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Runoff Discharge from Border and Furrow Irrigation

Prof. Dr. Safa N. Hamad
Water Resources Eng. Dept., College of Eng.
Baghdad University, Baghdad, Iraq

Asst. Lect. Abdul-Sahib T. Abdul-Sahib
Environmental Eng. Dept., College of Eng.
Al-Mustansiriya University, Baghdad, Iraq

Abstract

In this research, two procedures have been developed to predict runoff hydrographs from graded border and furrow irrigation systems. One of the procedures is based upon volume balance principle and the other is based upon the application of Manning's formula.

The results of the two procedures were compared with actual measured field data in different locations and good agreement has been noticed between measured and predicted runoff discharges. Also, it has been found that the results of the two procedures coincide with each other through a proper selection of the time increment. The developed procedures can be used to design of graded border or furrow irrigation systems.

الخلاصـــــــة

تم في هذا البحث اعداد طريقتين لحساب تصاريف مياه السيح من نظم الري الشريطي المدرجة وري المروز . أحدى هاتين الطريقتين أعتمدت على مبدأ الموازنة الحجمية فيما أعتمدت الطريقة الثانية على أستخدام معادلة ماننك .

وقد تم تحقيق نتائج الطريقتين باستخدام البيانات الحقلية التي جمعت من قبل باحثين سابقين في مواقع متعددة وقد لوحظ تقارب جيد بين النتائج النظرية و البيانات الحقلية. كذلك لوحظ أن نتائج الطريقتين تنطبق على بعضهما اذا ما أحسن أختيار الزيادة الزمنية بشكل يؤدي الى تقليل الأخطاء العددية. ويمكن أستخدام أيا من هاتين الطريقتين لأعداد التصاميم المناسبة لمنظومات الري الشريطي المدرجة أو ري المروز .

1. Introduction

Border strip and Furrow irrigation systems are those of the oldest, practical, and most common types of surface irrigation systems. It affords high irrigation efficiency if properly designed.

Flow of water in surface irrigation is a kind of unsteady, non-uniform, open channel flow over a porous bed. The hydraulics of surface irrigation has been studied by many researchers in the past. The results of those researches led to a better understanding of water flow problem on porous media, specifically the behavior of soil infiltration rate and water advance phenomena. Kostiakov [1] proposed a simple infiltration formula with two parameters. Smerdon and Hohn [2] developed a mathematical model based on volume balance principle to describe the relationship between advance and furrow intake rates. Christiansen, et. al. [3] related soil infiltration parameters to the advance function in surface irrigation. Hart, et. al. [4] studied the hydraulics of border irrigation systems. Singh and Chauhan [5] developed a relationship to estimate water advance rate in surface irrigation by introducing surface and sub-surface shape factors in the continuity equation.

Hamad [6] developed two methods to predict water advance function and runoff hydrographs for furrow irrigation systems by assuming the shapes of surface and subsurface water fronts and using an integration process to calculate the volumes of surface and subsurface-stored water.

Al-Samerrai [7] developed a mathematical model to study the relationships among furrow intake, advance, and runoff. His model helps the designers to predict runoff volume, study the alternatives to reduce it, and increase irrigation efficiency. The model was also based upon volume-balance principles and utilizes an empirical advance function.

Modelers of furrow irrigation have used Manning's formula to describe flow in their models (Elliote et. al. [8]; Walker and Gichuhi, unpublished report, 1985; Ross, unpublished notes, 1986; Wallender [9]; Strelkoff [10]). Esfandiari and Maheshwari [11] used Manning's formula to model overland flow in furrow irrigation.

Al-Zubaidy [12] investigated the effects of using curved surfaces on water advance down a border strip. His mathematical model was verified by using published experimental data on plane surfaces and data gathered from conducted field experiments on three different curved surfaces. Gilfedder et. al. [13] presented the results from a detailed field experiment of water movement on a border strip in Northern Victoria, Australia. Oyonarte et. al. [14] estimated infiltration variability in blocked furrow irrigation systems by using the combination of variance techniques.

Previous researchers have utilized the volume-balance approach to predict runoff hydrographs from furrow irrigation only by assuming the shapes of the surface and subsurface water fronts. Such an assumption may giver erroneous values of runoff volumes. Furthermore, all researches have applied Manning’s formula at the head of the border or furrow, but no one has applied it at the end. In this research, two systematic procedures have been suggested to predict runoff discharges from border or furrow irrigation systems. The first procedure is based upon volume-balance principle and the other applies Manning's formula at the end of the border or furrow.

2. Border Irrigation Systems

Runoff from border strips can be prevented by using end blocks. Such a process, however, increases Irrigation Efficiency but reduces Distribution Uniformity. Thus, limited work can be found about runoff from border strip irrigation. In this research, two methods have been developed to predict runoff from graded border irrigation systems.

2-1 Volume–Balance Approach

The analysis of the runoff phase presented herein is based upon the volume balance principle, where the volume of water applied equal to the sum of surface and sub-surface stored volumes. **Figure (1)** is a schematic longitudinal section along a border strip during the advance and runoff phases and shows surface and sub-surface stored water at different time instants. The basic assumptions made are:

1. Inflow rate to the border is constant,
2. The border strip has a uniform slope and a prismatic cross section,
3. The time of advance down the border strip can be expressed as a power function of advanced distance [15].
4. The water front is assumed to be quarter of an ellipse whose center is at the beginning of the border strip [16], and
5. The border strip is infinite and any water passes the physical end of border is considered as runoff.

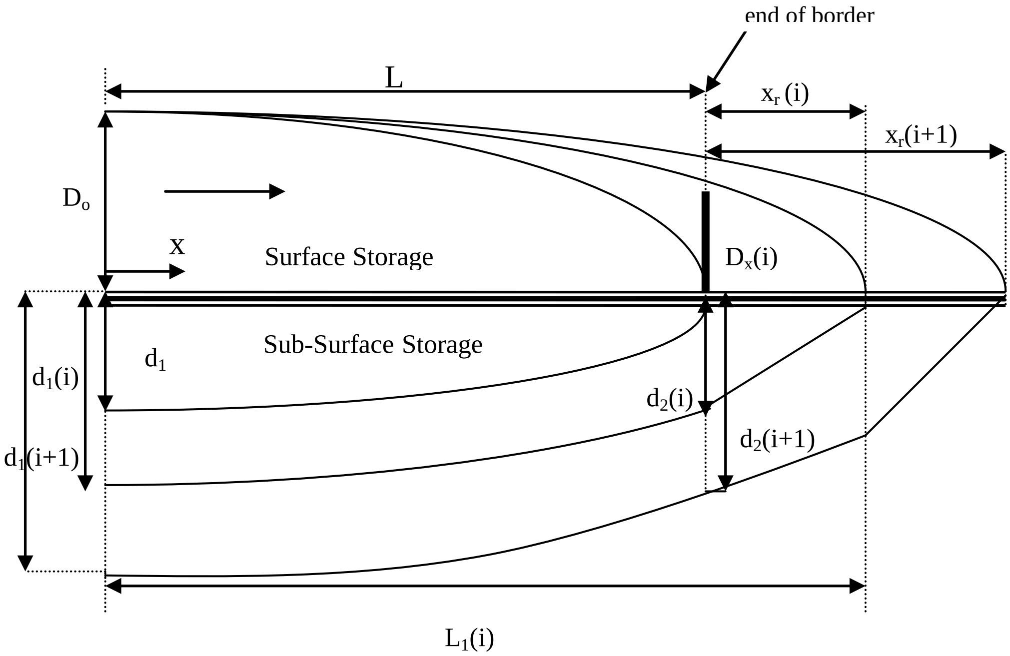


Figure (1) Longitudinal sections along a border (or furrow) strip during advance and runoff phases

2-1-1 Surface-Stored Water

The volume of water stored in the border strip (or furrow) is a function of water front profile, therefore:

$$\left(\frac{x}{L_1(i)}\right)^2+\left(\frac{D_x(i)}{D_0}\right)^2=1$$

Or

$$\mathbf{D_x(i)=D_0\sqrt{1-(\frac{x}{L_1(i)})^2}} \quad \ldots\ldots\ldots \mathbf{(1)}$$

where:

D_o: depth of flow at the head of the border (or furrow) and can be calculated from Manning's formula, m.

