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ANALYSES OF THE HYDRAULIC PERFORMANCE OF A CONTINUOUS-FLOW DRIP IRRIGATION SYSTEM TESTED ON A TOMATO FIELD IN BAUCHI, NIGERIA

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Abstract

A low-cost, low-tech continuous flow drip irrigation system was constructed and tested in Bauchi. The measured hydraulic performance parameters were analysed using computer based regression, correlation and path analyses. Results showed that the total flow energy of the system is most sensitive to variations in pressure energy. Without flow regulation, fluctuation in the system discharge is influenced largely by plugging and hydraulic design parameters. However, flow regulation using 'Medi emitter' cushions discharge variations caused by hydraulic design. This leaves variation due to plugging as the sole source of discharge fluctuation with the system. A set of regression equations is equally provided for speedy design and evaluation of similar drip systems under same operating conditions. The set of regression equations in particular, includes a systems specific form of the Bernoulli's Equation that may be used for computations of flow energy requirements. Inferences from the regression analysis revealed that the maximum practicable lateral length of the continuous-flow drip system is 4.6 m.

1. Introduction

The concept of Affordable Micro-Irrigation Technology which started in the early 70s with the works of Richard D. Chapin in Senegal (Polak, 2001; Keller, 2001) has today been identified as a functional technological paradigm in alleviating hunger and poverty particularly within rural communities of developing countries. Existing Affordable Micro-Irrigation systems are structured for different income levels to suit the generic income stratification among farmers. The cheapest of such systems is the Bucket kit (Behr and Naik, 1999; Postel *et al.*, 2001; Keller *et al*, 2001; ALIN, 2002; Anon, 2004), which could be expanded in stages through the drum kit to the relatively large stationary micro-tube system (Postel *et al.*, 2001).

The continuous-flow drip irrigation system is a recent low-cost micro-irrigation concept developed and tested in Bauchi state, Nigeria (Mofoke *et al.*, 2004*a*). The system applies the crop water requirement on a continuous basis through out the 24 hrs of a day. This is achieved through a network of cheap pipelines and a high precision low-tech emitter known as the "Medi-Emitter" (Mofoke *et al.*, 2004*b*). The continuous flow drip irrigation reduces the number of farm visits, and so permits farmers to engage themselves in other revenue generating enterprises as a means of augmenting family income. This system therefore exhibits promising prospects for adoption within the poor communities of the world. However, successful adoption of this novel technology requires comprehensive analyses of the systems performance and its sensitivity to the design constraints.

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The aim of this study was to analyse the hydraulic performance and sensitivity of the continuous-flow drip irrigation systems so as to furnish insight on its critical design and operational characteristics.

2. Materials and method

2.1 Determination of systems performance parameters

Description of the continuous-flow drip system as well as its operational principles are well explained in Mofoke *et al.* (2004*a*). The system was constructed and field-tested in Bauchi State, Nigeria with tomato as trial crop. Bauchi lies within latitude $10^{o}17^{1}$ N and longitude $09^{o}49^{1}$ E on a mean altitude of 609.3 m above sea level. The performance parameters used for the systems appraisal were: application efficiency (AE), irrigation efficiency (IE), distribution uniformity (DU) and adequacy of irrigation (AI). AE was calculated as the ratio of the average depth of water infiltrated and stored in the root zone to the average depth of water applied and expressed as a percentage (Merriam *et al.*, 1980). Irrigation efficiency was calculated from Equation 1. (Perrier and Salkini, 1991) as follows:

$$IE = \frac{ET}{IR} \times 100\% \qquad 1$$

where:
IE = irrigation efficiency, %
ET = actual crop evapotranspiration, mm
IR = irrigation water applied, mm

Distribution uniformity was computed from Equation 2 (Merriam *et al.*, 1980):

$$DU = \frac{\overline{x_{lq}}}{\bar{x}} \times 100\% \qquad 2$$

where:
$\overline{x_{lq}}$ = *average low-quarter depth of water received, mm.*
$\bar{x}$ = *average depth of water received, mm.*

Adequacy of irrigation is the percent of an irrigated field receiving the desired amount of water or more (James, 1988). The desired amount of water implied in this definition is subjective because it refers to the measure of water required to maintain the quantity and quality of crop production at a “profitable” level. The desired amount of water was taken as the pre-determined continuous-flow discharge of 0.04 l/hr (Mofoke, 2006). AI was determined through extrapolation from a generated frequency distribution plot of applied depth against cumulative percent area (James, 1988). An overall systems efficiency (SE_{ff}) was calculated by multiplying together AE, IE, AI, and DU (James, 1988).

