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Evaluating Flexible Gated Pipes Flow Rate, Effect of Slope and Furrow Length on Irrigation Performance

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Abstract: ***Furrow irrigation is the most common method of applying water to sugarcane in Zimbabwe. Sugar cane plantations face challenges with respect to irrigation water management. A study was conducted from 2015 to 2016 to evaluate lay flat pipe irrigation and the effect of slope, furrow length and flow rate on irrigation performance. A split-split plot design with three treatments of slope, furrow length and flow rate, each with three levels; 0.06, 0.08 and 0.1% slope, 100, 200 and 300m furrow length and 0.8, 1.2 and 3 l/s flow rate. Performance indicators of application, requirement efficiency and distribution uniformity were evaluated. Discharge and pressure showed strong relationship for all three openings. Discharge varied along the length of the pipe for each slope with the mean coefficient of variation (CV) value of 26.97%. The minimum and maximum values for Ea, Er and distribution of uniformity (DU) were 52.32 and 65.65%; 95.73 and 97.7%; 81.74 and 88.4%, respectively. Performance indices indicated that the effect of slope was not statistically significant (p>0.05) on all indices except DU. Furrow length and flow rate were highly significant (p<0.01) on all performance indicators. The variation of means due to the interaction effects of furrow length and flow rate were found to be significant (p<0.05) on all performance indices. As furrow length increases all performance indices except Er showed a decreasing trend. All indices except Er showed increased as flow rate increased. Further research incorporating cutoff and irrigation intervals is recommended.***

Key words: Furrow irrigation, performance indices, flexible gated pipes, lay flat irrigation

1. Introduction

1.1 Background of the study

Design, soil and water management are the major factors that impact on the performance of furrow irrigation. The design variables include the land slope which affects the speed of advance and recession and also the furrow length, which determines the stream size required. The infiltration characteristic of the soil determines rate of infiltration into the soil and hence controls both the rate of advance and recession of water down the furrow length. The depth of application, flow rate and time to stop the irrigation are management variables. For most irrigators, time to cutoff is the only quantity that can be varied to achieve a desired level of irrigation performance (Raine & Smith, 2007), whereas the stream size can be a limiting factor to reach the desired level.

Increasing the volume of stream flow can be used in getting a more uniform irrigation especially on long furrows (Walker, 2003). A second approach is to increase the contact time at the lower quarter of the furrow through blocking the furrow end. Eldeiry *et al.*, (2005) detected that furrow length and stream size are the main management and design parameters affecting application efficiency in clay soil.

The infiltrated volume at any point within a furrow is a function of the contact time and is thus sensitive to the infiltration rates in any locations upstream of that point (Gillies *et al.*, 2011). Furrow irrigation attains high application efficiencies once the infiltrated depth from the inlet to the end of furrow almost uniform. To achieve this condition, the stream size and contact time during irrigation should be uniform along the furrow length. This is impossible, given that irrigation water begins to infiltrate at the inlet and if the stream size is small and the slope is almost flat, deep percolation results at the top end of the furrow.

To attain the required irrigation depth and uniformity, irrigators tend to increase the application times, usually resulting in deep percolation upstream and runoff from the downstream end. Deep percolation losses are also prevalent in highly permeable soils under surface irrigation systems (Koech, 2013). Shorter application times may reduce the risk of deep percolation and excessive runoff, but may also lead to insufficient water at the downstream end. Infiltration variability in surface systems presents, one of the biggest challenges to designers, irrigators and greatly reduces irrigation water use efficiency (Gillies, 2010).

To increase the sustainability of irrigated agriculture, the design of efficient irrigation systems at farm level has to be considered (Hsiao *et al.*, 2007). Irrigation systems improvement requires the consideration of the factors influencing the hydraulic processes, water infiltration and the uniformity of water application to the entire field. The consideration of all these aspects makes irrigation management a complex decision making and field practice process. Playan and Mateos (2006) reported that, generally all irrigation systems can attain approximately the same level of efficiency, when they are well designed and appropriately selected for the specific condition, due to that, irrigation is site specific. However, differences among irrigation systems appear in many areas as a consequence of design, management and maintenance.

Sugarcane is widely irrigated using furrow, overhead and drip irrigation methods. Furrow irrigation is the most common method of irrigating sugarcane in Zimbabwe. Greenfuel, Chisumbanje Estate has been using furrow irrigation since its establishment in 2008 when it took over from the Agricultural Rural Development Authority (ARDA), but there is little quantitative information about the field performance of irrigation systems, except for some work by Mark (2015). The sugar cane fields consist of 350 m furrow length on one side of feeder canals at 0.05% slope. This length, hamper the efficiency of tillage and harvesting activities. Flexible gated pipes were introduced 2014 and irrigators have found it hard to establish the optimum design and management parameters such as; furrow length, slope and geometry, inflow rate and cutoff time.