$D_x(i)$: depth of flow at any distance, x, during the runoff phase, m.

$L_1(i)$: total distance advanced during a given time $[t_a+\Delta t(i)]$, and equal to $[L+x_r(i)]$, m.

x: any given distance measured from the head of the border (or furrow), m.

i: an index, and

t_a: time required for the water to advance the whole length of run, min.

The time of advance can be expressed as a power function of advanced distance, as follows [15]:

$$\mathbf{T_x = a\,x^b} \quad \ldots\ldots\ldots \mathbf{(2)}$$

where:

a: coefficient of the empirical advance function.

b: exponent of the empirical advance function, and

T_x: time to advance any distance measured from the beginning of water application, min.

Thus, $x_r(i)$ can be calculated from Eq. (2) as follows:

$$\mathbf{x_r(i)=\left(\frac{t_a+\Delta t(i)}{a}\right)^{(1/b)}-L} \quad \ldots\ldots\ldots \mathbf{(3)}$$

where:

L: border (or furrow) length, m,

$x_r(i)$: distance measured from the end of border (or furrow) after a time $[t_a+\Delta t(i)]$, m, and

$\Delta t(i)$: a time increment during the runoff phase, min.

The total volume of surface-stored water per unit width of border would then be (**Fig.(1)**):

$$V_{sb}(i) = \int_{x=L}^{x=L_1(i)} D_x(i)\,dx \quad \ldots\ldots (4)$$

Substituting Eqs.(1) and (3) in Eq.(4) and integration from x = L to x = $L_1(i)$, the total volume of surface-stored water during a given time $[t_a + \Delta t(i)]$ would be:

$$V_{sb}(i) = \frac{D_0 L_1(i)}{2}\left[\frac{\pi}{2} - \frac{1}{2}\sin\left(2\sin^{-1}\left(\frac{L}{L_1(i)}\right)\right) - \sin^{-1}\left(\frac{L}{L_1(i)}\right)\right] \quad \ldots\ldots (5)$$

where:

$V_{sb}(i)$: total volume of surface-stored water in a border during a given time $[t_a + \Delta t(i)]$, m^3/m width.

2-1-2 Sub-Surface Stored Water

Sub-surface storage includes the volume of water infiltrated along border reach. The developed model is based upon Kostiakov's infiltration function which can be written as follows:

$$d = c_1\, t^{m_1} \quad \ldots\ldots (6)$$

where:

d: accumulated depth of infiltration, m,
c_1: coefficient of infiltration function,
m_1: exponent of infiltration function, and
t: time of infiltration, min.

The volume of sub-surface stored water during the first time interval, $\Delta t(i)$, after the beginning of runoff can be calculated by approximating the wetting front by a straight line as follows [6] (**Fig.(1)**):

$$V_{ib}(i) = c_1\,[\Delta t(i)^{m1}\, x_r(i)]\,/\,2 \quad \ldots\ldots (7)$$

During the following time intervals, the wetting front can be approximated by a number of straight lines connected together, and the total volume of sub-surface stored water would, thus, be:

$$V_{ib}(i) = \sum_{i=2}^{n_d}\sum_{j=2}^{i}\left[\left(\frac{c_1(\Delta t(j))^{m_1} + c_1(\Delta t(j-1))^{m_1}}{2}\right)\left(x_r(i+2-j) - x_r(i+1-j)\right)\right] \quad \ldots (8)$$

where:

$V_{ib}(i)$: volume of sub-surface stored water in a border during a time interval, $\Delta t(i)$, m^3/m width,
n_d: number of time increments, and
j: an index.

2-1-3 Runoff Discharge

The average runoff discharge during any time interval, $\Delta t(i)$, can be calculated from:

$$\mathbf{Q_{ra}(i) = (\frac{50}{3})\frac{V_{sb}(i)+V_{ib}(i)}{\Delta t(i)}} \quad \ldots\ldots\ldots\ldots \quad \mathbf{(9)}$$

where:

$Q_{ra}(i)$: average runoff discharge from a border during any time interval, $\Delta t(i)$, lps/m width.

2-2 Kinematic Approach

This technique is based upon the same assumptions adopted in the volume balance approach and in addition to those Manning's formula can be used to calculate runoff discharge at the end of the border.

The total distance advanced [6] during a given time $[t_a+\Delta t(i)]$, $L_1(i)$, can be calculated as shown before from Eqs.(2) and (3), since $L_1(i) = L + x_r(i)$. Therefore, the depth of surface storage at the end of the border at that moment, $D_x(i)$, can be calculated by using Eq.(1). The variation of this depth with time is relatively small, thus, the flow at the end of the border can be assumed steady over a short time interval. By doing so, and since $D_L(i)$ represents the depth of flow at the end of the border, Manning's formula can be applied to calculate the discharge which represents the runoff discharge after a time $[t_a+\Delta t(i)]$ from the beginning of irrigation, or a time, $\Delta t(i)$, from the beginning of runoff phase. Therefore:

$$\mathbf{Q_{ra}(i) = \frac{\sqrt{S_o}}{n}\frac{(w.D_L(i))^{5/3}}{(w+2D_L(i))^{2/3}}} \quad \ldots\ldots\ldots\ldots \quad \mathbf{(10)}$$

and when combined with Eq.(1) gives:

$$\mathbf{Q_{ra}(i) = \frac{\sqrt{S_o}}{n}\frac{\left(w.D_o\sqrt{1-(\frac{L}{L_1(i)})^2}\right)^{5/3}}{\left(w+2D_o\sqrt{1-(\frac{L}{L_1(i)})^2}\right)^{2/3}}} \quad \ldots\ldots\ldots\ldots \quad \mathbf{(11)}$$

where:

S_o: longitudinal slope of border strip, m/m,

n: Manning's roughness coefficient, and

w: border width, m, and

$D_L(i)$: depth of flow at end of the border (or furrow) during the advance phase, m.

This procedure can be repeated by selecting other time intervals, i.e., $2\Delta t(i), 3\Delta t(i)$, ………etc and the runoff discharge is calculated at each instant.

3. Furrow Irrigation Systems

An analysis similar to that used in border irrigation can be applied to furrow irrigation systems with two major modifications and these are:

1. Infiltration rates from furrows are calculated by using modified Kostiakov's intake function as was recommended by Al-Samerrai (1985).
2. Sub-surface water is distributed on a width equals the wetted perimeter of the furrow channel.

3-1 Volume–Balance Approach

The same assumptions adopted for border irrigation systems can be applied to furrow irrigation systems and the schematic longitudinal section shown in **Fig.(1)** can be used.

3-1-1 Surface–Stored Water

A typical furrow cross-section at any given point, x, is shown in **Fig.(2)**. As can be seen, the flow cross-sectional area would be:

$$\mathbf{A_x(i) = [B_o + z\, D_x(i)]\, D_x(i)} \quad \ldots\ldots \mathbf{(12)}$$

where:

$A_x(i)$: flow cross-sectional area at any given point, x, m^2,

B_o: bed width of a prismatic furrow channel, m, and

Z: side slope of a prismatic furrow channel.

