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Effect of Stream Sizes and Furrow Geometry on Furrow Irrigation Erosion in Samaru, Northern Nigeria

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Authors' contributions

This work was carried out in collaboration between all authors. Author JMD designed the study, wrote the protocol and wrote the first draft of the manuscript and performed most of the editing of the paper. Author HEI played a part in the designing of the study and editing of the manuscript. Literature searches, analyses of the study, discussions of the result and drawing the conclusion were jointly handled by all the authors. In addition, authors BGU and AUB handled the largest share of the funding. All authors read and approved the final manuscript.

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ABSTRACT

Furrow irrigation is one the most widely used means of water application to crops in Samaru and environs. Erosion created by furrow irrigation is threatening the sustainability of furrow irrigation in Samaru. The continuous loss of soil rich in plant nutrients depresses the productive capacity of soils. This study explored the effects of three irrigation stream sizes (2.5, 1.5 and 0.5 l/s) two furrow lengths (90 and 45 m) and two furrow widths (0.75 and 0.9 m) on furrow irrigation-induced erosion. Measurements of runoffs and sediment concentrations in furrows during irrigation events were made in the dry irrigation seasons of 2009/2010 (trial 1) and 2010/2011 (trial 2) on an area of 0.36 and 0.2 ha respectively. Soil erosion in each furrow was computed from the runoff, sediment concentrations and the furrow wetted area. Wooden profilometers were used to examine the

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dynamics of soil erosion along the furrows. The variations in soil erosion among the treatments were significant at P<0.001. The application of 2.5 l/s stream size induced the highest soil erosion of 0.4697 t/ha/season and runoff volume of 104.47 l/season. The use of 45 m-long furrow length resulted into the highest soil erosion of 0.4986 t/ha/season. And soil erosion of 0.4700 t/ha/season was recorded in 0.75 m-wide furrows. The results evidently showed that stream size was principally responsible for the erosion losses during furrow irrigation. Short furrows that limit redistribution of eroded soil particles, were more prone to erosion than long furrows. The result also pointed that increasing furrow width from 0.75 m could be a means of limiting furrow irrigation erosion. The in-field soil erosion measurements showed that bulk of the soil erosion occurred from the head end of the furrows and deposited on the lower portions of the furrows.

Keywords: Furrow irrigation; soil erosion; stream sizes; furrow geometry; samaru; Nigeria.

1. INTRODUCTION

Furrow irrigation is one of the extensively used means of irrigating crops in many developing countries. It is especially recommended for growing row crops on medium to heavy textured soils and is preferred over other surface irrigation methods due to its simplicity and low capital cost [1]. Furrow irrigation method has been identified as one of the common farming practices that causes soil erosion in irrigated farms. Soil erosion threatens human efforts towards sustaining global population with food and fiber and it is closely linked to economic vitality, environmental quality and human health concerns. Sojka et al. [2] reported that 75% of Idaho furrow-irrigated fields lost their entire ‘A’ horizon in the upper reaches. There was also 2 to 4-fold increase in “topsoil” at the lower ends, reducing productivity by 25% relative to pre-erosion and reducing yields by 20–50% in areas where top soil was lost. Brown et al. [3] also reported soil loss of 40 to 100 Mg ha^{-1} from furrow irrigated hops on a 3.5% slope. Koluvec et al. [4] reported that 21% of the 15 million hectares of irrigated land in United States of America (USA) are affected by soil erosion. Losses at this scale are not sustainable and result in increasing dependence on costly inputs such as fertilizers and soil amendments that are used to make up for the beneficial qualities that were present in the lost topsoil [5]. Erosion results in the degradation of a soil’s productivity in a number of ways: It reduces the efficiency of plant nutrient use, damages seedlings, decreases plants’ rooting depth, reduces the soil’s water-holding capacity, decreases its permeability, increases runoff and reduces its infiltration rate. Nasri et al. [6] reported depressed maize growth and yield in response to furrow irrigation erosion in Iran. The loss of nutrients alone resulting from soil erosion translates to severe economic and environmental costs to farmers and the nation at large. In the United States, more than 60 percent of water-eroded soils end up in watercourses [5]. This leads to the sedimentation of dams, disruption of aquatic ecosystems and contamination of drinking water supplies. Furrow irrigation-induced erosion (FIIE) has accordingly been acknowledged as one of the greatest global threat to sustainable agricultural productivity and clean water. Preventing irrigation-induced erosion from irrigated agriculture is therefore imperative to the preservation of natural ecosystems [2].

