Using simulation modelling to improve the design and management of furrow irrigation in smallholder plots.

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Abstract

Over 70 % of all irrigated land in Sub-Sahara Africa is currently under surface irrigation. However, the performance of surface irrigation in this region is often low resulting in significant deep drainage losses and sustainability concerns. This is of a particular concern for tenant based large scale irrigation scheme located in arid and semi-arid areas which are prone to salinity and drainage problems. Field design and irrigation management practices have a significant impact on performance but have received only limited consideration to date. Externally funded irrigation projects in the region are usually constructed using generic design parameters with limited or no analysis of local soil and operational conditions. Similarly, irrigation design and management guidelines for in-field irrigation management are generally lacking due to the high cost and time involved in obtaining data for traditional evaluations. This paper uses data collected from small-holder irrigation plots in the Tana River Basin to demonstrate the benefits of using the simulation program SIRMOD to evaluate the performance of surface irrigation practices. It also discusses the benefits of simulation modelling for identifying irrigation performance indices and guidelines for improving the design and management practices of small-holder irrigation plots.

Keywords: Agricultural water management; furrow irrigation; modeling

1.0 Introduction

Over 70% of irrigated land is currently under surface irrigation in Sub-Sahara Africa (SSA) and it seems likely to continue to be widely practised for the foreseeable future. However, the performance of surface irrigation in this region is often low resulting in significant deep drainage losses and sustainability concerns (Gichuki 1996; Kandiah 1997; Kirpich et al. 2000). This is of a particular concern for tenant-based irrigation schemes located in arid and semi-arid areas (Hughes 1984; Maingi & Marsh 2001; Ledec 1987) which are prone to salinity and drainage problems (Bakker et al. 2006).

Field design and irrigation management practices have a significant impact on surface irrigation performance (Clemmens 2000; Horst 1998; Raine et al. 1998) but have received only limited consideration to date (Horst 1998). Improper design and management of furrow irrigation systems may result in water wastage, water-logging and losses of fertilisers and pesticides out of root zones. Externally funded irrigation projects in the SSA region are usually constructed using generic design parameters with limited or no analysis of local soil and operational conditions (Horst 1998). Similarly, irrigation design and management guidelines for infield irrigation management are generally lacking due to the high cost and time involved in obtaining and analysing data for traditional evaluations.

Furrow irrigation system design and management parameters which can be altered by farmers with little effort and cost include inflow rates and irrigation cut-off time (Walker & Skogerboe 1987; Zerihun et al. 2001). Traditionally, inflow rates and cut-off time are determined at the beginning of the irrigation growing season. Farmers are often guided by previous irrigation experiences in making decisions regarding these parameters and often, where experience is lacking, identification and adoption of appropriate management practices is difficult. It is also common for farmers to make decisions on cut-off based on how long water is made available by the managing statutory authorities. Hence, farmers often irrigate for longer than is necessary.

The use of simulation models to develop irrigation guidelines for design and management practices provides opportunities for advisors and farmers to make more informed and timely irrigation decisions. The objective of this paper is to demonstrate the potential to use simulation modelling to improve the performance of surface irrigation practices using data collected from smallholder irrigation plots in the Bura Irrigation Scheme, Kenya.

2.0 Methods and Materials

2.1 Field data

The field data used in this evaluation was obtained from Mwatha and Gichuki (2000) who conducted furrow irrigation trials in the Bura Irrigation Scheme, Kenya. The Bura Irrigation Scheme is located in the Tana River Basin and was initially developed in 1979 to settle landless farmers and grow irrigated cotton for export. The Bura area is located at latitude 10^{o} 8’S and longitude 39^{o} 45’ E and has an elevation of 110 m above sea level. The mean annual rainfall and evaporation are 400 and 2490 mm, respectively. The rainfall is bimodal, with long rains occurring in March to May and short rains occurring in November to December. Soils in the Bura area are shallow sandy clay loams and heavy cracking clays overlying saline and alkaline sub-soils of low permeability (Mwatha & Gichuki, 2000).