2.2 Determination of systems hydraulic parameters

The total flow energy and its components were calculated using Equation 3 (Dake, 1983; Camp *et al.*, 1997) in a step by step manner.

$$\frac{p_{DT}}{\rho g}+\frac{v_{DT}^2}{2g}+Z_{DT} = \frac{p_e}{\rho g}+\frac{v_e^2}{2g}+Z_e + H_{(DT-e)} \qquad 3$$

where:

$\frac{p_{DT}}{\rho g}$ and $\frac{p_e}{\rho g}$ are pressure heads at distributary tank and emitter points respectively, m;

$\frac{v_{DT}^2}{2g}$ and $\frac{v_e^2}{2g}$ are velocity heads at distributary tank and emitter points respectively, m;

Z_{DT} and Ze are elevations of water surface (potential energy) in distributary tank and at the emitter center lines respectively, m;

$H_{(DT-e)}$ is head loss from distributary tank to emitter, m; and comprised both minor and major head losses.

Head loss from the distributary tank to the lateral inlet was calculated from the Darcy Weisbach formula in Equation 4 (Giles *et al.*, 1994). However, head loss along the lateral was computed from Equation 5 (Schwab *et al.* 1993) because of the lateral outflows along the lateral.

$$h_f = f\left(\frac{L}{d}\right)\left(\frac{V^2}{2g}\right) \qquad 4$$

where:

h_f = energy head loss through pipe, m

f = friction factor

L = pipe length, m

d = diameter of sub-main, m

V = velocity of water flow through pipe, m/s

g = acceleration due to gravity, m/s^2

$$H_f = \frac{K_s L Q^{1.75}}{D^{4.9}}\left(4.10\times10^6\right)F \qquad 5$$

where:

K_s is Scobey's coefficient of retardation.

L = pipe length, m

Q = upstream discharge through the pipe, m^3/s

D = lateral diameter, m

F = correction factor to compensate for lateral outflows

It was necessary to qualify different discharge coefficients of variation because discharge through drip lines is affected by both hydraulic and emitter factors. Four discharge coefficients of variation were used for the systems evaluation. These are:

- Coefficient of variation of emitter flow caused by hydraulic design CV(H).
- Coefficient of variation of emitter flow caused by manufacturing processes CV(M).

- Coefficient of variation of emitter flow caused by hydraulic design and manufacturing processes CV(HM).
- Coefficient of discharge variation caused by plugging CV(P).

CV(H) was taken as the ratio of standard deviation of estimated theoretical emitter discharges to the mean emitter discharge (Camp *et al.*, 1997; Keller *et al.*, 2001). The theoretical emitter discharges were obtained by substituting the calculated total energy head at each emitter centre line into the flow function of the medi-emitter at 50% opening. The flow function used is of the form given by Equation 6 (Mofoke, 2006)

$$q_e = 0.02e^{3.83Pe}; \qquad 6$$

where:
q_e = emitter discharge, l/hr
P_e = available energy head at the emitter, m

CV(M) was calculated from measured emitter discharges taken at 50% emitter opening, while CV(HM) was computed from Equation 7 (Wu *et al.*, 1985):

$$CV(HM) = \sqrt{CV^2(H) + CV^2(M)} \qquad 7$$

CV(P) was calculated from Wu (1997) as follows:

$$CV(P) = \sqrt{\frac{P}{1-P}} \qquad 8$$

Where P is the level of plugging, (%)

The systems hydraulic performance parameters were subjected to regression and correlation analysis using the MINITAB statistical software (MINITAB, 1996). The Regression analysis produced algebraic relationships among the performance parameters which provide a basis for synthesis and mathematical interpretations of the systems performance. The Pearson's correlation coefficients were used to assess the degree of association between pairs of the system's performance indices. A sensitivity analysis was carried out using a computer simulated path analysis software according to Agada and Babatunde (2006). The sensitivity analysis reveals the crucial factors affecting the systems performance and for which operational precautions are needed.

3. Results and discussion

Table 1 shows the sensitivity of the total flow energy to the three energy components of the continuous-flow drip irrigation system. The Table reveals that total flow energy of the drip system is most sensitive to potential energy component. The sensitivity of the total flow energy to changes in pressure energy is apparently small. This observation substantiates earlier trends reported by Mofoke *et al.*, (2004*a*) in which very small absolute variations in pressure energy along the lateral length for the continuous-flow drip system was reported. The very small absolute value of the residual term in Table 1 illustrates that no other extraneous factor could contribute considerably to the total flow energy of the low-cost continuous-flow drip system. This remark conforms to the Bernoulli's equation applicable to fluid systems, which states that the total flow energy at any point in a fluid system is the sum of potential, pressure and kinetic energies at that point (Giles *et al.*, 1994).