Given standard parameters such as field details, constant or variable inflow data, furrow geometry, infiltration parameters and irrigation deficit, the Surface Irrigation Simulation, Calibration and Optimatisation (SISCO) model can be used to calibrate and optimise the required level of irrigation performance. The SISCO model was developed by Dr. Malcom Gillies at the University of South Queensland in Toowoomba, Australia (2015). The model is capable of estimating the infiltration parameters and Manning roughness from the inflow hydrograph and any combination of the advance and recession data, runoff hydrograph and water depth measurements (Gillies, 2015). Using the calibrated data, optimum surface irrigation parameters can be established and these parameters be used to improve efficiency of that irrigation system.

Surface Irrigation Simulation, Evaluation and Design (SIRMOD), WinSRFR and Furrow Irrigation Design Optimiser (FIDO) models can be used for the same purpose as the SISCO model. The SISCO model is based on complete hydrodynamics model and therefore potentially more accurate than WinSRFR, that uses simplified forms of the momentum equation. The main difference between the SISCO and SIRMOD model is that the former is self-calibrating. The calibration process involves the estimation of the three modified Kostiakov infiltration parameters and Manning roughness can be undertaken using either one or a combination of the following variables: advance data, runoff, recession and water depth in the furrow. Simulation of the irrigation can be performed on a single or multi-furrow basis.

The other vital feature of SISCO over various models is the optimisation tool. This tool simulates all possible combinations of up to two management variables (e.g. inflow rate and cut off time) and assists the user in identifying the optimal combination of these variables in order to satisfy the performance criteria specified by the irrigator. SISCO is a robust model that presents a suitable platform for the determination of optimum combination of management and design parameters which achieve the desired performance of irrigation.

1.2 Flexible gated pipe

Gated pipes are an option in improving furrow irrigation, in which the conventional head ditch and siphons are replaced by an above ground pipe. Gated pipes used for irrigation of furrows can either be rigid (plastic or aluminum) or flexible (polyethylene) with outlets to each furrow. Fixed or adjustable outlets are spaced according to the crop row spacing. Rigid gated pipes are rarely used in the irrigation sector due challenges met in transportation. Flexible gated pipes are widely used in the sugar industry (Smith and Gillies, 2009), since they are relatively low cost, easily transportable and requires less storage space.

Hassan (1998), noted that gated pipes have improved furrow irrigation efficiency, operation and maintenance. This technique has attained an application efficiency of 90% (Tilly and Chapman, 2009). According to Hassan (2008), gated pipe irrigation may result in a 35 to 60 per cent reduction in water and labour costs. Gated pipe provides a more equal distribution of water into every furrow and eliminates seepage and evaporation losses which occur in unlined irrigation canals. Omara (1997), found out that the irrigation application efficiency and irrigation distribution efficiency increased to 72.5% and 92%, respectively by using gated pipe furrow systems. Osman (2000), mentioned that good design of gated pipes with precision land leveling improved the water distribution uniformity and saved irrigation water by 12 and 29 % in cotton and wheat respectively.

Jensen (2003), reported that irrigators might increase the uniformity of water application to their furrow irrigated crops by frequent regulation of the size of stream flowing into the furrow. Small and easily adjusted gate facilitate controlling the size of the stream delivery to the furrows. Adjustable gated outlets minimise the effect of pressure head differences on discharge rate. Trout and Mackay (1988), reported a coefficient of variation of 25% in furrow inflows from a gated pipe (rigid) delivery system.

The Surface Irrigation Simulation Calibration and Optimisation (SISCO) model

SISCO is a one dimensional hydraulic simulation model based on the full hydrodynamic equations. The model has been adapted from the software package FIDO, is similar in many aspects to the pioneer SIRMOD model (Walker 1997). It requires standard parameters such as the field details, inflow data (either constant or variable), furrow geometry, infiltration parameters and irrigation deficit. It is also based on the complete hydrodynamic model and therefore potentially more accurate than WinSRFR which uses simplified forms of the momentum equation.

SISCO is a full hydrodynamic model, which is a representation of surface water flow, ability to model furrow, border strip, basin and reverse grade furrow, estimation of soil infiltration and Mannings roughness from the field measurements, both individual and multiple furrow from field measurements, tool for optimisation of design and management and integration with a central database for bench marking.

One different main feature of SISCO over other models is the optimisation tool. This tool simulates all possible combinations of up to two management variables (e.g. inflow rate and cut off time) and assists the user in identifying the optimal combination of these variables in order to satisfy the performance criteria specified by the irrigator. SISCO is a robust model and presents a suitable platform for the development of real time optimisation simulation models.

The study evaluated flexible gated pipe flow in terms of discharge and pressure along the pipe length, performance of furrow irrigation and determine optimum combination of furrow length, slope and flow rate using SISCO model.