The irrigation water in the Bura Irrigation Scheme is pumped from the Tana River into settling basins and main scheme canals before being siphoned into 0.9 m spaced furrows within the small-holder irrigation fields. Mwatha and Gichuki (2000) reported data for two irrigations (fifth irrigation is considered in this paper) during the 1989 growing season from four irrigated cotton fields (lengths of 275-300 m). Furrow characteristics, soil moisture content and irrigation parameters data were collected from February to October 1989 when cotton was growing. The evaluation data were obtained from four fields with average slopes of 0.09, 0.13, 0.25 and 0.31 % denoted in this paper as 9S, 13S, 25S and 31S, respectively. Within each field there were three inflow rate treatments (1.5, 2.0 and 3.0 L s^{-1} $furrow^{-1}$) and data were collected from four furrows in each treatment. Inflow was measured using Parshall flumes spaced at 50 m intervals along the furrows and for the purpose of this analysis it was assumed there was no inflow variability. All data were collected from plots located on the same soil type (Mwatha and Gichuki, 2000). The fifth irrigation had a deficit of 63 mm as measured by the difference in the volumetric soil moisture content taken at 50 m distances along the field before the irrigation and two days after irrigation (Mwatha and Gichuki, 2000). Table 1 shows the measured furrow characteristics while the irrigation inflow and advance parameters for the four fields are given in Table 2.

Table 1: Geometry characteristics for furrows in the Bura Irrigation Scheme (from Mwatha and Gichuki, 2000)

Parameter	Value
Furrow length	275-300m
Furrow spacing	0.9 m
Furrow slope	0.05 %- 0.3%
Cross-section	parabolic
Top-width (T) ^{A}	$T= 2.8y^{0.62}$
Wetted perimeter (wp) ^{A}	$wp=2.8y^{0.65}$
Area of flow ^{A}	$A=1.48y^{1.55}$

^{A} y is the depth of flow

Table 2: Advance parameters for the fifth irrigation event, Bura Irrigation Scheme (from Mwatha and Gichuki, 2000)

Slope (%)	**Inflow ($L\ s^{-1}$)**	**Advance parameters**		
		p	***r***	**t_L (mins)**
0.09 (S9)	1.5	12.7	0.49	572
	2.0	6.1	0.67	308
	3.0	10.2	0.57	345
0.13 (S13)	1.5	12.6	0.56	262
	2.0	11.3	0.57	290
	3.0	18.3	0.53	177
0.25 (S25)	1.5	13.5	0.56	231
	2.0	22.2	0.46	256
	3.0	16.2	0.61	110
0.31 (S25)	1.5	16.5	0.55	179
	2.0	17.9	0.53	186
	3.0	13.4	0.68	90

2.3 Infiltration parameters

Infiltration parameters for the furrows were estimated using an inverse solution technique and the software INFILT (McClymont and Smith, 1996). This software is designed to calculate soil infiltration parameters using only inflow and advance data and has been used over a range of soils and situations (Bakker et al., 2006; Khatri and Smith, 2005; Smith et al., 2005; Raine et al., 2005). The soil infiltration characteristics are derived from the advance trajectory assuming a power advance function (Walker and Skogerboe, 1987):

$$x = p(t_a)^r \qquad \text{Equation 1}$$

where t_a is the time taken for the water to reach advance distance x, and p and r are fitted advance parameters. INFILT calculates the soil infiltration characteristics from the fitted power curve parameters based on the equivalent furrow infiltration Kostiakov-Lewis equation:

$$z = k(\tau)^a + f_o(\tau) \qquad \text{Equation 2}$$

where z is the cumulative infiltration (in m), τ is the time the water has been applied to the soil (in minutes), f_0 is the steady state infiltration rate of the soil (in m^3/min/m) and k and a are fitted parameters. INFILT uses three or more advance points to determine best fit values for the three infiltration parameters a, k and f_0. Where a minimum of four advance points are provide, it is also able to estimate the cross-sectional area of flow term ($\sigma_y A_o$) if this term is fixed as an input parameter. However, in this study, the inlet area of flow (A_o) was calculated using the Manning's equation and the measured furrow geometry (Table 1).