In Samaru and environs, northern Nigeria, studies on the variability and trend in furrow irrigation-induced erosion are not well documented in the literature, suggesting that not much research has been done. The bulk of available studies dwelled on understanding, reducing and mitigation soil erosion under rainfall characteristics. The need for information on furrow irrigation erosion presses harder in the face of the high degree of unskillful handling of irrigation practices among many Nigerian farmers [7]. Typical furrow irrigation practice in the area could be described as haphazard as the selection of the flow stream sizes, length of furrows, furrow widths, depth of tillage, choice of direction of flow of water, frequency of water application, cropping pattern, among others, do not follow specific pattern, determinants or schedule. Mostly, the length of the farms determines the lengths of furrows or it is irregularly sub-divided into smaller lengths, sometimes as short as 20 m. However, the quantitative estimate of soil loss due to furrow irrigation is uncertain, especially with reference to particular flow stream size, furrow length, furrow width. A reliable quantitative data on the extent and rates of soil erosion is necessary for sustainable and comprehensive assessment of the magnitude of the problem for developing effective soil conservation measures. The aim of this study was to examine the effect of stream sizes, furrow lengths and furrow widths on furrow irrigation-induced erosion in Guinea Savannah agro-ecological environment of northern Nigeria.

2. MATERAILS AND METHODS

2.1 Study Area

The Field experiments were conducted during the 2009/2010 and 2010/2011 irrigation seasons at the Irrigation Research Field of the Institute for Agricultural Research (IAR) farm, Samaru-Zaria, along the Zaria-Sokoto road (11º1´N, 7º38´E, on the altitude of 686 m above mean sea level). Samaru is situated within the Northern Guinea savanna zone of Nigeria. It receives average 1,100 mm of rainfall spread between May and October [8]. The soil of the experimental site was classified as luvisols [9], belonging to sandy loam textural class on the USDA textural triangle with a mean bulk density of 1.6 gcm^{-3} (Table 1). The soil analysis indicates a moderate percentage of organic matter content but generally found to be poor in calcium, sodium, nitrogen and potassium. The mean values of organic carbon, pH and cation exchange capacity of the soil were 1.18, 5.5 and 7.45; implying that the soil is poor in organic matter content and slightly acidic in nature. There was no rainfall recorded during the studies. The mean values of air temperature and relative humidity during the study periods were 26.44ºC and 16.46% respectively in 2009/2010, and 25.56ºC and 15.73% in 2010/2011.

2.2 Experimental Treatments and Field Layout

The experimental factors studied were stream size Q, furrow length L and furrow widths W at 3, 2 and 2 levels respectively. The stream sizes were 2.5, 1.5 and 0.5 l/s; furrow lengths were 90 and 45 m and furrow widths were 0.75 and 0.9 m. The combination of the stream sizes, furrow length and furrow widths resulted in to twelve (12) different treatments that were imposed on the field (Table 2). The layout of the experiment was a randomized complete block laid in a split plot design with four replications in both 2009/2010 (trial 1) and 2010/2011 (trial 2) seasons. The stream sizes were placed in the main plots, while furrow lengths and furrow widths were studied in the sub-plots. In both seasons, each replication comprised of three plots and each experimental plot had three and two ridges in trials 1 and 2 respectively. A ridge was used to separate plots while two ridges to separated two adjacent replications. A total of 0.36 ha and 0.2 ha were used in trials 1 and 2, respectively.

The experimental field was ploughed, harrowed and ridged at 0.75 m spacing. Plots were marked out and treatments allocated in accordance with the randomization. Short (45 m long) and long furrows (90 m long) and the conventional (0.75 m wide) and (0.9 m wide) furrows were marked out and adjusted accordingly manually.