2. Materials and Methods

2.1 Site Description

A field experiment was conducted from August 2015 to September 2016 in Section C (400 ha) of Greenfuel, Chisumbanje Estate, Manicaland, Zimbabwe ($20^0$51`09.04``S, $32^0$14`55.58E). The area receives an average of 600 mm, unimodal rainfall from late December to March. The average maximum and minimum temperature is 37^0C and 23^0C respectively. The soil (Chisumbanje 3B soil) is a dark grey to black vertisol soil (clay content 60-75%) overlying weathered basalt, with soil depth varying from moderately shallow to moderately deep (50-100cm) (Bechtel, 1984). The high clay content of the basalt results in a high water retention of 210mm/m. Infiltration rates into dry cracked soil surface area are very high (400mm/hour), however rates drop rapidly (1mm/hour) as the surface soils swell and seal the cracks (Bechtel, 1984).

2.2 Field Layout

The slopes within the cane fields at Greenfuel, Chisumbanje Estate are classified as flat (0 to 0.05%), mild (0.05 to 0.1%) and steep (>1.0%) slopes. The typical longitudinal and lateral slopes of the study area were 0.05 and 0.06%, respectively. Trapezoidal furrows spaced at 1.8 metres were formed after primary and secondary tillage and these gradually changed to a parabolic shape by the end of the season. The furrow slope was checked at 10 m interval using line level. Cane setts were planted end-to-end within the furrow bottom using a sugarcane planter of two lines per bed.

2.3 Experimental set up

In order to assess water distribution uniformity along the outlets of gated pipes, the chosen fields were divided into three; as upstream, middle and downstream reaches based on their proximity to the inlet box of the pipe. In each compartment, one irrigation set was selected to conduct the measurements. An irrigation set comprised of 30 outlets on one side of the pipe, of which 20 were opened at a time, while the remaining 10 outlets were used for maintaining uniform flow and pressure throughout the measurement. The outlets were numbered from one to twenty, starting from the guider or a check dam at each irrigation set and located at downstream of the pipe. Hence, labelling of the outlet near the guider was identified as number 1 and the upstream outlet as number 20.

Field C6, which is 600 by 300 metres, with an average longitudinal and lateral slope of 0.035 and 0.05% respectively, was selected for the evaluation. The field was divided into six equal plots of 100 by 300 metres. These plots were randomly assigned the design slopes. Each plot was separately levelled to the required lateral slopes for each replication. Each plot was divided into three sets consisting of fifteen furrows spaced at 1.8 m. Furrow length was randomly assigned to each furrow set. Each furrow set was divided into three sub sets consisting of five furrows. Flow rate treatments were assigned to the sub sets randomly. The middle furrows in a subset were used to monitor the irrigation events and outer furrows used as buffers.

2.4 Experimental design and treatments

The treatments were slope, furrow length and flow rate. Each treatment had three levels with two replications for the main plot factor (slope). The treatment levels were 0.6, 0.8, 1% furrow slopes, 100, 200, 300 m lengths and 0.8, 1.2, 3 l/s flow rates. The experiment was designed as split-split plot arrangement, where slopes, furrow length and flow rates constituted the main plot factor, sub-plot factors and sub-sub-plot factors respectively.

2.5 Data Collection

Sugar cane variety, ZN10 was planted on 30th of September 2015. Soil moisture, stalk diameter and height, juice brix and % pol data were collected.

2.5.1 Determination of outlet discharges and pressure heads

Flexible gated pipes of 425 mm internal diameter and 100 m length were used to assess water distribution under fixed outlet area along the length of the pipe and to determine pressure versus outlet discharge relations. The pipe had variable adjustable 38 mm circular outlets, 1.8 m apart, corresponding to the furrow spacing. This is a gravity flow system which requires a minimum of 150 mm water head at the inlet (water source) and a maximum head of 1.4m at any given point along the pipe. Pressure and discharge were measured simultaneously starting from outlet number one for all twenty outlets. Pressure was measured using a nozzle with clear tubing connected to the measuring ruler using the capillary action. Discharge was measured at each outlet using the volumetric method.

Total available water (TAW) in the soil was estimated using the irrigation scheduling model IrrigWeb, a web based sugarcane irrigation scheduling tool based on CANEGRO developed by SQR Software. IrrigWeb provides advice on sugarcane crop water use and development. It combines crop water use estimates, user defined irrigation system constraints and crop cycle inputs to compile an irrigation schedule. Crop water use estimates were based on a validated sugarcane specific version of the Penman-Monteith equation. Climate inputs were obtained daily either from as the meteorological stations or directly from local automatic weather stations and were linked to respective fields. A single block was assigned its own irrigation management rule; soil type and other field information were entered accordingly. Output data from IrrigWeb was provided by a range of graphical and tabular reports. Charts depicting the soil water balance, canopy development, water stress, crop water use and yield components are combined with tables of irrigation schedules and historical reporting. IrrigWeb schedules future irrigation events and hence water requirements can be estimated allowing the user to generate Estate wide water orders. IrrigWeb also produces reports which allow the user to evaluate the management of a specific field.