2.4 Simulation

The estimated soil infiltration parameters from INFILT, measured inflow rates (Table 2) and furrow geometry (Table 1) were used in the latest version of the surface irrigation model SIRMOD (version 4) (Walker 2001) to reproduce each irrigation event as measured. Calibration of the model for each event was conducted by adjusting the hydraulic resistance term (Manning n) until the simulated advance matched the measured advance at the end of the furrow.

After calibration, the model was used to evaluate the performance of a range of different designs (e.g. furrow length) and management (e.g. inflow rate, irrigation period) options. SIRMOD has the capability of modifying the infiltration function based on changes in furrow wetted perimeter (Equation 3) at different inflow rates:

$$\psi = \left\{ \frac{WP_2}{WP_1} \right\}^b$$

Equation 3

where WP_1 is the wetted perimeter (in m) for inflow rate Q_1, WP_2 is the wetted perimeter (in m) for simulated inflow rate Q_2 and b is an empirical exponent. In this study, the exponent was assumed to be unity for simplicity although Alvarez (2003) and Mailhol et al. (2005) have indicated that greater benefits may be obtained by measuring it for any particular site or soil type.

The performance of a furrow irrigation system can be described by three different, but interacting, indices: application efficiency (E_a), requirement efficiency (E_r) and distribution uniformity (DU) (Zerihun et al. 2001). It is commonly assumed that deep percolation and run-off is weighted equally in optimisation of application efficiency.

This study evaluated the potential irrigation performance that can be attained under the present design conditions assuming adequate farmer irrigation management practices. Other assumptions included: (a) furrow length of 285 m, (b) 3.0 L s^{-1} inflow rate is the non-erosive limit in the study area, and (c) the farmer practice is to ensure that the irrigation requirement efficiency is met (i.e. $E_r \geq 90\%$). The infiltration function obtained from the 1.5 L s^{-1} treatment furrow in each field was used for the performance predictions using SIRMOD. The optimisation involved varying inflow rates (Q_o), cut–off time (t_{co}) and the presence or absence of furrow end-dyking. Current farmer management was assumed to be the performance obtained if the irrigation was cut-off when the water advance reached the end of the furrow. However, it should be noted that this may have overstated the existing performance as many farmers cut-off long after the water advance has reached the end of the field to ensure that the root zone soil water is completely recharged.

3.0 Results and discussion

3.1 Effect of inflow rates and cut-off time

The application efficiency for the existing design and management practices ranged from 31 to 99%. Distribution uniformity ranged from about 70 to 91% and requirement efficiency from 75 to 99.5%. Field S9 had a low application efficiency (<38%) irrespective of the management strategy which suggests that design changes (in field length) are required to improve the performance of this field.

For fields S13, S25 and S31, increasing inflow rate from1.5 to 3.0 L s^{-1} and optimising cut-off time increased the average application efficiency from 79.4 to 87.5%. However, increasing inflow rate to 3.0 L s^{-1} and cut-off when the advance reaches the end of the field produced an average application efficiency of 84.5%. Increasing the inflow rate and reducing the cut-off time to equal 90% of the advance time improved the application efficiency to 88.7% across the fields. Introducing furrow end-dyking increased the distribution uniformity by between 0.3 and 5.2% but did not significantly affect application or requirement efficiency. However, the furrow end-dykes were over-topped by the irrigation in some events (e.g. field S31 with inflow rate of 3.0 L s^{-1}). It should also be noted that end-dyking may also cause surface drainage problems under high rainfall conditions.

Traditional furrow irrigation design and management commonly attempts to maximise the requirement efficiency (i.e. $E_r \sim 100\%$). However, where the distribution uniformity is high, the only implication of a low requirement efficiency (i.e $E_r < 90\%$) is that the next irrigation is required to be sooner than originally planned. Lower requirement efficiencies may also offer a greater opportunity to capture and utilise in-season rainfall. Farmers in schemes like

Bura, generally have little understanding of either the interval between irrigations or irrigation opportunity time required to satisfy the desired soil-water deficit. Irrigation application is often continued as long as water is available or until it is convenient to be manually switched off. Thus, significant water losses due to excessive drainage and tail water run-off may be experienced.