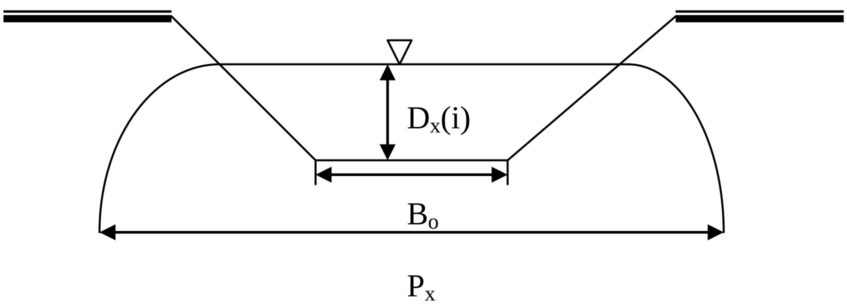


Figure (2) Typical cross-section of a furrow channel at given point, x, along the furrow

The volume of water stored in the furrow channel is a function of furrow geometry and water front profile, and the water front is assumed to be quarter of an ellipse with its center being at the beginning of the furrow channel as given in Eq.(1). The total volume of surface-stored water would be (**Fig.(1)**):

$$V_{sf}(i) = \int_{x=L}^{x=L_1(i)} A_x(i)\,dx \quad \text{.......... (13)}$$

Substitution of Eqs.(1) and (12) in Eq.(13), yields:

$$V_{sf}(i) = \int_{L}^{L_1(i)} \left(B_o + zD_o\sqrt{1-\left(\frac{x}{L_1(i)}\right)^2} \right)\left(D_o\sqrt{1-\left(\frac{x}{L_1(i)}\right)^2} \right) dx \quad \text{.......... (14)}$$

By integrating Eq.(14) from x = L to x = L_1(i), the total volume of surface-stored water during time [t_a+ Δt(i)] would be:

$$V_{sf}(i) = \begin{array}{l} \dfrac{B_oD_oL_1(i)}{2}\left[\dfrac{\pi}{2} - \dfrac{1}{2}\sin\left(2\sin^{-1}\left(\dfrac{L}{L_1(i)}\right)\right) - \sin^{-1}\left(\dfrac{L}{L_1(i)}\right)\right] + \\ zD_o^{\,2}\left[0.667L_1(i) - \left(L - \dfrac{L^3}{3L_1(i)^2}\right)\right] \end{array} \quad \text{.......... (15)}$$

where:

V_{sf}(i): total volume of surface-stored water in a furrow during a given time [t_a+ Δt(i)], m^3.

3-1-2 Sub-Surface Stored Water

Sub-surface storage includes the volume of water infiltrated along a furrow reach and can be calculated by using modified Kostiakov's intake which is:

$$I = K\, t_o^{\,n1} + c \quad \text{.......... (16)}$$

where:

I: instantaneous intake rate at any opportunity time, t_o, m/min,

K: coefficient of modified Kostiakov's intake rate function,

n1: exponent of modified Kostiakov's intake rate function,

c: basic intake rate, m/min, and

t_o: intake opportunity time at any point, min.

The accumulated depth of infiltration at any point, x, and any opportunity time, t_o, can be obtained by integrating Eq.(16), or:

$$d_i(i) = k\, t_o^{\,m} + c\, t_o \quad \text{.......... (17)}$$

where:

d_i(i): accumulated depth of infiltrated water at any point, x, during an opportunity time, t_o, m.

k: an empirical coefficient equal to $\dfrac{K}{n1+1}$, and

m: an empirical exponent equal to (n1 + 1).

The empirical advance function (Eq. 2) can be re-written as follows:

$$\mathbf{x = a_1\, T_x^{\,b1}} \quad \ldots\ldots \quad \mathbf{(18)}$$

where:

a_1: coefficient of the empirical advance function, and

b_1: exponent of the empirical advance function.

The time required for the water front to advance a total distance $L_1(\, i\,)$ is $T_1(i)$, which can be calculated from Eq.(2). Thus, Substituting t_o, T_x, and $T_1(i)$ in Eq.(17), yields:

$$\mathbf{d_1(i) = k\,(T_1(i) - a\,x^b)^m + c\,(T_1(i) - a\,x^b)} \quad \ldots\ldots \quad \mathbf{(19)}$$

The wetted width at a point, x, measured from the head would be (**Fig.(2)**):

$$\mathbf{Px(i) = Bo + 2\,Dx(i)\sqrt{1+z^2}} \quad \ldots\ldots \quad \mathbf{(20)}$$

which can be combined with Eq.(1) to yield:

$$\mathbf{P_x(i) = B_o + 2\,r\,D_o\sqrt{1-\left(\frac{x}{L_1(i)}\right)^2}} \quad \ldots\ldots \quad \mathbf{(21)}$$

where:

$P_x(i)$: wetted perimeter at any given distance, x, measured from the head of the furrow, m, and

r: side slope factor which is equal to $\sqrt{1+z^2}$.

Thus, the total volume of sub – surface storage (Figure 1) would be:

$$\mathbf{V_{if}(i) = \int_{x=L}^{x=L_1(i)} \left[d_i(i)P_x(i)\right] dx} \quad \ldots\ldots \quad \mathbf{(22)}$$

Substitution of Eqs.(19) and (21) in Eq.(22), gives:

$$\mathbf{V_{if}(i) = \int_{x=L}^{x=L_1(i)} \left[k(T_1(i)-ax^b)^m + c(T_1(i)-ax^b)\right]\left[B_o + 2rD_o\sqrt{1-\left(\frac{x}{L_1(i)}\right)^2}\,\right] dx} \quad \ldots \quad \mathbf{(23)}$$

By using binomial expansion, combining terms, and integrating from x = L to x = $L_1(i)$, it can be shown that:

$$\mathbf{V_{if}(i) = k B_o T_1(i)^m \Bigg[L_1(i)\left(1+\sum_{j=1}^{\infty}\frac{m(m-1)(m-2)\ldots\ldots\ldots(m-j+1)}{j!}\left(-\frac{a}{T_1(i)}\right)^j \frac{L_1(i)^{(jb)}}{(jb+1)}\right)}$$

$$-L\left(1+\sum_{j=1}^{\infty}\frac{m(m-1)(m-2).......(m-j+1)}{j!}\left(-\frac{a}{T_1(i)}\right)^j\frac{L_1(i)^{(jb)}}{(jb+1)}\right)\Bigg]$$

$$+\Big[c\,B_0\,T_1(i)\,\{L_1(i)-L\}\Big]-\Big[\frac{caB_o}{(b+1)}\{L_1(i)^{(b+1)}-L^{(b+1)}\}\Big]$$

$$+\ r.D_o k T_1(i)^m\Bigg[2L_1(i)\left(1+\sum_{j=1}^{\infty}\frac{m(m-1)(m-2)......(m-j+1)}{j!}\left(-\frac{a}{T_1(i)}\right)^j\frac{L_1(i)^{(jb)}}{(jb+1)}\right)$$

$$-2L\left(1+\sum_{j=1}^{\infty}\frac{m(m-1)(m-2)......(m-j+1)}{j!}\left(-\frac{a}{T_1(i)}\right)^j\frac{L_1(i)^{(jb)}}{(jb+1)}\right)$$

$$-L_1(i)\left(\frac{1}{3}+\sum_{j=1}^{\infty}\frac{m(m-1)(m-2)........(m-j+1)}{j!}\left(-\frac{a}{T_1(i)}\right)^j\frac{L_1(i)^{(jb)}}{(jb+3)}\right)$$

$$+\frac{L^3}{L_1(i)^2}\left(\frac{1}{3}+\sum_{j=1}^{\infty}\frac{m(m-1)(m-2)........(m-j+1)}{j!}\left(-\frac{a}{T_1(i)}\right)^j\frac{L_1(i)^{(jb)}}{(jb+3)}\right)$$

$$-\frac{L_1(i)}{4}\left(\frac{1}{5}+\sum_{j=1}^{\infty}\frac{m(m-1)(m-2)........(m-j+1)}{j!}\left(-\frac{a}{T_1(i)}\right)^j\frac{L_1(i)^{(jb)}}{(jb+5)}\right)$$