2.5.2 Soil moisture determination

Soil moisture measurement for performance evaluation was done by taking soil moisture samples at 25 metre interval along the furrow length from each plot at two depths, 0-30 cm and 30-60 cm, using a soil auger. This was done before an irrigation event and moisture content was determined using the gravimetric method. The volumetric moisture content (θ_v) was computed by multiplying the dry weight soil moisture fraction (W) by bulk density of the soil in gm/cm^3 (ρb) and divided by specific weight of water (ρw). The allowable moisture depletion was 0.5 of the total available moisture in the soil. The irrigation scheduling model, IrrigWeb was used to estimate the next date of an irrigation event.

2.6 Determination of Field Evaluation Parameters

The methodology used for evaluation of furrow irrigation followed Merriam and Keller (1978) as adapted by Gillies *et.al.,* 2015). Measurements included inflow rate furrow geometry, advance and recession rates, hydraulics roughness, soil moisture deficit and infiltration. However, the hydraulic roughness and infiltration were simulated by the SISCO model which was used to evaluate the performance of the irrigation.

2.7 Inflow rate

The inflow rate of the flexi flume outlets were determined by the volumetric method using a 20 litre container. The discharge was also controlled by the pressure in the flexi flume. The different opening of the outlets varied the inflow rate. The ¼, ½ and fully opened outlets, had discharges of 0.8 l/s, 1.5 l/s and 3 l/s respectively which were the treatments.

2.8 Furrow geometry

The furrow dimensions were measured using a metre rule so that they would be used to simulate water movement using the SISCO model. The top (A), middle (B), bottom (C) and depth (D) were measured (Figure 1).

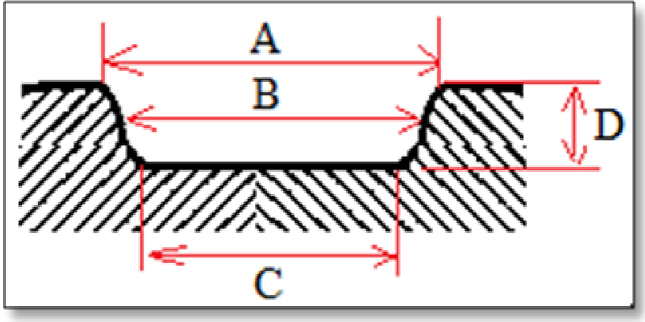

Figure 1: Measured furrow dimensions

2.9 Advance rate

Advance times were measured for each furrow lengths, flow rate and slope combinations (treatment plots). Pegs were driven into the soil along the furrows at 25 m intervals with 0 metres being at the inlet end of the furrow, giving five, nine and thirteen stations for furrow lengths of 100, 200 and 300 m, respectively. Advance times were recorded at the time when water reached each peg from the start of water entry to the furrows.

2.10 SISCO Model

The SISCO model was used to determine the Manning's roughness, infiltration parameters, performance of irrigation parameters which are requirement and application efficiency, distribution uniformity and their relationship for each combination of treatments. The following data was used in the SISCO model: inflow rate, furrow geometry, advance rates, hydraulics roughness, soil moisture deficit and soil analysis data.

2.11 Method of Data Analysis

The data were analysed using Genstat, Version 12 and the mean separation was done using ANOVA at 5% significance level.

3. Results

3.1 Lay flat evaluation

Figure 2 shows the relationship between pressure and discharge per outlet for fully, ¾ and ½ opened single outlets. The value of R^2 indicated that there was a strong relationship between outlet pressure and discharge for all the three openings. Discharge per outlet depends on the pressure inside the lay flat, which depended on the slope along the gated pipe (bed slope) and area of outlet opening. The resulting lines on the log-log scale are relatively parallel, had similar slope and gave outlet characteristic equations:

$y = 0.0252x + 0.8671$, $y = 0.0254x + 0.5114$, $y = 0.0231x + 0.1871$ for outlets being fully, ½ and ¼ open, respectively.

