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Research Article

STAGE-DISCHARGE RELATIONSHIP FOR IRRIGATION CHANNELS

KAPIL ROHILLA*
Haryana Space Application Centre, (HARSAC), Hisar, 125004, India
*Corresponding Author: Email - rohilla21@gmail.com

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Abstract: In this study, a numerical model was used to derive rating curves for irrigation channels and the Saint Venant and sediment continuity equations were solved by using MacCormack scheme based on finite difference method to analyse the overland flow and sediment transport. Richard's equation was used to analyse the subsurface flow, which was solved by using mass-conservative fully implicit finite-difference method.

Keywords: *Aggradation, Degradation, Infiltration, Irrigated channels*

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Introduction

Irrigated channels are commonly used for surface irrigation, particularly in developing countries like India. Stage-Discharge relation is often used for the management of irrigation system in irrigation channels. Rate of flow significantly affects the uniform distribution of flow along the channel length. Fertilizers and nutrients necessary for crops attached to soil surface are transported along the channel by the irrigated flow. Sediment laden water is often supplied directly from rivers or canals to the farm through irrigation channels. Therefore, the deposition takes place along the length of irrigation channels. Many a times, water from the wells, which is sediment free, is also used for irrigation. It is supplied at the inlet of irrigation channels. In such situations, the water flow has high tractive force and low sediment load at the inlet of irrigation channel.

Consequently, erosion takes place at the upstream reaches of irrigation channel due to flowing water. Efficient nutrients delivery to crops requires accurate predictions of flow and sediment transport in irrigation channels. Rating curve maintains uniformity of flow in irrigation channel during irrigation and provides stage corresponding to particular discharge, which is essential for maintaining uniform depth of flow along length of the irrigation channels. The sediment transport in an irrigation channel depends on the rating curve, infiltration rate, slope and length of the field, size of the sediment and sediment carrying capacity of the channel. Since water flows along the irrigation channel, the flow rate decreases with distance due to infiltration [1-4]. Therefore, it is imperative to have a thorough understanding of infiltration effect on rating curve and its quantification from irrigation channels to provide advice for proper flow and irrigation management.

Various numerical models have been used for estimating the sediment transport in irrigation channels [5-12]. Bjorneberg *et al*. (2006) observed that the concentration of dissolved reactive phosphorus (DRP) increased with distance and decreased with time and infiltrates. Based on several hypothetical dam failure cases, Mohapatra (2007) [13] developed rating curves for dam-break flows. It was found that the area of non-dimensional loop is decreased as the flood wave moved down stream reaches and increased with breach width. Raghuwanshi *et al*. (2011) [14] measured the Kostiakov infiltration model parameters by using the waterfront advance data with the method of one and two points at 50, 75 and 100% of the border length.

They also compared the various irrigation efficiencies such as inflow volume, application efficiency, tail to water ration, deep percolation ration and low quarter distribution uniformity. The efficiencies were obtained by using two points method, giving better results as compared to one point method. They also found that the coefficient of Kostiakov infiltration model decreased along the border length and exponent had no fixed pattern. The infiltration parameters were estimated by 75% of the field length, giving better irrigation performance. Also, a cutoff strategy was arrived based on advancement of wetting front by 75% of the field length.

This strategy not only reduced the deep percolation loss but also increased the application efficiency. Zhang *et al*. (2012) developed a numerical model to simulate unsteady flow, sediment transport and infiltration in irrigation furrows by using the modified St. Venant equations. They used Kostiakov equation to compute infiltration. Mailapalli *et al*. (2013) developed a furrow irrigation model with a steady state sediment transport. They also used various infiltration models such as Kostiakov-Lewis, 1D-Green Ampt and 2D-Fok for calculating the infiltration.

Greco (2015) [15] proposed a one-dimensional (1D) entropy-based model for evaluating the water discharge in rough and smooth irrigation channels based on relative submergence. He proposed that corresponding to low flow depth entropy parameter for flow in the presence of high and intermediate roughness depends on the relative submergence. Laboratory experiments were carried out to assess the performance of model.