Table 1: Sensitivity of energy components to the total energy of the low-cost continuous-flow drip irrigation system

Type of contribution	Level of Sensitivity (%)
Potential energy	74.792
Pressure energy	1.299
Kinetic energy	6.189
Interactive effect	17.777
Residual	-0.057
Total	100.00

The sensitivity of the systems overall efficiency to some efficiency terms are shown in Table 2. Results in the Table show that the systems overall efficiency is most sensitive to irrigation efficiency and application efficiency, and is least affected by distribution uniformity. The low sensitivity to distribution efficiency is probably due to a relatively narrow variation margin of this performance parameter occasioned by the regulatory ability of the medi-emitter. Thus the systems efficiency tends to be most sensitive to irrigation efficiency over which an irrigator has little direct control. The low response of overall systems efficiency to adequacy of irrigation insinuates that this performance parameter originally developed for surface irrigation systems (James, 1988), has limited application to this continuous-flow drip system. The table also demonstrates that variations in application efficiency and irrigation efficiency constitute the critical contributor to changes in the overall systems efficiency of the continuous-flow drip system. Other combinations among the performance parameters are apparently minor indicators of the systems performance.

Table 2: Sensitivity of the overall systems efficiency of the low-cost continuous-flow drip irrigation system to some efficiency terms and distribution uniformity

Type of contribution	Level of sensitivity (%)
Application Efficiency	34.6
Irrigation Efficiency	49.8
Distribution Uniformity	0.60
Adequacy of Irrigation	16.8
Interactive effect	-1.63
Residual	-0.08
Total	100.09

Table 3 contains the sensitivity levels of the overall hydraulic variations [CV(HM)]to its various components. From the Table, changes in coefficient of variation due to plugging [CV(P)] and coefficient of variation due to hydraulic design [CV(H)] subscribe the largest proportions to differences in CV(HM). Use of the Medi-emitter, however, cushions flow variation caused by hydraulic design because the device has facility for precise flow regulations. CV(P) is therefore, the sole source of discharge variation with this small-holder continuous-flow drip system. According to Wu (1997), flow through emitters is highly sensitive to plugging, which is a major problem to drip systems. The recorded high sensitivity (88.0%) of the overall discharge coefficient of variation to CV(P) illustrates that even with adoption of the medi-emitter, the flow behaviour of the continuous-flow drip system conforms with the general character for drip systems as reported by Wu (1997).

Table 3: Sensitivity of the overall hydraulic variation of the low-cost continuous-flow drip irrigation system to some component coefficients of variation*

Type of Contribution	Level of Sensitivity (%)
CV(H)	225.386
CV(M)	47.376
CV(HM)	54.051
CV(P)	87.921
Interactive effect	-314.685
Residual	-0.048
Total	100.00

* The component coefficients of variation are:
CV(H): Coefficient of variation due to hydraulic design
CV(M): Coefficient of variation due to manufacturing
CV(P): Coefficient of variation due to plugging
CV(HM): Coefficient of variation due to hydraulic design and manufacturing

With reference to Table 4, it is observed that the theoretical discharge through the emitters is more sensitive to energy contribution from the lateral caused by elevation differences. This is obviously because the water level in the distributary tanks is maintained constant (Mofoke *et al.*, 2004a). The relatively high residual sensitivity in Table 4 suggests that some factors other than those considered here in this analysis appreciably affect the theoretical emitter discharge. One of such prominent influences is the adjustment level of the emitter.

Table 4: Sensitivity of theoretical emitter discharge of the Affordable Continuous-flow drip System to hydrostatic pressure components

Type of Contribution	Level of Sensitivity (%)
Pressure contribution from lateral	54.085
Pressure contribution from distributary tank	2.041
Total Available pressure head at Emitter centre line	0.099
Interactive effects	14.246
Residual	29.538
Total	100.00

The equations in Table 5 provide a speedy reference for design of similar drip systems. For example, Equation 8 in Table 5 is a systems specific form of the Bernoulli's equation applicable to the continuous-flow drip system. The adjusted R^2 value of this equation (100%) demonstrates a perfect association among the energy terms. This lends further credence to same deduction given by the low residual term of Table 1. Equation 6 (Table 5) gives direct information on the maximum lateral length that may be used for the system under a maximum continuous-discharge of 0.08 l/hr (21 drops/min). The maximum practicable length is delineated by the point on the lateral where there is no energy to cause flow: that is, at E_{total} = 0. Thus, by setting E_{total} = 0 in Equation 6, a maximum lateral length of 4.59m is obtained. In practice, however, the maximum lateral length may be different from this projection due to dissimilar rolling land slopes and variations in other operating conditions.