2.3 Field Measurements

2.3.1 Irrigation/Erosion related data

Prior to commencement of irrigations, water-sediment collection stations were established 5 m before the end of each furrow by placing a 30-cm wooden peg. A sample consisting of a mixture of water and soil sediment herein is referred to as water-sediment sample. Flow of water in the furrows were measured using a cutthroat flume installed 5 m from entry at the upstream of each of the furrows, and at the tail end of the furrows for the measurement of outflows. Water flowing out of the furrows was measured as runoff. One-liter of water-sediment samples were collected at each of the established measurement points for determination of sediment concentrations. These samples were filtered into pre-weighed metal containers; the collected residues were oven-dried at 105ºC over 24-hour period and re-weighed in laboratory. The sediment concentrations (g/l) that were calculated from the dried residues and the runoff volumes were used to calculate soil erosion per furrow. Runoff volume was calculated as the product of the runoff discharge (l/s) (from the downstream flumes) and duration of runoff discharge. Soil erosion at the end of the furrows was calculated as the product of the sediment concentrations and runoff volumes divided by the wetted area. The wetted areas were calculated as the product of the top widths of flow of water and the lengths of the furrows [10,3,11,12].

2.3.2 Measurement of soil erosion in the furrow cross section

Wooden profilometers were constructed and installed at the up-, middle- and down-stream of some selected furrows to monitor soil scouring and/or deposition during irrigation events. A profilometer is a device used to measure changes in surface's profile aimed at quantifying its roughness and thickness [13]. The profilometers constructed and used in this study is made up of a wooden bar 1 m long that were perforated 3 cm apart and cut longitudinally then joined again at the two ends by means of metal screws. Graduated wooden pins (approximately 70 cm long each) were pushed into each of the holes. The furrow lengths that were 90 m long were divided into three segments of 30 m each and the profilometers were installed mid way in each of the segments before each irrigation with the pins adjusted vertically such that each of them barely touched the furrow surface. The screws at each end were then tied to keep the pins in place, the initial positions of the pins were recorded and the assembly removed. After an irrigation event, the profilometer assembly was brought back, the pins were adjusted to barely touch the soil surface again and new readings were taken. The vertical differences on the pins between the initial and final positions were recorded. These values were plotted in a Microsoft Excel to obtain a clear difference between the initial and final profile of the furrow and a cavity between them signifying earth movement or deposition. Scouring was indicated by the appearance of the final furrow profile being positioned below the initial one, otherwise it is a deposition. Major Gridlines were inserted in each of the plots and every complete cell in a cavity was assigned a value of 1 m^2, incomplete cell were joined together to a complete one. Thus, the areas within each of the cavities were estimated. These areas were multiplied by the lengths of the representative segments to arrive at the volume of soil moved or deposited within the segment. Profilometers were employed by many researchers such as Oyonarte and Mateos [14] and Dilawari and Kaleita [13] to characterize disturbances and changes in the soil surface.

2.4 Data Analysis

All data collected related to soil erosion were analyzed with the General Linear Model (GLM) procedure using the SAS package. The combined analysis was used to analyze the results for the two trials with split-plot arrangement. Treatment means were compared by using the Duncan Multiple Range Test (DMRT)'s Least Significant Difference (LSD) test at the 0.05 and 0.01 probability levels.

3. RESULTS AND DISCUSSION

3.1 Sediment Concentration and Soil Erosion

The average sediment concentration, (ASC), runoff volume, ROV and erosion, E were all significantly ($P<0.05$) affected by stream sizes, furrow lengths and furrow widths (Table 3). Both the seasonal and combined analysis showed that the values of ASC, ROV and E, at 2.5 and 1.5 l/s stream size were at par, but were statistically higher than those recorded at 0.5 l/s.

The combined analysis of the two years' data further revealed that soil erosion that resulted from 2.5 l/s was only 9% higher than the values recorded from 1.5 l/s. The results of ASC, ROV and soil erosion show that the erosive powers of the 2.5 and 1.5 l/s stream sizes were not significantly different. The flow velocities of the three stream sizes were 0.175, 0.148 and 0.1034 m/s for 2.5, 1.5 and 0.5 l/s stream sizes. Brown et al. [3] reported incidences of higher erosion and runoff rates in higher stream sizes compared to lower ones. High stream size is however a relative term depending on the type of soil at hand and slope amongst others. Cater [15] found that a stream size of 2.0 l/s yielded soil erosion of 821.4 kg and 504 l runoff on sandy loam soil compared to erosion of 87.2 kg and 608.4 l runoff on a silty clay soil in only one hour furrow irrigation.

Generally, the result shows that soil loss decrease with stream size. The shear stress and sediment transport capacity are greater in larger stream sizes [11]. The sediment load, defined as the rate of sediment leaving any section of a channel is equal to the product of the sediment influx into the section and erosion less deposition [16].

This result demonstrated the relationship between soil erosion in furrow and stream sizes; provided that the slope and other soil physical properties remain constant the same.