Many of these studies are either experimental or considered simpler analytical equations for treating the infiltration term. In this study, a comprehensive numerical model was used by coupling Saint-Venant's equation governing overland flow with Richard's equation governing vertical flow through subsurface and sediment continuity equations. In irrigation channels, the rating curve played a vital role in maintaining uniformity of flow in channel, especially when the soil is dry and needs to be determined accurately. The objectives of the study were (i) to develop a rating curve for irrigation channel.

Governing Equations

Sediment transport in irrigated channels is often analysed by solving coupled differential equations governing overland flow and subsurface flow along with sediment continuity equation.

In the present study Saint Venant and sediment continuity equations are used to analyse overland flow and sediment transport, while Richard's equation is used to analyse subsurface flow.

Overland Flow

The partial differential equations governing overland in an irrigated channel (Bhallamudi and Chaudhry 1991) are;

Continuity equation for water

$$\frac{\partial h}{\partial t}+\frac{\partial q}{\partial x}+I=0 \tag{1}$$

Momentum equation for water

$$\frac{\partial q}{\partial t}+\frac{\partial}{\partial x}\left(\frac{q^2}{h}+\frac{gh^2}{2}\right)+gh\frac{\partial z}{\partial x}+ghs_f=0 \tag{2}$$

Where q =water discharge per unit width, h=flow depth, s_f=friction slope, n=Manning roughness coefficient, I =volumetric rate of infiltration per unit area. χ is the space co-ordinate and t is the time co-ordinate. The friction slope in momentum equation (2) is determined by Manning equation

$$s_f=\frac{q^2n^2}{h^{3.33}} \tag{3}$$

Sediment transport equation

Sediment continuity equation can be represented as:

$$\frac{\partial}{\partial t}\left[(1-p)z+\frac{q_s h}{q}\right]+\frac{\partial q_s}{\partial x}=0 \tag{4}$$

Where z = bed elevation; q_s = unit sediment discharge; g = acceleration due to gravity and p= porosity of bed.

In the present study, sediment discharge (q_s) is estimated by an empirical power function of the flow velocity (Colby 1991) [16] as

$$q_s=a\left(\frac{q}{h}\right)^b \tag{5}$$

Where a, b are empirical constants whose values depend on the sediment size.

Subsurface Flow

To compute the sink term I present in continuity equation [Eq-1], one needs to know the amount of water infiltrated into the ground. In this study, for the analysis of infiltration process,

Richard's equation governing vertical flow in the unsaturated zone is adopted [17]. The mixed form of Richard's equation [18] for one dimensional vertical flow can be written as

$$\frac{\partial}{\partial z}\left[K(\psi)\left(\frac{\partial \psi}{\partial z}+1\right)\right]=\frac{\partial \theta}{\partial t} \tag{6}$$

Where, ψ = pressure head, θ= volumetric moisture content, K= hydraulic conductivity, Z= vertical co-ordinate taken positive upwards, and t = time co-ordinate. [Eq-6] is nonlinear in nature, because, both the flow and storage properties (K and θ) are function of the dependent variable ψ and its solution requires constitutive relationships for θ -ψ and θ - K. In the present study, the relationships proposed by Van Genuchten (1980) [19] are adopted for θ -ψ and θ - K relationships. The θ -ψ relationships is described as follows.

$$S_e=\left[\frac{1}{1+\left(\alpha_v|\psi|^{n_v}\right)}\right]^{m_v} \quad \text{for } \psi<0$$

$$S_e=1 \quad \text{for } \psi\geq 0 \tag{7}$$

Where α_v and n_v are unsaturated soil parameters with $m_v=1-(1/n_v)$, $n_{v>1}$ and S_e = effective saturation defined as

$$S_e=\frac{(\theta-\theta_r)}{(\theta_s-\theta_r)}$$

Where θ_s and θ_r are saturated moisture content and residual moisture content of the soil respectively.

The K- θ relationship is described as follows

$$K=K_sS_e^{1/2}\left[1-\left(1-S_e^{1/m_v}\right)^{m_v}\right]^2 \quad \text{for } S_e\leq 1$$

$$K=K_s \quad \text{for } S_e=1 \tag{8}$$

Where K_s = saturated hydraulic conductivity of the soil.