$$+\frac{L^5}{4L_1(i)^4}\left(\frac{1}{5}+\sum_{j=1}^{\infty}\frac{m(m-1)(m-2).......(m-j+1)}{j!}\left(-\frac{a}{T_1(i)}\right)^j\frac{L_1(i)^{(jb)}}{(jb+5)}\right)$$

$$-\frac{L_1(i)}{8}\left(\frac{1}{7}+\sum_{j=1}^{\infty}\frac{m(m-1)(m-2)...........(m-j+1)}{j!}\left(-\frac{a}{T_1(i)}\right)^j\frac{L_1(i)^{(jb)}}{(jb+7)}\right)$$

$$+\frac{L^7}{8L_1(i)^6}\left(\frac{1}{7}+\sum_{j=1}^{\infty}\frac{m(m-1)(m-2).........(m-j+1)}{j!}\left(-\frac{a}{T_1(i)}\right)^j\frac{L_1(i)^{(jb)}}{(jb+7)}\right)+.........\Bigg]$$

$$+\ \frac{2rcD_oT_1(i)L_1(i)}{2}\left[\frac{\pi}{2}-\frac{1}{2}\sin\left(2\sin^{-1}\left(\frac{L}{L_1(i)}\right)\right)-\sin^{-1}\left(\frac{L}{L_1(i)}\right)\right]$$

$$-2rcaD_o\Big[L_1(i)^{(b+1)}\left(\frac{1}{(b+1)}-\frac{1}{2(b+3)}-\frac{1}{8(b+5)}-\frac{1}{16(b+7)}+..................\right)-L^{(b+1)}$$

$$\left(\frac{1}{(b+1)}-\frac{L^2}{2L_1(i)^2(b+3)}-\frac{L^4}{8L_1(i)^4(b+5)}-\frac{L^6}{16L_1(i)^6(b+7)}+..................\right)\Big]\ ....\ (24)$$

where:

$V_{if}(i)$: volume of sub-surface stored water in a furrow during a given time $[t_a+\Delta t(i)]$, m^3.

3-1-3 Runoff Discharge

The average runoff discharge during any time increment, $\Delta t(i)$, can be calculated from:

$$\mathbf{Q_{fa}(i)} = \left(\frac{50}{3}\right)\frac{\mathbf{V_{sf}(i)+V_{if}(i)}}{\mathbf{\Delta t(i)}} \quad \text{...} \ \mathbf{(25)}$$

where:

$Q_{fa}(i)$: average runoff discharge in a furrow during any time increment, $\Delta t(i)$, lps.

3-2 Kinematic Approach

An analysis similar to that carried out for border irrigation can be applied to furrow irrigation to yield the average runoff discharge during any time interval, $\Delta t(i)$, as follows:

$$\mathbf{Q_{fa}(i)} = \frac{\sqrt{S_o}}{n}\frac{\left(B_oD_L(i)+zD_L(i)^2\right)^{5/3}}{\left(B_o+2D_L(i)\sqrt{1+z^2}\right)^{2/3}} \quad \text{..} \ \mathbf{(26)}$$

and when combined with Eq.(1) gives:

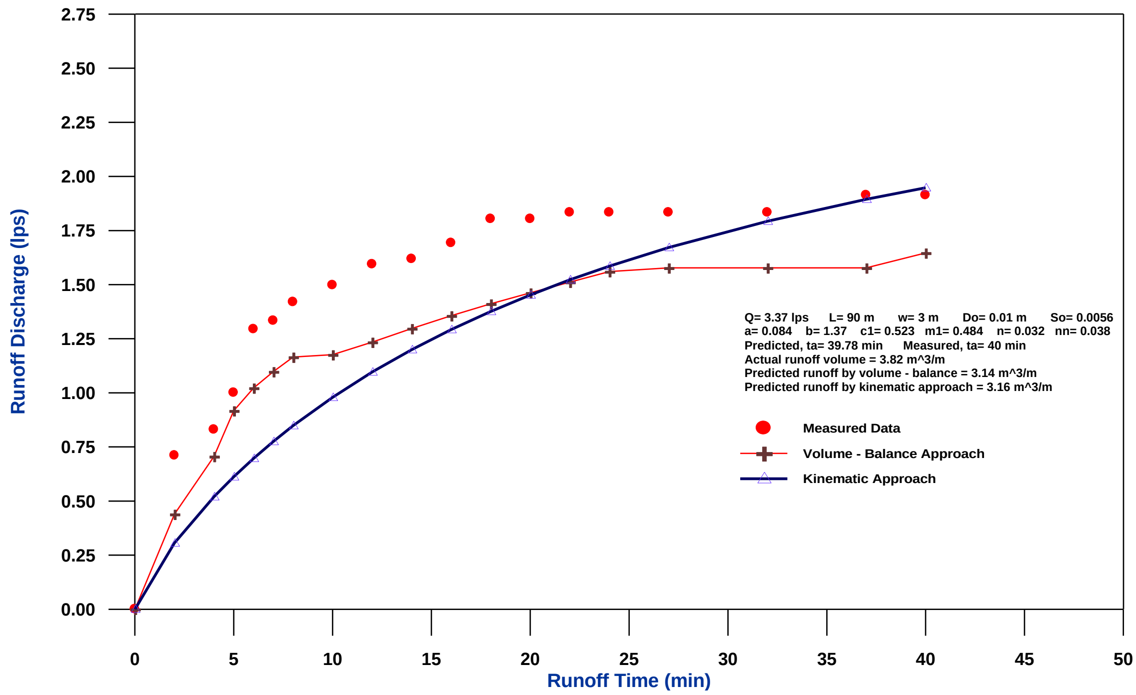
$$\mathbf{Q_{fa}(i)} = \frac{\sqrt{S_o}}{n}\frac{\left(B_oD_o\sqrt{1-\left(\frac{L}{L_1(i)}\right)^2}+zD_o^{\,2}\left[1-\left(\frac{L}{L_1(i)}\right)^2\right]\right)^{5/3}}{\left(B_o+2rD_o\sqrt{1-\left(\frac{L}{L_1(i)}\right)^2}\right)^{2/3}} \quad \text{.........................} \ \mathbf{(27)}$$

4. Results and Discussion

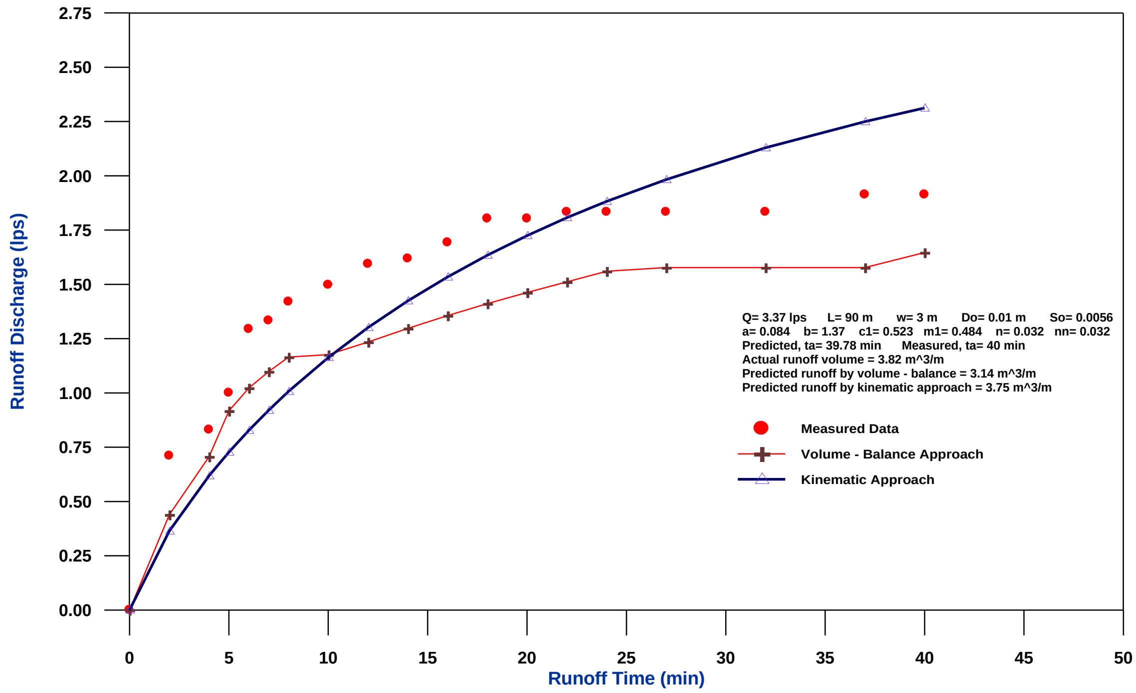
In order to check the accuracy of the developed procedures, gathered field data from References (7) and (12) have been used. Pertinent mathematical equations for the two procedures were first computerized to simplify the computational task, and then they were applied to actual field data.