Table 3 also shows the ROV in shorter furrows was 23% larger than those that flowed from the longer furrows. The ASC in the short furrows were also 26.2% compared to those from the longer furrows and this had translated to 22% increase in erosion. The differences in these values were attributed to the high runoff discharge rates in the shorter furrows and low soil cover, especially at the early stage of the irrigation. Furrow stream sizes are reduced by the effect of infiltration along the furrows. This phenomenon is limited by length in short furrows and hence the high ROV. Carroll et al.[17] reported similar findings. Differences among soil types, terrains, and management practices explain this variation.

Table 1. Some physico-chemical properties of the soil at the experimental site (0–90 cm from the topsoil)

	Sand (%)	Silt (%)	Clay (%)	Textural class	O.C	ρ	Exchangeable Cations ($cmolKg^{-1}$) Ca	Mg	K	Na	CEC	pH (H_2O)	pH($CaCl_2$)	TN
2009/2010	67.1	16.5	13.5	Sandy loam	1.20	1.50	4.20	2.60	0.09	0.07	8.7	5.2	4.7	0.105
2010/2011	68.5	17.5	17.8	Sandy loam	1.16	1.6	3.7	1.82	0.15	0.14	6.2	5.8	4.8	0.153
Mean	67.8	16.45	15.65	Sandy loam	1.18	1.6	3.95	2.21	0.12	0.105	7.45	5.5	4.75	0.29

Key: O.C = organic matter content (%), ρ = Mean bulk density (gcm^{-3}); TN=Total nitrogen (%), C.E.C= cation exchange capacity; K = potassium, Na = sodium; Mg = Magnesium; Ca = Calcium

Table 2. Description of the experimental treatments

Treatments	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}	T_{12}
Description	$Q_1L_1W_1$	$Q_1L_1W_2$	$Q_1L_2W_1$	$Q_1L_2W_2$	$Q_2L_1W_1$	$Q_2L_1W_2$	$Q_2L_2W_1$	$Q_2L_2W_2$	$Q_3L_1W_1$	$Q_3L_1W_2$	$Q_3L_2W_1$	$Q_3L_2W_2$
Remarks	Q_1 = 2.5 l/s, Q_2 = 1.5 l/s, Q_3 = 0.5 l/s, L_1 = 90 m furrows, L_2 = 45 m furrows, W_1 = 0.75 m-wide furrows, W_2 = 0.9 m-wide furrows											

Table 3. Effect of stream sizes, furrow lengths and furrow widths on average sediment concentration, runoff volume and soil erosion

Treatments	ASC (g/l)			ROV (l)			Soil erosion (t/ha/season)		
Stream sizes (L/s)	2009/2010	2010/2011	Combined	2009/2010	2010/2011	Combined	2009/2010	2010/2011	Combined
2.5	37.35a	35.02a	36.23a	101.56a	107.39a	104.47a	0.47a	0.47a	0.47a
1.5	33.67a	30.30b	31.99b	100.26a	101.96a	101.11a	0.44a	0.42a	0.43a
0.5	29.48b	30.03b	29.76b	99.09b	93.17b	96.13b	0.32b	0.31b	0.32b
SE ±	0.448	0.362	0.380	18.651	19.747	2.60	0.0007	0.0007	0.02
Furrow length (m)									
90	28.84b	22.96b	23.90b	85.93b	88.42b	86.99b	0.37b	0.40a	0.39b
45	32.48a	37.74a	35.11a	112.01a	115.26a	112.96a	0.54a	0.46a	0.49a
SE ±	0.298	0.2415	0.310	12.434	13.166	2.13	0.0004	0.0005	0.01
Furrow width (m)									
0.75	34.01a	33.08b	34.31a	100.84a	108.76a	104.79a	0.47a	0.48a	0.47a
0.9	31.32b	30.61b	30.97b	87.10b	90.91b	89.00b	0.41b	0.43b	0.43b
SE ±	0.298	0.2415	0.310	12.434	13.166	2.13	0.0004	0.0005	0.01

Means followed by the same letter within the same column are not significantly different at 5% level of significance using DMRT

Evidently, soil erosion is severer in short furrows than in the longer ones. This is because irrespective of lengths of run, soil erosion is greater at the upstream end where the stream size is largest and the energy to erode is greatest [17]. As the stream size gradually decrease along the furrow by the effect of infiltration [11], the sediment detachment, and transport capacity decreases and so does soil erosion along the furrow. Deposition and redistribution do occur along the furrow lengths as the flow advances down, the effect of this deposition and redistribution is limited by distance in shorter furrows, consequently, soil loss is most likely to be higher in shorter furrows than in the longer ones.