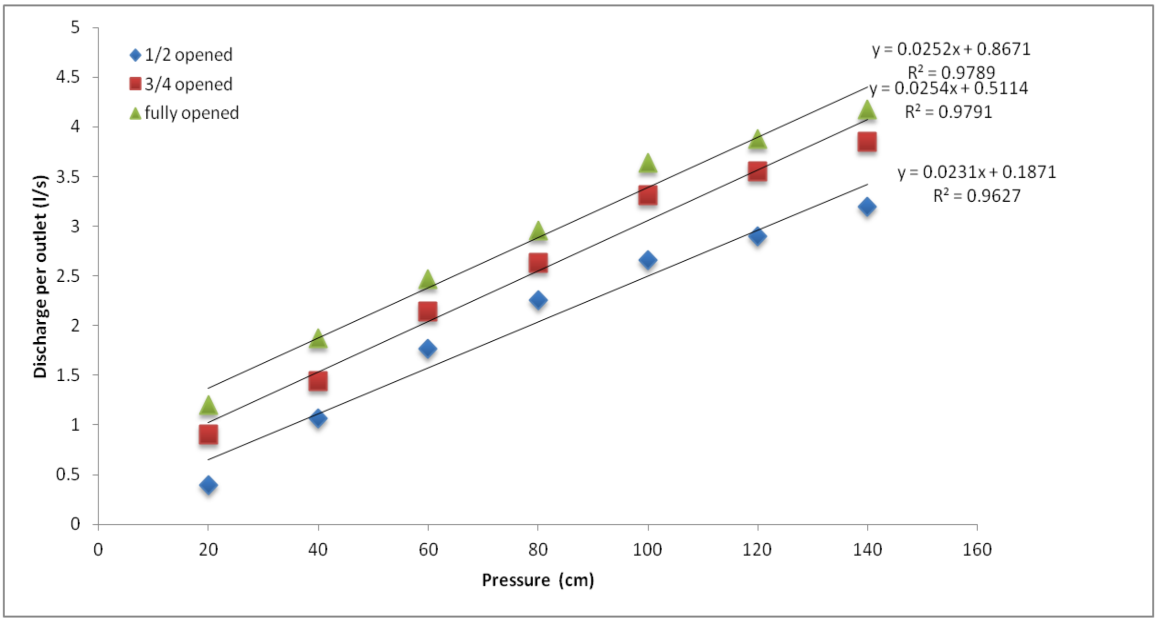

Figure 2: Outlet discharge and pressure relationships of gate

The patterns of discharge along the flexible gated pipe for each of the trials are shown in Figure 3. The lower ends of the pipes had a general increase in discharge. Table 1, shows the analysis of the discharge measurement made for fields of different bed slopes. The result indicated that the outlet discharge along the length of the pipe varied differently for each fields. The mean values of discharge along the length of the pipe for slopes 0.5%, 0.8% and 1.0% were 1.98, 2.00 and 2.04 l/s respectively, which is less than the design discharge of 2.5 l/s. The coefficient of variation for field with slope 0.5, 0.8 and 1.0% were 24.79, 28.91 and 27.2% respectively. These results were slightly higher than those by Trout and Mackey (1988), who got the inflow rate variability, with mean CV value of 25 % and ranges of values between 13-42 %.

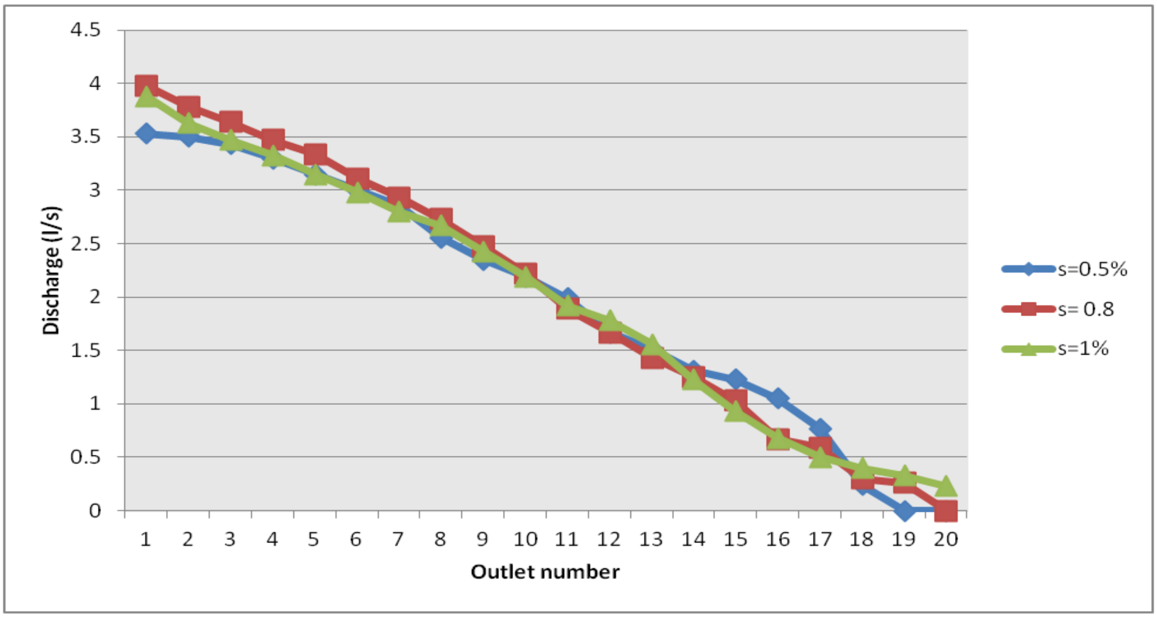

Figure 3: Discharge variation along the length of the layflat in different fields

The gate discharge variation increased as the slope increases, these dictate that the gravity water flow in pipe is slope dependent. The 0.5% slope had smaller CV value showing relatively small variation in gate discharge whereas the greater CV value of 0.8% slope shows non uniform distribution of discharge along the pipe.