Figures (3) and **(4)** show measured and predicted runoff hydrographs from graded border irrigation systems. Good agreement between measured and predicted runoff hydrographs can be noticed from the figures.

A slight underestimation of the runoff discharge predicted by the two procedures occurs, especially at the early stages of the runoff phase. Such an under estimation can be attributed to the two basic assumptions adopted in the derivation namely infinite border length and applicability of the empirical advance function on the whole length. However, the total volumes of measured and predicted runoff volumes are very close.

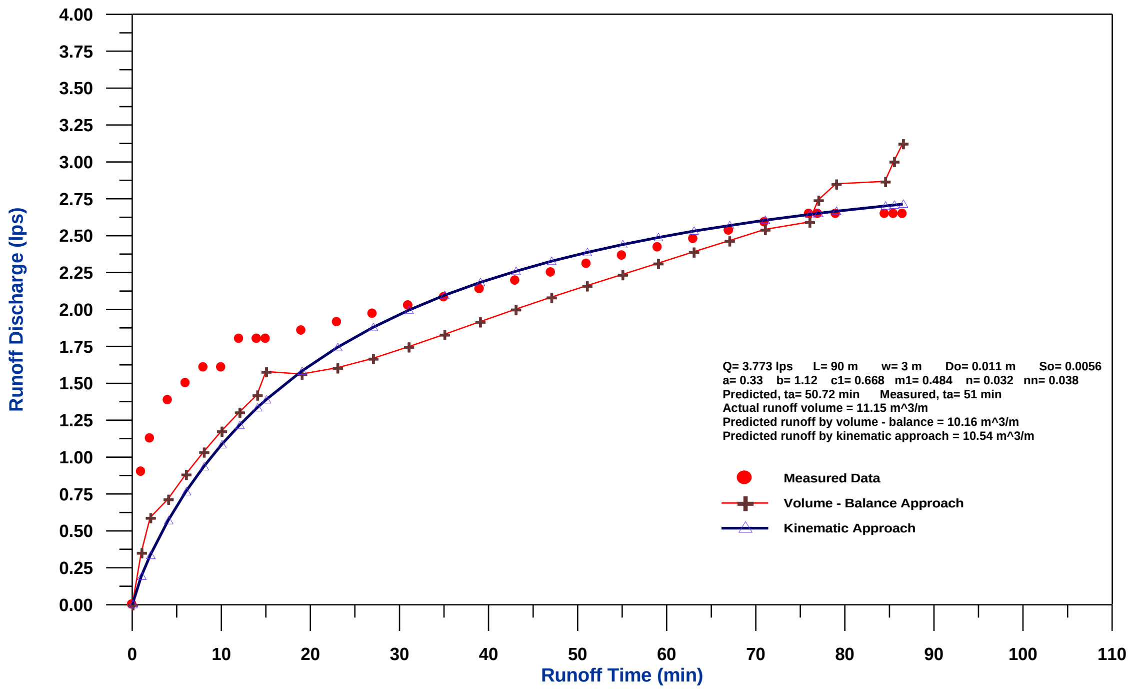


(a)

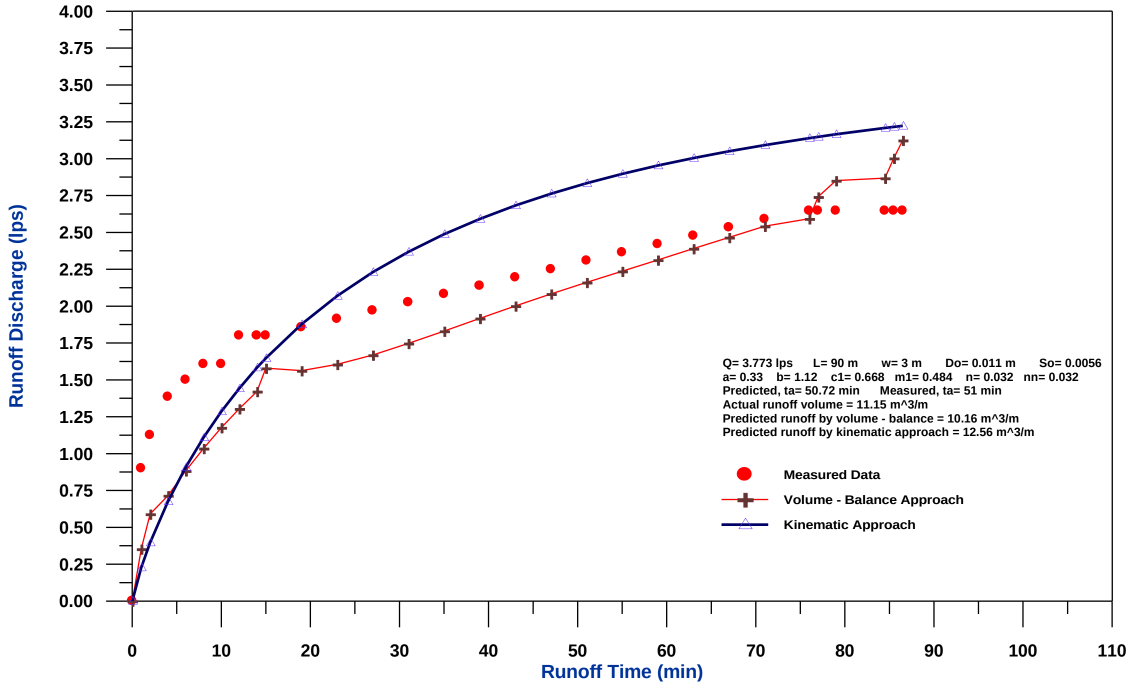


(b)

Figure (3) Predicted and measured border runoff discharges [Data were taken from Ref.(12) form No.1]