Numerical Scheme

[Eq-1, 2, 4 and 6] are a set of nonlinear equations, and closed-form solutions are available only for idealized cases and one has to resort to numerical schemes for solution to be applicable for practical situations. In the present study, MacCormack finite difference scheme (Bhallamudi and Chaudhry 1991) is used for solving overland flow and sediment continuity equations, [Eq-1, 2, and 4] and a mass conservative fully implicit finite difference numerical scheme (Celia *et al.* 1990) is used for solving subsurface flow equation, [Eq-6]. The details of numerical scheme are given in Rohilla *et al.* (2016) [20].

The length of the irrigated channel is divided into uniform segments of length Δx along the x direction. The overland flow and sediment continuity equations [Eq-1, 2, and 4] are solved numerically using MacCormack scheme to obtain the flow depth at each surface nodal point. Having obtained the flow depths at each of the surface nodal points, this depth is imposed as the driving head to analyze the moisture flow through the subsurface by solving the Richard's equation [Eq-6] along the numerical grid below the surface nodal points. The numerical grid is divided into uniform segments of length Δz along z direction. Having obtained the pressure heads in the subsurface nodal points, the infiltration rate I in [Eq-1] is computed at each surface node by applying Darcy's law between the surface node and the node immediately below the surface node, and [Eq-1, 2, and 4] are solved for q,h and z. The process of solving overland flow and Richard's equation is continued iteratively until the difference between computed flow depths of two successive iterations falls below a specified tolerance level.

Results and discussion

Various numerical simulations were carried out to develop stage-discharge relationship for the irrigation channel.

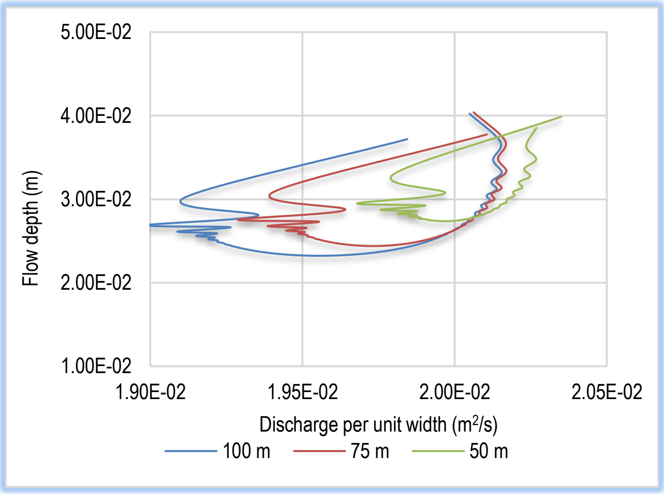

Fig-1 Rating curve at various locations due to irrigated flow

This stage-discharge relationship for irrigation channel was not a single value relation though it was a looping curve as in [Fig-1], which provides rating curves along the channel length at various locations. As the wetting front moved from upstream to downstream reaches of channel, the rate of flow reduced due to infiltration along the channel length.

It can be seen from [Fig-1] that the area of looping curve was smaller at upstream section (50 m) as compared to downstream section of channel (100 m), which represents the dynamic behavior of flow in channel during the process of advance and recession phase. Rate of flow was greater and changing dynamically for looping curve at location of 50 m as compared to looping curve at locations of 75 and 100 m.

Conclusion

The rating curve was derived from the simulation of hypothetical irrigation channel by coupling equations governing overland flow (Saint Venant's equation) and sediment continuity with Richard's equation, which governs subsurface flow. The numerical model used MacCormack scheme for solving overland flow and a mass-conservative fully implicit scheme for solving subsurface flow.

Application of research: The above equations were applied to study the effect of infiltration on rating curve in irrigation channels. Area of looping curve is function of length of irrigated channel. It is lower at upstream section of channel, whereas it is greater at downstream section of channel.

Research Category: Irrigated channels

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