The relationship between inflow rate and cut-off time, and the application or requirement efficiency for the S31 field, is shown in Figure 1. This figure can be used as a decision support aid in irrigation management to provide advice or strategies to reduce water and energy costs and give improved environmental management. For example, a farmer using an inflow rate of 2.0 L s^{-1} can achieve an application and requirement efficiency of 79 and 98%, respectively by irrigating for 180 min. However, irrigating for longer periods will significantly reduce application efficiency without improving the requirement efficiency. Hence, switching off the irrigation at an appropriate time would not only reduce the volume of tailwater run-off but also the volume of water lost as deep percolation and, thus, save a significant quantity of water.

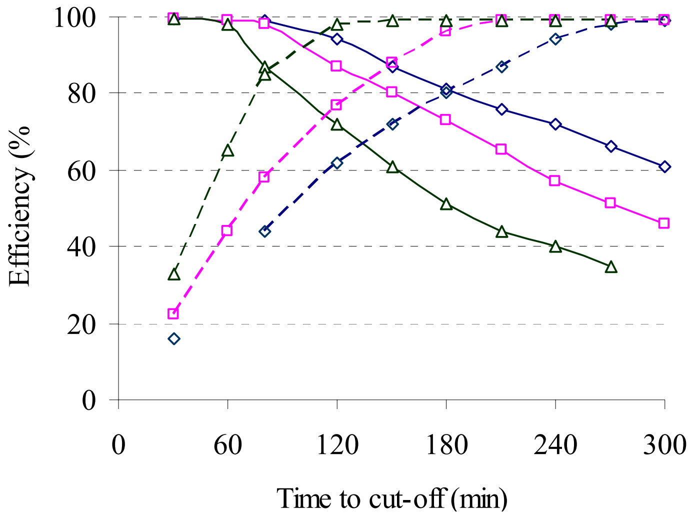

Figure 1: Effect of irrigation cut-off time on application (—) and requirement (— —) efficiencies for a 300 m field length and water application discharges (Δ =1.5, □ = 2.0 and ◊ = 3.0 L s^{-1}) for field S13.

3.3 Effect of furrow length

Significant deep drainage due to surface irrigation has the potential to affect groundwater levels and contribute to salinity in the river basin. On high infiltration soils (e.g. field S9), changes in furrow length may be needed to reduce deep drainage. For the S9 field, optimisation of cut-off time for various furrow lengths was conducted to identify the opportunity to improve performance. Deep percolation ratio is defined as the ratio of volume of irrigation water lost below the root zone to the total volume of water applied.

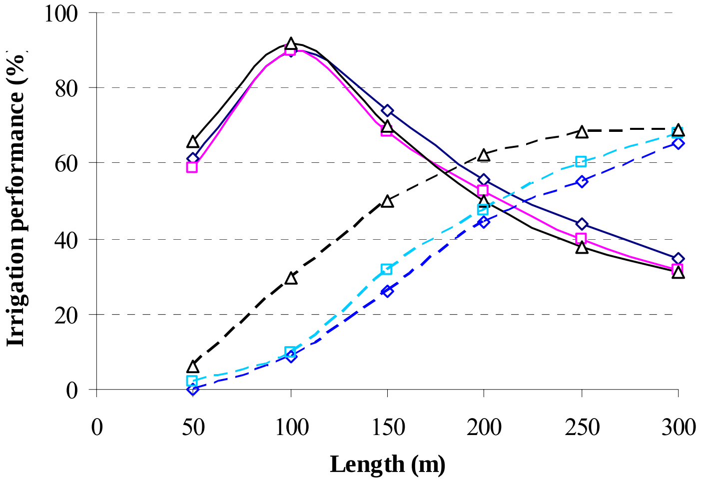

Figure 3: Application efficiency (——) and deep percolation ratio (— —) as a function of furrow length for fifth event with different inflow rates (Δ = 1.5 ls^{-1}, □ = 2.0 ls^{-1}, ◊ = 3.0 ls^{-1}) for field S9.