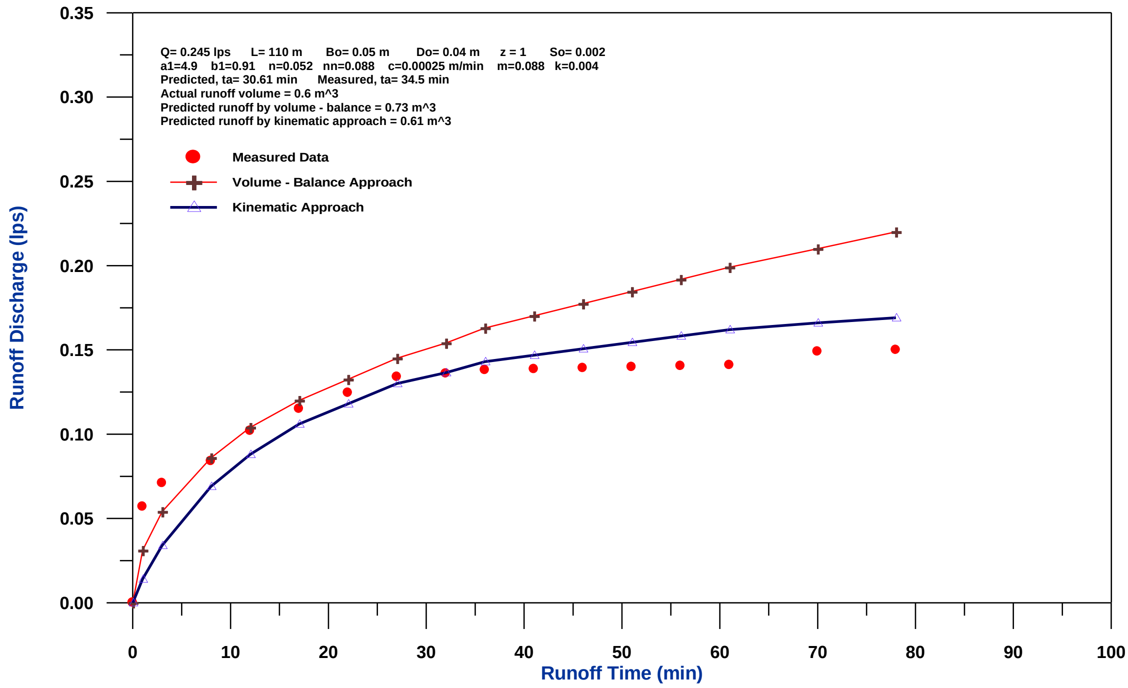
(a)



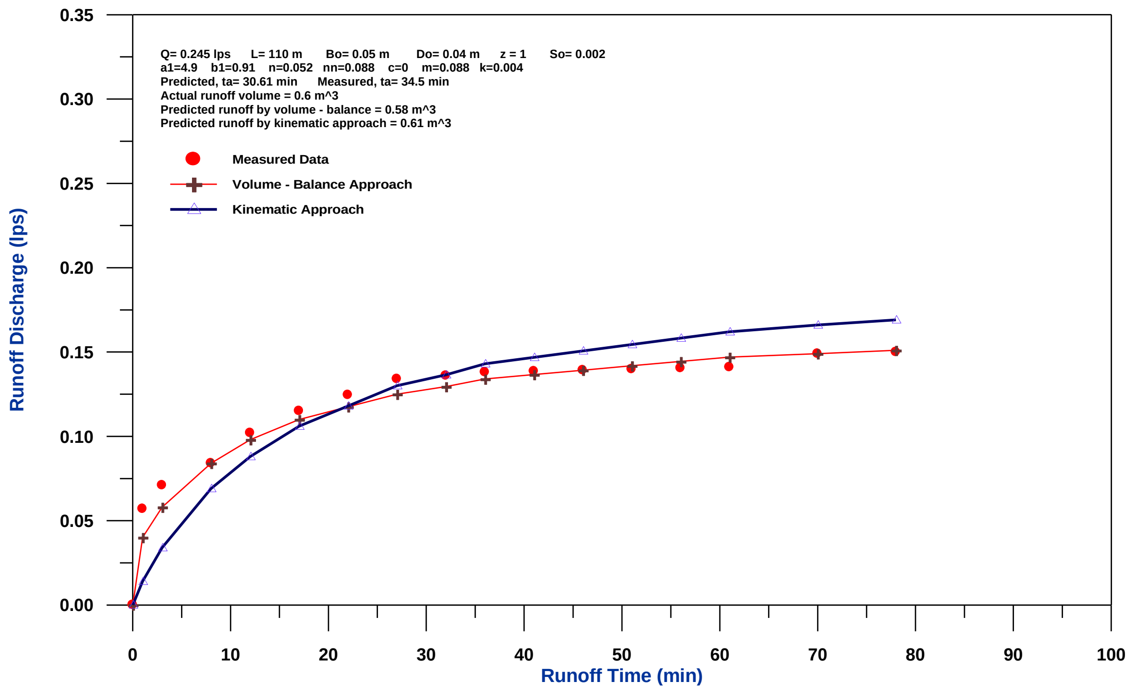
(b)

Figure (4) Predicted and measured border runoff discharges [Data were taken from Ref.(12) form No.3]

Figures (5) through **(7)** show measured and predicted runoff hydrographs from furrow irrigation systems. Again good agreement can be noticed between measured and predicted runoff hydrographs.



(a)



(b)

Figure (5) Predicted and measured furrow runoff discharges [Data were taken from Ref.(7) form I-3, No.8]