Table 1: Discharge distribution along the length of gated pipe

	Discharge (l/s) per outlet		
Field slope	0.50%	0.80%	1%
Mean	1.98	2.04	2
S. D	1.23	1.43	1.34
C. V	24.79	28.91	27.2

3.2 Irrigation Performances

The analysis of performance indices such as application efficiency, requirement efficiency and distribution uniformity was carried out for the average values of irrigation events to represent the performance of the system throughout the whole period.

3.2.1 Application Efficiency

The application efficiency obtained was from 52.72% to 64.47%, with the maximum value was obtained for 100 m furrows length, 1.2 l/s inflow rates and 0.1% furrow slope interaction. Table 2 showed that statistically, there was no significant ($p>0.05$) variation on application efficiency due to the main effect of furrow slope. This showed that the unevenness of the slope along the furrow length affects efficiency rather than the value of the slope.

Table 2: Effects of flow rate and furrow length on application efficiency (%)

Furrow length (m)		Mean application efficiency (%)		
		Flow rate (l/s)		
	0.8	1.2	3	Mean
100	61.12^{h}	64.47^{g}	59.96^{i}	61.85^{a}
200	55.45^{k}	59.02^{j}	62.16^{h}	58.88^{b}
300	52.72^{l}	56.77^{k}	58.63^{ij}	56.04^{c}
Mean	56.43^{f}	60.09^{e}	60.25^{d}	
SE	F	Q	F x Q	
	0.329	0.674	1.009	
LSD (0.05)	0.805	1.417	2.094	
CV%	0.6	2.3	2.3	

*Means followed by the same superscripts in the same column or row are not statistically different.

The effect of furrow length on E_a was highly significant ($p<0.01$). The mean values of E_a were 61.85, 58.88 and 56.04% for 100, 200 and 300 m furrow lengths, respectively (Table 2). The effect of flow rate on E_a was highly significant ($p<0.01$). Mean values of E_a were 56.04, 58.88 and 61.85% for 0.8, 1.2 and 3 l/s flow rates, respectively. E_a has shown increasing trend as flow. Interaction effect between furrow length and flow rate on E_a was also highly significant ($p<0.01$) as summarised in Table 2.

3.2.2 Distribution Uniformity

Slope had an effect on distribution uniformity. The analysis of variance showed that the effect of slope on distribution uniformity was significant at $p<0.05$ and the mean distribution uniformities were 84.67, 85.33 and 86.46% for 0.06, 0.08 and 0.1% slopes respectively. The maximum DU was obtained with 0.1% slope. This value was in statistical parity with 0.8% slope. DU showed an increasing trend as slope increased.

Table 3: The effect of slope on distribution uniformity

Slope (%)	Mean distribution uniformity (%)
0.06	84.67^{b}
0.08	85.33^{ab}
0.1	86.46^{a}
SEm+	0.097
LSD (0.05)	0.589
CV%	0.19

*Means followed by the same superscripts are not statically different

The analysis of variance showed that the effect of furrow length and flow rate on distribution uniformity was highly significant at $p<0.01$ (Table 4). The mean DU with respect to furrow length was found to be 87.23, 85.05 and 84.18%, for lengths of 100, 200, and 300 m, respectively and that of flow rate was 83.62, 85.40 and 88.44%, for 0.8, 1.2, and 3 l/s flow rates, respectively (Table 4). The effect of interaction between furrow length and flow rate on DU was also highly significant ($p<0.01$ (Table 4). The maximum value of 88.41% was obtained for 100 m furrow length and 3 l/s flow rate; whereas the minimum value of 81.74% was obtained for flow rate of 0.8 l/s flow rate and 300 m furrow length. The maximum value was in statistical parity with the interaction effects of 100m furrow length with 1.2 and 3 l/s flow rates.

Table 4: Effects of flow rate and furrow length on distribution uniformity

Furrow length (m)		Mean of distribution efficiency (%)		
		Flow rate (l/s)		
	0.8	1.2	3	Mean
100	85.90^{hi}	87.38^{fg}	88.41^{fg}	87.23^{a}
200	83.21^{j}	85.25^{h}	86.69^{g}	85.05^{b}
300	81.74^{k}	83.57^{i}	87.23^{f}	84.18^{b}
Mean	83.61^{e}	85.40^{d}	88.44^{c}	

	F	Q	F x Q	
	0.370	0.492	0.788	
LSD (0.05)	1.280	1.463	2.302	
CV%	0.6	0.70	0.70	

*Means followed by the same superscripts in the same column or row are not statistically different.

3.2.3 Requirement Efficiency

Results of requirement efficiency indicated that there was no statistically significant ($p>0.05$) variation due to slopes. The effect of both furrow length and flow rate on E_r was statistically highly significant ($p<0.01$ (Table 5)**.**

The mean values of E_r were 96.399, 97.081 and 97.698% for furrow length of 100, 200, and 300 m, and 97.333, 97.048 and 96.797% for flow rates of 0.8, 1.2, and 3 l/s, respectively.