Application efficiencies of less than 40% were achieved with furrow lengths of 275-300 m regardless of inflow discharge used. However, reducing the field length to approximately 100 m would improve the application efficiency to greater than 80% and reduce deep percolation ratio to <10% for flow rates ≥2.0 L s^{-1} (Figure 3). Lower flow rates (i.e. 1.5 L s^{-1}) still have high (≥80%) application efficiencies but the proportion of water lost as deep drainage increases to ≥20% (Figure 3).

4.0 Conclusion

Alternative irrigation system and management practices were evaluated to identify strategies to improve irrigation performance. A simple decision support aid to improve irrigation performance in the Bura Irrigation Scheme of the Tana River Basin has been demonstrated. This work has shown that farmers, with the assistance of the Tana River Development Authority (TARDA) among others, may obtain performance benefits by optimising irrigation inflow rates and cut-off times. In some cases, field re-design to optimise furrow lengths may be required to achieve satisfactory performance.

References

Alvarez, RJ 2003, 'Estimation of advance and infiltration equations in furrow irrigation for untested discharges.' *Agricultural Water Management* **60**, pp 227-239

Bakker, DM, Plunket, G, & Sherrard, J 2006, 'Application of efficiencies and furrow infiltration functions of irrigations in sugar cane in the Ord River irrigation area of North Western Australia and the Scope of the improvement', *Agricultural Water Management*, vol. 86, no. 1-2, pp. 162-72.

Gichuki, FN 1996, *Sustainability concerns in African irrigation*, in Pereira, LS, Feddes, RA, Gilly, JR & Lesaffre, B (eds) Sustainability of irrigated Agriculture, Kluwer Academic publishers, Dordrecht.

Horst, L 1998, *The dilemas of water division: considerations and criteria for irrigation system design.* International Water Management Institute (IWMI), Colombo.

Khatri, KL & Smith, R 2005, 'Evaluation of methods for determining infiltration parameters from advance data.' *Irrgation and drainage*, no. 55, pp. 1-16.

Ledec, G 1987, 'Effects of Kenya's Bura Irrigation Settlement Project on Biological Diversity and other conservation concerns', *Conservation Biology*, vol. 1, no. 3, pp. 247-58.

Mailhol, JC,Ruelle, P & Povova, Z 2005, ' Simulation of furrow irrigation practices: a field scale modelling of water management and crop yield for furrow irrigation', *Irrigation Science* **24**: pp 37-48

McClymont, DJ & Smith, RJ 1996, 'Infiltrarion parameters from the optimisation on furrow irrigation advance data', *Irrigation Science*, vol. 17, pp. 15-22.

Mwatha, S & Gichuki, FN 2000, 'Evaluation of the Furrow Irrigation System in Bura Scheme', in Gichuki, FN, Mungai, DNGachene, CK & Thomas DB, ‘Land and Water Management in Kenya: towards sustainable land use’, proceedings of the Fourth National Workshop, Wida Highway Motel, Soil and Water Conservation Branch, Ministry of Agriculture and Rural Development & Department of Agricultural Engineering, University of Nairobi.

Raine, SR, McClymont, DJ & Smith, RJ, 1998, 'The effect of variable infiltration on design and management guidelines for surface irrigation', Proceedings of ASSSI National Soil conference, Brisbane, 27-29 April.

Raine, SR, Purcel, J & Schimidt, E 2005, ‘Improving whole farm and infield irrigation efficiencies using irrimate TM tools restoring the balance’, Proc. Nat. Conf. Irr. Assoc. of Aust. 17th- 19th may Townsville pp5

Smith, RJ, Raine, SR & Minkevich, J 2005, 'Irrigation application efficiency and deep drainage under surface irrigated cotton', *Agricultural Water Management*, vol. 71, pp. pp 117-30.

Walker, WR & Skogerboe, G. V. 1987, *Surface irrigation: theory and practice*, prentice-Hall, INC. Englewood Cliffs, New Jersey.

Walker, WR 2001, *SIRMOD II - Surface Irrigation Simulation, Evaluation and Design. User's Guide and Technical Documentation.* Utah State University.