightly in way the cutback flow computed. This algorithm uses continuity flow to compute the advance time to field end and half the distance to field end. The algorithm inputs included two types of variables, one constant (a, k, f_o, Z_{req}, n, S_o, σ_y, p_1 and p_2) and the other variables (L, Q and W), and they were defined in furrow in this study. The results indicated that the Muskingum-Cunge algorithm achieved a higher application efficiency compared to the other algorithms for the free-draining, graded furrow irrigation systems employing cutback flows. It's recommended to conduct sensitivity analysis of the inputs each algorithm to evaluate the effect of changing the inputs on the performance of furrow irrigation. In addition to conducted field experiments to compare the results of the algorithms with the field results.

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