Table 5: Effects of flow rate and furrow length on requirement efficiency (%)

Furrow length (m)		Means requirement efficiencies (%) *		
		Flow rate (l/s)		
	0.8	1.2	3	Mean
100	96.865^h	96.597	95.737^j	96.40^c
200	97.435^g	96.853^g	96.955^c	97.1^b
300	97.7^d	97.693^f	97.7^f	97.7^a
Mean	97.3^b	97.2^b	96.8^e	
	F	Q	F x Q	
SEm+	0.048	0.047	0.082	
LSD (0.05)	0.167	0.14	0.24	
CV%	0.1	0.2	0.2	

* Means followed by the same superscripts in the same column or row are not statistically different

Interaction effect between furrow length and flow rate was highly significant ($p<0.01$) on difference of means of requirement efficiency as shown in Table 5. E_r has shown an increasing trend for increase in furrow length and decrease in flow rate. The maximum E_r which is 97.689% was achieved for flow rate of 0.8 l/s and furrow length of 300 m and the minimum E_r 95.737% was obtained for 100 m furrow length and flow rate of 3 l/s.

4. Discussions

The relationships between pressure heads and flow discharges of a single pipe outlets with fully, ¾ and half of the area opened were investigated and showed strong relationship for all openings. Discharge flow from each outlet was dependent on pressure head inside the gate while the pressure heads depend on bed slope of the pipe and size of openings. Outlet discharges along the pipe varied for each slopes with mean values of 1.98, 2.04 and 2.00 l/s for 0.3, 0.7 and 1.01% bed slopes, respectively. Once water is channeled into the gated pipe, it encounters a closed system; the particular gradient upon which the gated pipe is placed has a substantial effect on the flow of water from the openings. The gradient of the field would tend to cause water at the lower end (end clamp) to have greater pressure and the resulting strong stream causes erosion of the field and crop. At the upstream end, pressure becomes small resulting in low stream size. This causes variation in outlet discharge along the length of the pipe. This variation of outlet discharge leads to non-uniform application of irrigation water. The uniformity of furrow inflow is a major determinant of irrigation performance at the field scale (Smith and Gillies, 2009). If irrigation application is not uniform, some part of the irrigated area will receive too much and some will get little water, which resulted in uneven plant growth. The CV value on the 0.8% slope was greater than that of 1%. In a field with a 1% slope, a lot of energy dissipaters were provided to maintain the pipe pressure within the range of permissible limit of working pressure. These structures break the natural ground slope to somewhat uniform slope which may be less than the slope of field (0.07% slope). This probably explains why the discharge variability was small. From this we conclude that gated pipe is best suited to fields with small uniform slopes.

The important performance indices used to characterise the irrigation system under study were application efficiency, requirement efficiency and distribution uniformity. In order to investigate the effects of crop resistances on performance, these performance indices were measured during irrigation events. Cane and sugar yield assessment together with their analysis of variances were undertaken for 11 months old crop.

The interaction effects of furrow lengths and flow rates were highly significant ($p<0.01$) in influencing application efficiency. The best result of 64.47% was achieved for treatment combination of 1.2 l/s and 100 m furrow length and the least 52.73% for treatment combination of 0.8 l/s and 300 m furrow length. Similarly, the application efficiency was significantly influenced by the sub-plot effects of furrow lengths and sub-sub-plot effect flow rates. E_a was higher than the recommended E_a for irrigation system design which is 50% (MoAFS, 2002) and lower than the works by Kandiah (1981), which was 70%. The result was in line with findings by Melaku (2006).

The highest application efficiency was observed for treatment interaction of small furrow length (100 m) and relatively moderate flow rate (1.2 l/s) with the mean value of 62.05%. The least E_a was recorded for treatment interactions of longer furrow length (300 m) and smaller flow rate (0.8 l/s) with mean value of 52.73%. This result disagrees with that reported by Swenet (2007). He obtained lower E_a for shorter furrow with higher flow rate. This is probably due to the difference in length of the test furrow he used. All the test furrows he used were much smaller than those used in this study. For the 100m furrow length, E_a has shown an increasing trend as flow rate increased. Teshome (2006), reported similar result, for longer furrow lengths of 100 m to 200 m. For a given flow rate, E_a has a decreasing trend as furrow length increased after certain optimal level. This is in agreement with the result of Eldeiry *et al.*, (2005), who stated higher efficiencies achieved for small furrow lengths with relatively low discharges and larger flow rates are needed as furrow length increases to obtain high efficiencies.

Requirement efficiency was significantly affected ($p<0.01$) by the interaction effect of furrow length and flow rate with the highest requirement efficiency of 97.6% for treatment combination of 300 m furrow length and 0.8 l/s flow rate and the lowest value of 94.8% for treatment combination of 100 m furrow length and 3 l/s flow rate. Similarly, the effects of furrow length and flow rate were also significantly different.