Table 5: Regression Equations of the Energy Components of the Continuous-flow DripIrrigation System

Regression Equation	R^2 [adj] (%)
1) $E_{Total} = 3.39 + 1.05E_{Potential}$	99.9
2) $E_{Total} = -55.0 + 17.3E_{Pressure}$	83.3
3) $E_{Total} = 4.08 + 273621E_{Kinetic}$	93.0
4) $E_{Total} = 2\times10^{-5} + 1.0E_{Potential} + 1.0E_{Pressure} + 0.203E_{Kinetic}$	100.0
5) $E_{total} = 13.2\times10^{-5} + 1.0\ E_{Potential} + 1.0\ E_{pressure} + 1.03E_{Kinetic}$	100.0
6) $Lth_{Lat} = 4.59 - 60.1E_{Total}$	98.9
Where:	
E = Energy (cm). The subscripts refer to the particular energy term	
Lth_{lat} *= Lateral length (m).*	

The Pearson's correlation coefficients in Table 6 essentially ratify the observed relationships between the energy components and total energy reported by Mofoke *et al* (2004). The Table validates the strong dependence of total flow energy on potential energy, showing a Pearson's correlation coefficient of 1.00 between these two energy terms. The negative correlation coefficients demonstrate a reduction in magnitude of all energy components down the lateral length. This is apparently due to increased cumulative outflows and head losses along the lateral length.

Table 6: Pearson's Correlation Coefficients between the Flow Energy Components and lateral length of the low-cost Continuous-flow drip system

	Lateral length	$E_{Potential}$	$E_{Pressure}$	$E_{Kinetic}$
$E_{Potential}$	-0.995			
$E_{Pressure}$	-0.920	0.916		
$E_{Kinetic}$	-0.968	0.963	0.988	
E_{Total}	-0.995	1.000	0.924	0.969

Table 7:Regression Equations between Emitter Discharge and Coefficients of Variation of the Continuous-flow Drip Irrigation System

Regression Equation	R^2 [adj] (%)
7) $CV(H) = 20.4 + 0.0285q_e$	82.8
8) $CV(M) = 8.04 - 0.00825q_e$	84.4

9) $CV(HM)=21.9 + 0.0237q_e$	83.0
10) $CV(P) = 83.4 – 2.47q_e$	84.4
Where:	
CV(H) = Coefficient of variation due to Hydraulic Design	
CV(M)= Manufacturer's Coefficient of variation	
CV(P) = Coefficient of variation due to Emitter plugging	
CV(HM) = Coefficient of variation due to Hydraulic Design and Manufacturing imperfection	
q_e = discharge in drops of water per minute. (1 drop/min = $4x10^{-3}$l/hr)	

Table 8: Pearson's Correlation coefficients between Emitter discharge and Discharge Coefficients of variation of the Continuous-low drip irrigation system

	Emitter Discharge	CV(H)	CV(M)	CV(HM)	CV(P)
CV(H)	0.941				
CV(M)	-0.947	-0.999			
CV(HM)	0.942	1.000	-1.000		
CV(P)	-0.947	-0.938	0.951	-0.943	
CV(HMP)	-0.949	-0.958	0.968	-0.962	0.998

The equations in Table 9 constitute a framework for quick evaluation of similar continuous–flow drip systems especially under different design and operational settings. Thus, if it is desired to operate a similar drip system at a continuous-flow rate of say 0.078 l/hr (20 drops/min), Table 9 indicates that the associated application efficiency and distribution uniformity would be close to 96.2 and 87.0% respectively, while the overall systems efficiency may approach 43.0%. The negative Pearson's correlation coefficients in Table 10 indicate inverse relationships between the specified pairs of parameters. Irrigation efficiency would obviously reduce with increase in discharge because of excessive non-evapotranspiration losses. On the other hand, the systems distribution uniformity increases with higher emission rates because of the stronger sweeping effect achievable at higher emitter discharges. This action cleanses the emitter tubes of fine clay and silt particles that may otherwise settle in the emission path to cause emitter plugging which reflect in low systems Distribution Uniformity. From Table 10, one way of increasing the DU is to use higher flow rates. This is because of the observed positive correlation between DU and emitter discharge. Unfortunately, higher discharges especially on a continuous basis imply reduced irrigation efficiency. This stems from the negative correlation coefficient in Table 10. However, with the increasing need for global water conservation, the focus is more on increasing the irrigation efficiency of existing irrigation methods. Thus, attempts to increase DU through increase in emission rate must be carefully compromised with the economic and environmental effects of low irrigation efficiencies.