Segreen and Trout [18] earlier showed that the deposition and redistribution of sediments along the furrows leads to a phenomenon known as surface sealing. This phenomenon, according to their findings, can reduce infiltration by 50%. The surface seal serves as a pavement and thus favours continued movement of sediment-carrying water that flows down the furrow. This explains why sediments are still captured at the tail end of the furrows irrespective of the length of the run. Fig. 1, however, shows that much of the soil loss occurred at the upstream of the furrows and those captured at the end of the furrow are left overs of the sediments that were eroded at the upstream end, since there is limited or no erosion at the downstream ends. For example sediments captured at the tail end in furrows irrigated with 2.5 l/s was 42.5% lower than the sediment captured in the upstream. This value was 50.6% in furrows irrigated with 0.5 l/s. This means much of the sediment eroded are redistributed along the furrow before reaching the end of the furrow. Carrol et al. [17] also reported that soil losses are greater in short furrows than in long furrows irrespective of length of flow and with or without soil protective cover.

The variation in furrow widths had resulted into significant differences among ASC, ROV and erosion in both the two seasons (Table 3). The use of 0.9 m wide furrow width had depressed ASC, ROV and soil erosion by 12%, 18% and 0.014 t/ha/season respectively. This means the conventionally used 0.75 m furrow spacing constricts the flowing water and thus “streambank” erosion becomes more pronounced in addition to the bed scouring action. This observation is buttressed by McKnight and Hess [19].

The effects of furrow width had mostly been ignored as a factor in sediment dynamics in irrigated furrows. However, the results of this experiment show that more soil erosion had occurred in 0.75 m-wide furrows than in 0.9 m-wide. This demonstrates that narrow furrows are more prone to soil erosion compared to the wider ones. The shear stress, τ, which is the force per unit area developed on a wetted area of channel acting in the direction of flow, is directly proportional to the hydraulic radius, R, which in turn depends on flow depth, d. For any particular stream size, d is smaller in wide furrow than in narrow ones. Hydraulic radius and hence shear stress are thus greater in narrow furrows. Wider furrows are therefore less susceptible to severe soil erosion [16].

The trend of soil erosion along the furrows appeared to be somewhat consistent for all the stream sizes studied. Erosion was highest at the first upper segment of the field and began to decrease, but remained fairly constant in the second segment and then decreased in the third and fourth segments of the field. This implies that maximum erosion had occurred at the first upper segment of the furrows and deposition began somewhat in the second segment, and continued to the end of the furrows. The erosion rate was highest at the upper end of the furrows partly due to the initial high flow erossivity at the entrance of the furrows and partly to higher initial transport capacity relative to the transport. As flow rate decreased along the furrows in response to infiltration, sediment concentration in the water increased and erosion decreased until the transport capacity of the flow was reached and net deposition began, but sediment transport continued till the end of the field.

Trout [11] found that in irrigation furrows, the flow rate decreases along the furrow as water is infiltrated and typically, 50 to 80% of the furrow inflow infiltrates before it reaches the furrow end, resulting in a corresponding flow rate decrease along the furrows. However, sediment transportation and distribution continues so long as inflow continues.

3.2 Soil Erosion Dynamics along a Furrow

Figs. 1, 2 and 3 present the variations in furrow cross sections following irrigation with 2.5, 1.5 and 0.5 l/s stream sizes. The Figs. also show that soil erosion trends along the furrows were generally highest at the upstream and progressively decrease as the flow goes down the furrow. The scouring effects of the stream sizes is clearer looking at the diagrams traced from the profilometer readings at up, mid and downstream of the furrows (Figs. 1 to 3). The gaps between the series 'Before' and 'After' represent how much soil that was eroded after the irrigation. Although this graph represents seasonal average of six numbers of irrigations, it could be observed that the gap Fig. 1a is wider, signifying more erosion in the upstream relative to the gap in Fig. 1b or c where scouring was limited.