Distribution uniformity was affected significantly by the main effect of slope with the values of 84.67, 85.33 and 86.46% for 0.05, 0.08 and 0.1% slopes respectively. It was significantly affected ($p<0.01$) by the interaction effect of furrow length and flow rate with the highest value of 93.49% for treatment combination of 300 m furrow length and 3 l/s flow rate and the lowest value of 79.74% for treatment combination of 300 m furrow length and 0.8l/s flow rate. These values revealed that the distribution uniformity was within acceptable limits and homogenous.

Similarly, the effects of both furrow length and flow rate on DU were also significantly different. This is similar to the reports by Zerihun (1998) and Holzaphel *et al.*, (2009), which stated that uniformity is an increasing function of flow rate and a decreasing function of furrow length. Increase in flow rates reduces the difference in wetting time between the head and tail of the furrow. This leads to uniform distribution along the furrow. The finding of was in agreement with results by Feyen and Zerihun (1999), that longer furrows show a decreasing trend of DU with increasing length. Under short furrows, infiltration opportunity time at the upper reaches of furrows is nearly the same with that of tail end. As furrow length increase, the variation in IOT between the upper reach and the tail end of the furrow also increases. As a result, water reaches the upper reach earlier and water percolates deeper while at tail ends the depth of penetration is proportionally less. This leads to variation in DU as furrow length increases. The values of the indices were also much higher than the advanced furrow irrigation systems, i.e., 70% (Raghuwanshi and Wallender, 1998). DU is influenced by the longitudinal slope of the furrow (Pereira and Luis, 1999). As the slope increases the advance rate becomes faster and the infiltration opportunity time becomes uniform. This uniformity of IOT leads to improvement of DU.

Interaction effects of slope, furrow length and flow rate on cane yield was found to be significant ($p<0.05$). The highest cane yield 13.46 t/ha/month was obtained from treatment combination of 0.08 % slope, 200 m furrow length and 3 l/s flow rate while the least 8.98 t/ha/month was obtained from treatment combination of 0.08 % slope, 200 m furrow length and 0.8 l/s flow rate. Similarly, the effects of flow rate on cane yield were also significant. On the other hand, sugar yield was significantly affected ($p<0.05$) by flow rate with mean values of 0.991,1.028 and 1.093 t/ha/month for 0.8, 1.2 and 3 l/s flow rates respectively). This happens due to the fact that better irrigation uniformity was attained in higher flow rates.

Ascough and Kiker (2002), reported that distribution uniformity of a system has an effect on the crop yield. The result showed that the different levels of the main plot (slope) and sub-plot (furrow length) have no effect on yield of sugarcane. This may be due to laser leveling which improves the uniformity in water distribution.

5. Conclusions

Furrow irrigation is the most widely used method of irrigation water application to sugarcane in Zimbabwe. Furrow irrigation needs to evolve into an efficient, cost effective, and environmentally technology. For the long term sustainability of an irrigation system, improvements in the performance of current water application and on-farm water management practices are mandatory.

Outlet discharges along the lay flat vary greatly depending on ground slope Therefore, lay flat application is best suited to fields with smaller longitudinal slopes (<0.5 %) so that the irrigation performance will not be affected.

Furrow irrigation system performance was significantly affected by furrow length, flow rate as well as their interaction, while distribution uniformity was affected by all the three variables. System management needs improvement as the application efficiencies are relatively low and system performance is appropriate as indicated by high distribution uniformities.

Flow rate substantially affected sugar cane yield, while slope and furrow length did not have much effect.

The best irrigation uniformity and cane field was given by the interaction of 0.08% slope, 300m furrow length and 3l/s flow rate. Therefore, this combination is better for sugar production at Greenfuel, Chisumbanje Estate.

5.1 Recommendations

Based on the result of the study, newly developed sugar cane plantations and expansions of existing cane areas having similar soil characteristics with that of the study site should consider their design for furrow slope up to 0.1%, longer furrow length with optimum flow rate combination.

The study was undertaken by constant inflow rates with different application time to manage water application level. Hence further research work should be done by incorporating cut off time and irrigation interval.

The variability of discharge along the length of the lay flat has two main components. These are variation resulting from pressure head and size in gate area. Therefore, further studies should be carried out to establish the relationship between gate pressure and opening areas.

Discharge distribution along the lay flat is variable and the downstream outlets have higher flow rates with significant furrow erosion. The extent of erosion and means of mitigation needs to be investigated. The need for placing check structures for steeper fields across their longitudinal slope should be evaluated in terms of improving distribution uniformity.

Reducing opening area of the gate is one means to minimise discharge variation along the length of the gated pipe. Currently circular adjustable variable outlets are used, but the sliding type of outlet are relatively easy to manage by the labourers, the Estate should shift to use sliding types.

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