Table 9: Regression Equations between some Efficiency terms and the overall systems Efficiency of the Continuous-flow Drip Irrigation System

Regression Equation	R^2 [adj] (%)
11) $AE = 93.2 + 0.149q_e$	96.9
12) $IE = 92.4 - 0.303q_e$	95.9
13) $DU = 73.8 + 0.661q_e$	72.5
14) $AI = 51.1 + 0.387q_e$	72.3
15) $SE_{ff} = 30.1 + 0.631q_e$	93.3
16) $SE_{ff} = -368 + 4.27AE$	97.8
17) $SE_{ff} = 214 - 1.99IE$	84.4
18) $SE_{ff} = -32.3 + 0.859DU$	92.2
Where:	
q_e = *Emitter discharge (Drops/min)*	
AE = Application Efficiency (%)	
IE =Irrigation Efficiency (%)	
DU= Distribution Uniformity (%)	
AI = Adequacy of Irrigation (%)	
SE_{ff} = *Overall systems Efficiency (%)*	
q_e = *discharge in drops of water per minute.* *(1 drop/min =* $4x10^{-3}$*l/hr)*	

Table 10: Pearson's Correlation Coefficients between typical Efficiency terms and the overall systems Efficiency of the low-cost Continuous-flow drip system

	q_e	AE	IE	DU	AI
AE	0.990				
IE	-0.986	-0.955			
DU	0.904	0.943	-0.862		
AI	0.903	0.834	-0.944	0.649	
SE_{ff}	0.977	0.993	-0.947	0.974	0.797

Tables 11 and 12 provide an insight into the behaviour of the theoretical emitter discharge (q_o) under varying pressure contributions from the distributary tank (H_{Tank}) and lateral ($H_{lateral}$). The correlation coefficients in Table 12 show that q_o increases down the lateral. This is surely because the rate of energy loss through friction and pipe fittings is exceedingly compensated by hydrostatic pressure gain down the lateral.

Table 11: Regression Equations between Theoretical Emitter Discharge and Hydrostatic Pressure Head Components of the Continuous-flow Drip Irrigation System

Regression Equation	R^2 [adj] (%)
19) $q_o = 0.451 + 0.0447Lat_{Node}$	61.8
20) $q_o = 0.469 + 0.104H_{Lat}$	66.0
21) $q_o = 6.87 - 1.78H_{Tank}$	59.5
22) $q_o = 0.097 + 0.109H_{Total}$	65.8
23) $q_o = 1.56 + 0.0879H_{Lat} - 0.30H_{Tank}$	60.7
24) $q_o = 0.66 + 0.375H_{Lat} - 0.03H_{Tank} - 0.121Lat_{Node}$	59.2

Where:
q_o =*Theoretical Emitter discharge (Drops/min)*
Lat_{Node} = *Lateral Node number (1, 2, ….9)*
H_{lat} = *Hydrostatic Pressure contribution from the drip lateral*
H_{Tank} = *Hydrostatic Pressure contribution from the distributory tank*
H_{Total} = *Total Hydrostatic pressure head*

Table 12: Pearson's Correlation coefficients between Theoretical Emitter discharge Hydrostatic pressure contributions of the Continuous-low drip irrigation system

	Lat_{Node}	H_{lat}	H_{Tank}	H_{Total}
H_{lat}	0.996			
H_{Tank}	-0.929	-0.939		
H_{Total}	0.996	1.000	-0.932	
q_o	0.816	0.838	-0.804	0.837

4. Conclusions

The continuous-flow drip irrigation system offers satisfactory hydraulic performance characteristic with drip irrigation systems. The systems flow energy is most sensitive to potential and kinetic energies. Thus, without flow control, good land levelling is necessary for attainment of high distribution uniformity with the system. Also, realisation of high irrigation efficiency is a major precursor for obtaining good overall systems efficiency with the drip system. Even with flow regulation by the Medi-Emitter, the systems discharge is largely affected by emitter plugging. However, the limit of discharge variation is small and thus, does not justify more technical and expensive ameliorative procedures.

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