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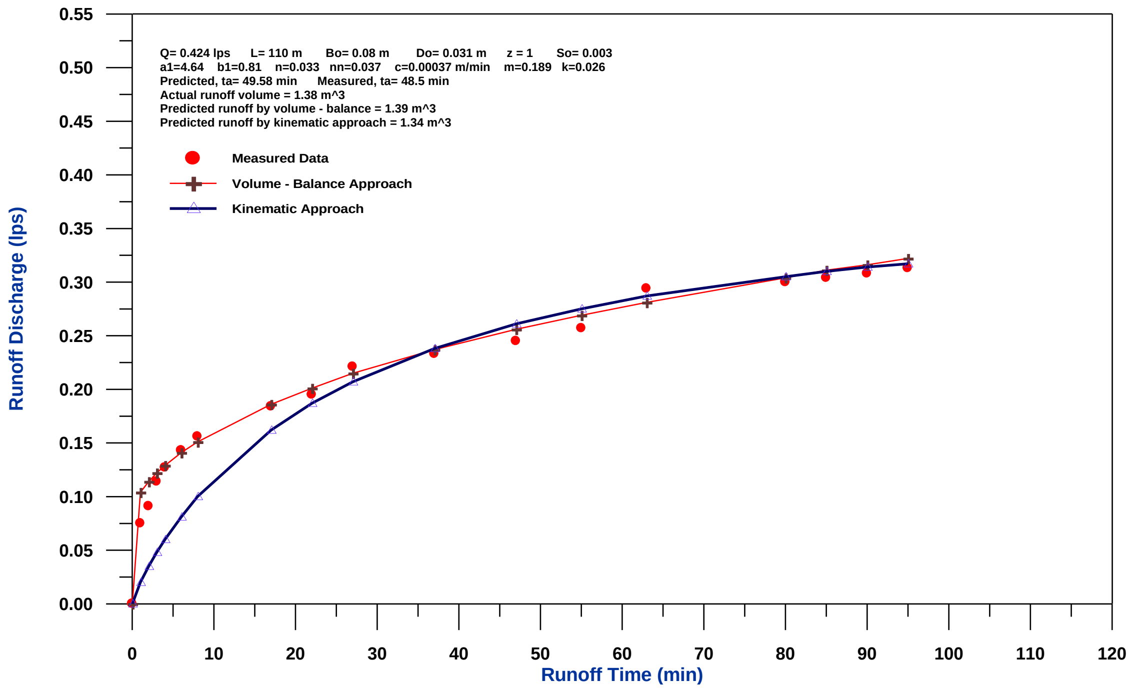
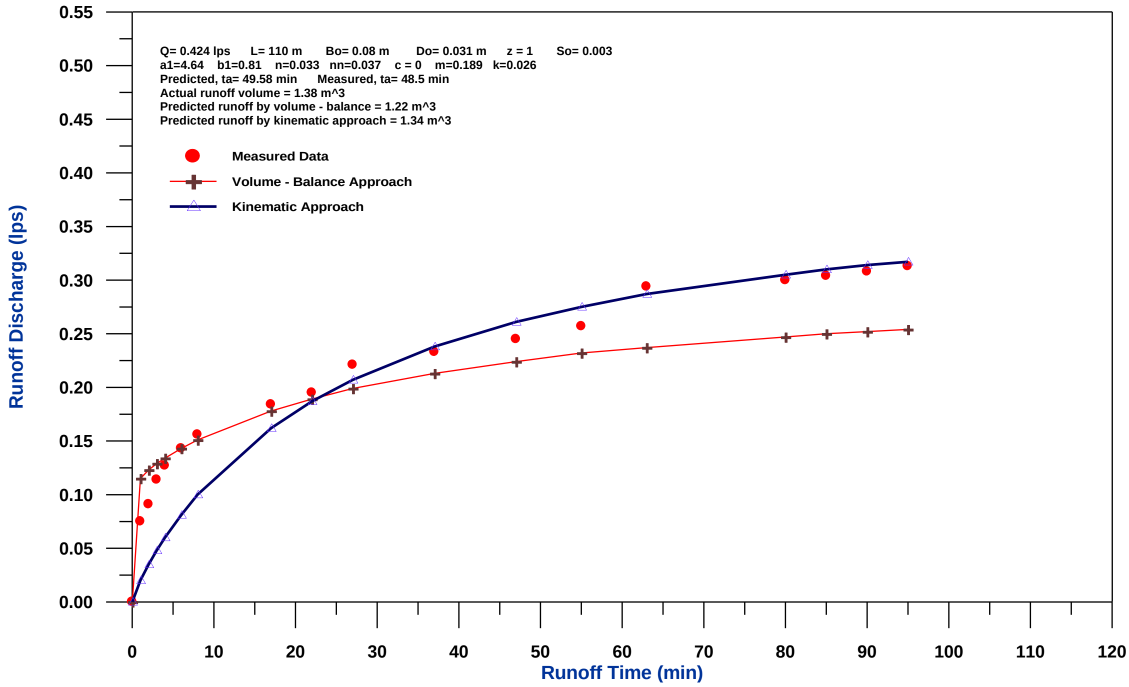
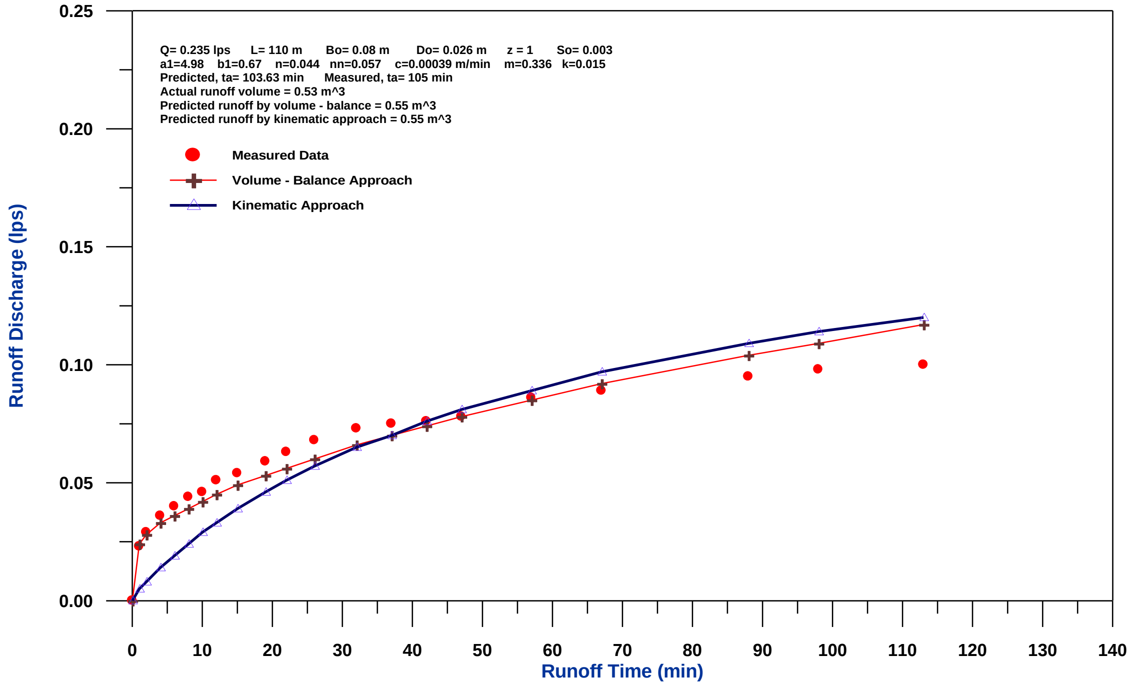


(a)

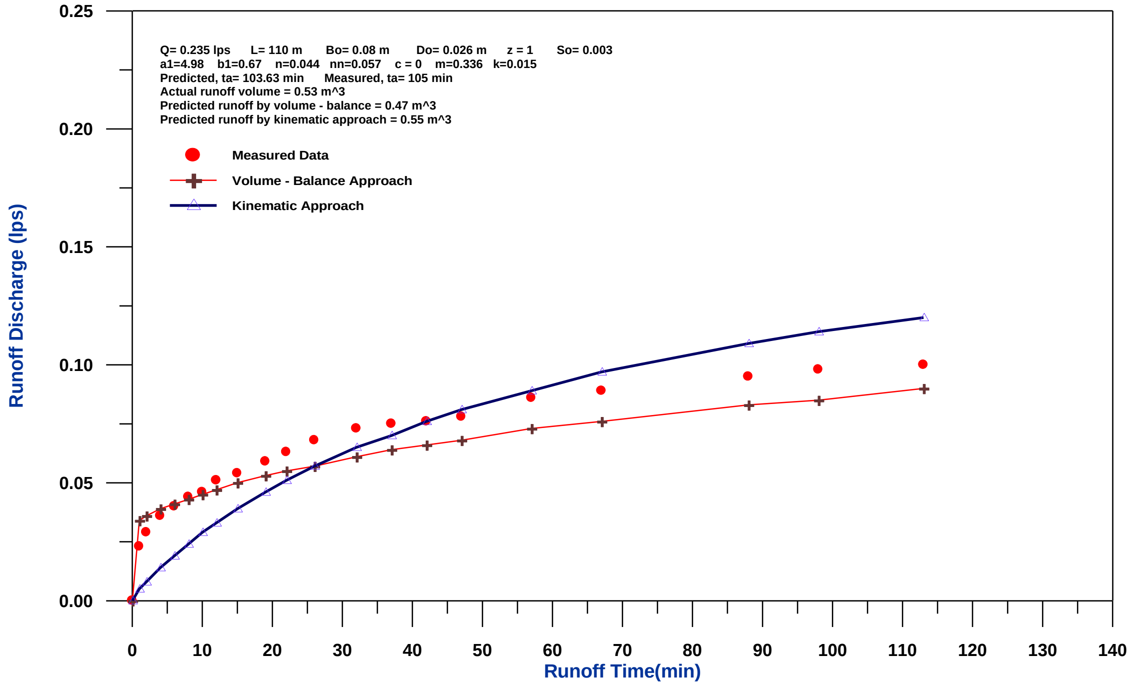


(b)

Figure (6) Predicted and measured furrow runoff discharges [Data were taken from Ref.(7) form I-4, No.7]



(a)



(b)

Figure (7) Predicted and measured furrow runoff discharges [Data were taken from Ref.(7) form I-8, No.7]

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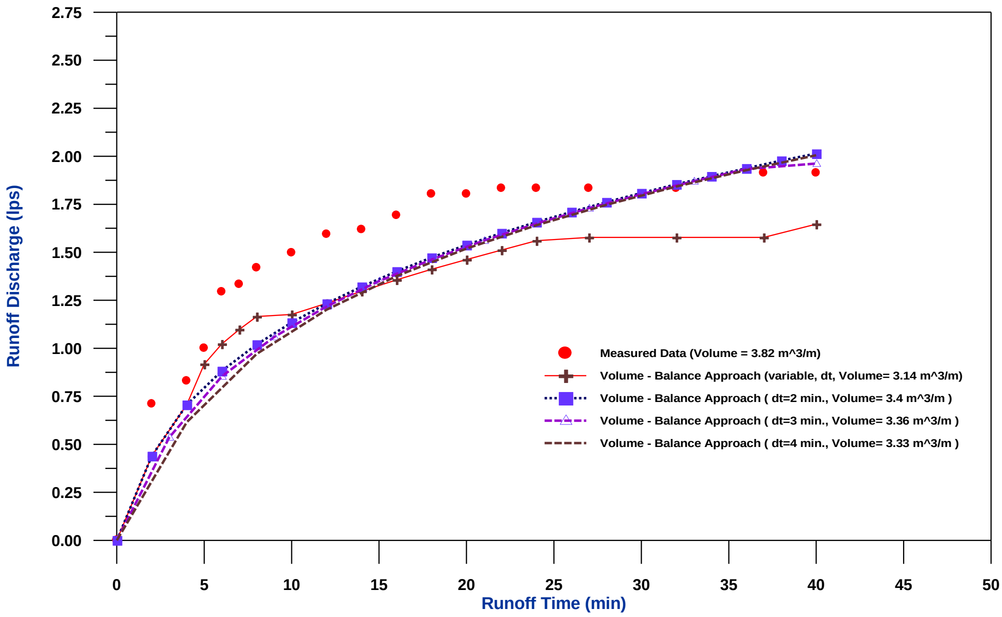
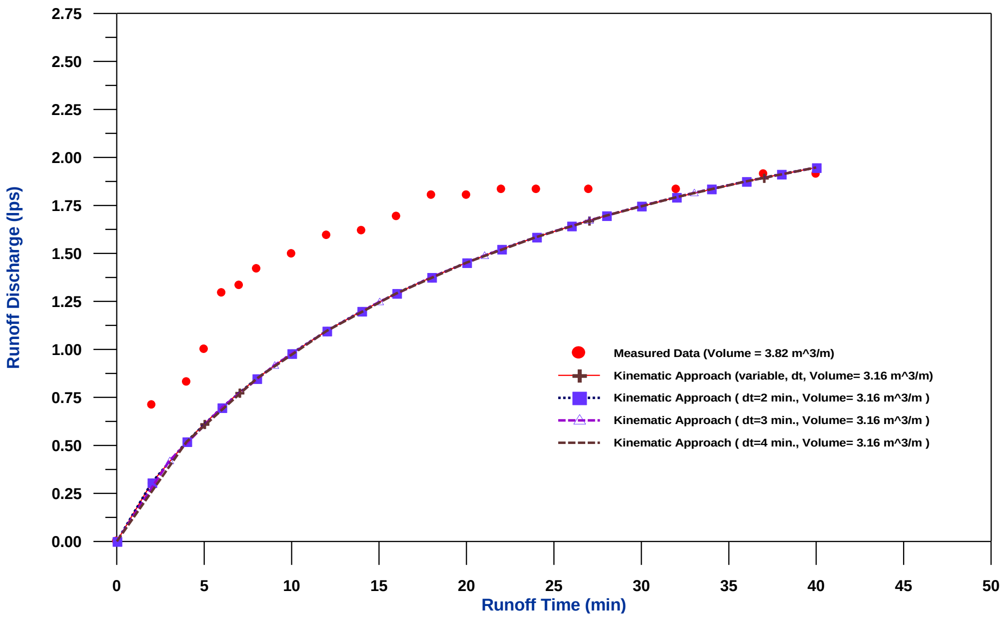
It is interesting to note from **Fig.(8)** that when a constant time increment, $\Delta t(i)$, is applied to both approaches, runoff hydrographs predicted by the two approaches coincide. Such a phenomenon occurs because of the reduction of numerical errors involved in the computational process. The time increments used in **Fig.(3)** through **(7)** were random and they were equal to the actual time increments used when conducting field experiments. Therefore, it can be concluded that a proper selection of the time increment greatly improves predicted runoff discharges.



(a) volume-balance approach



(b) kinematic approach

Figure (8) Comparison between measured data and predicted runoff hydrographs for border irrigation systems for different time increments [Data were taken from Ref.(12) form No.1]

5. Summary and Conclusions

In this research, two new procedures have been developed to predict runoff hydrographs from graded border and furrow irrigation systems. One of the procedures is based upon volume balance principle and the other is based upon the application of Manning's formula (kinematic approach).

The results of the two procedures were compared with actual measured field data from References (7) and (12) and good agreement has been noticed between measured and predicted runoff discharges. Also, it has been found that the results of the two procedures coincide with each other through a proper selection of the time increment. The developed procedures can be used to execute proper designs of graded border or furrow irrigation systems.

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Notations

The following symbols are used in this paper:

$A_x(i)$: Flow cross-sectional area at any given point, x, m^2,
a: Coefficient of the empirical advance function,
a_1: Coefficient of the empirical advance function,
B_o: Bed width of a prismatic furrow channel, m,
b: Exponent of the empirical advance function,
b_1: Exponent of the empirical advance function,
c: Basic intake rate, m/min,
c_1: Coefficient of infiltration function,
D_o: Depth of flow at the head of the border (or furrow) and can be calculated from Manning's formula, m,
$D_L(i)$: Depth of flow at end of the border (or furrow) during the advance phase, m,

$D_x(i)$: Depth of flow at any distance, x, during the runoff phase, m,
d: Accumulated depth of infiltration, m,
$d_i(i)$: Accumulated depth of infiltrated water at any point, x, during an opportunity time, t_o, m,
I: Instantaneous intake rate at any opportunity time, t_o, m/min,
i: An index,
j: An index,
K: Coefficient of modified Kostiakov's intake rate function,
K: An empirical coefficient equal to $\frac{\mathbf{K}}{\mathbf{n1+1}}$,
L: Border (or furrow) length, m,
$L_1(i)$: Total distance advanced during a given time $[t_a + \Delta t(i)]$, and equal to $[L + x_r(i)]$, m,
m: An empirical exponent equal to (n1 + 1),
m_1: Exponent of infiltration function,
n: Manning's roughness coefficient,
nn: Manning's roughness coefficient during the runoff phase,
n_d: Number of time increments,
n1: Exponent of modified Kostiakov's intake rate function,
$P_x(i)$: Wetted perimeter at any given distance, x, measured from the head of the furrow, m,
$Q_{fa}(i)$: Average runoff discharge from a furrow during any time increment, $\Delta t(i)$, lps,
$Q_{ra}(i)$: Average runoff discharge from a border during any time interval, $\Delta t(i)$, lps/m width,
r: Side slope factor which is equal to $\sqrt{1+z^2}$,
S_o: Longitudinal slope of border strip, m/m,
T_x: Time to advance any distance measured from the beginning, min,
t: Time of infiltration, min,
t_a: Time to advance the border (or furrow) length, min,
t_o: intake opportunity time at any point, min,
$V_{ib}(i)$: Volume of sub-surface stored water from a border during a time interval, $\Delta t(i)$, m^3/m width,
$V_{if}(i)$: Volume of sub-surface stored water from a furrow during a given time $[t_a+\Delta t(i)]$, m^3,
$V_{sb}(i)$: Total volume of surface-stored water from a border during a given time $[t_a+\Delta t(i)]$, m^3/m width,
$V_{sf}(i)$: Total volume of surface-stored water from a furrow during a given time $[t_a+\Delta t(i)]$, m^3,
w: Border width, m,
x: Any given distance measured from the head of the border (or furrow), m,
$x_r(i)$: Distance measured from the end of border (or furrow) after a time $[t_a+\Delta t(i)]$, m,
z: Side slope of a prismatic furrow channel, and
$\Delta t(i)$: A time interval during the runoff phase, min.