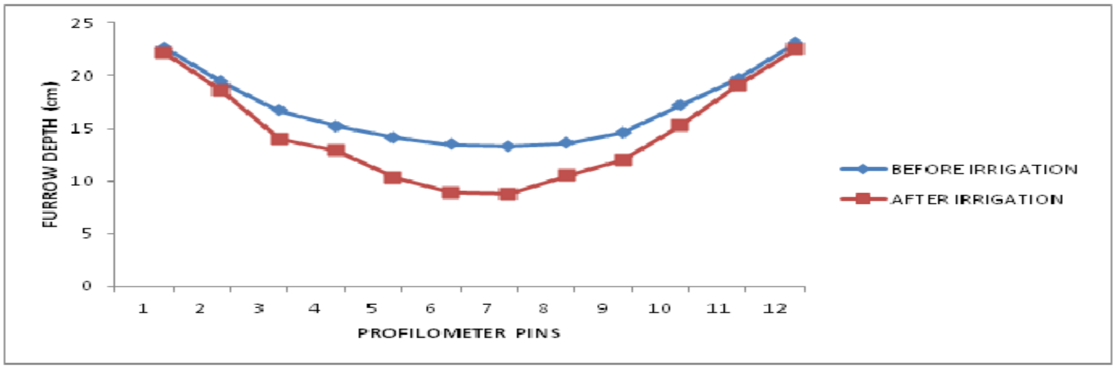

Fig. 1a

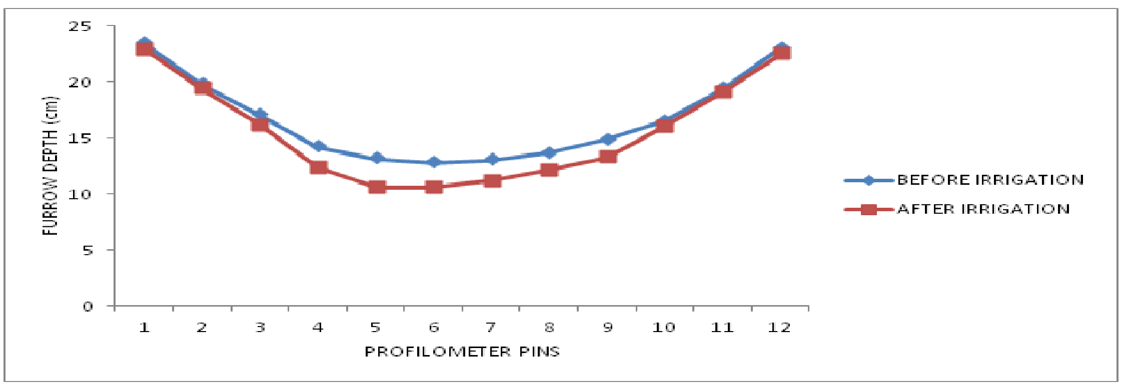

Fig. 1b

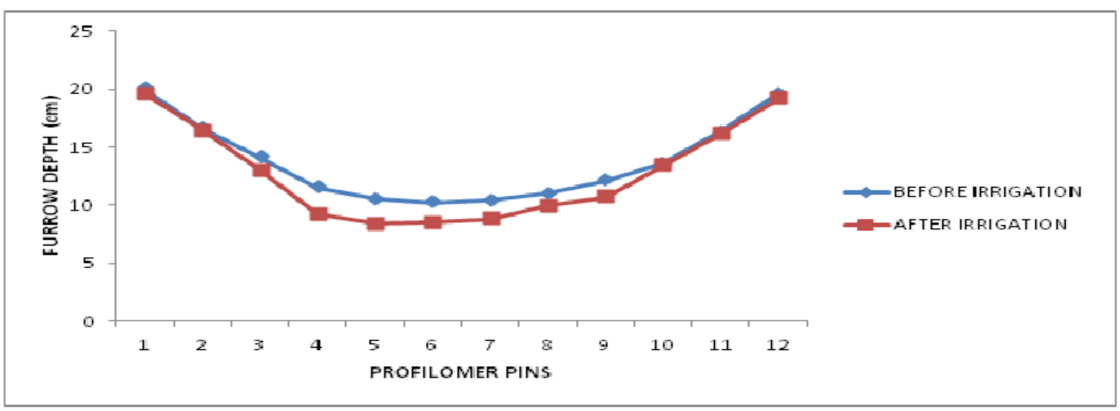

Fig. 1c

Fig. 1. Variations in furrow cross section (a) upstream (b) midway and (c) downstream of the furrow before and after irrigation with 2.5 l/s

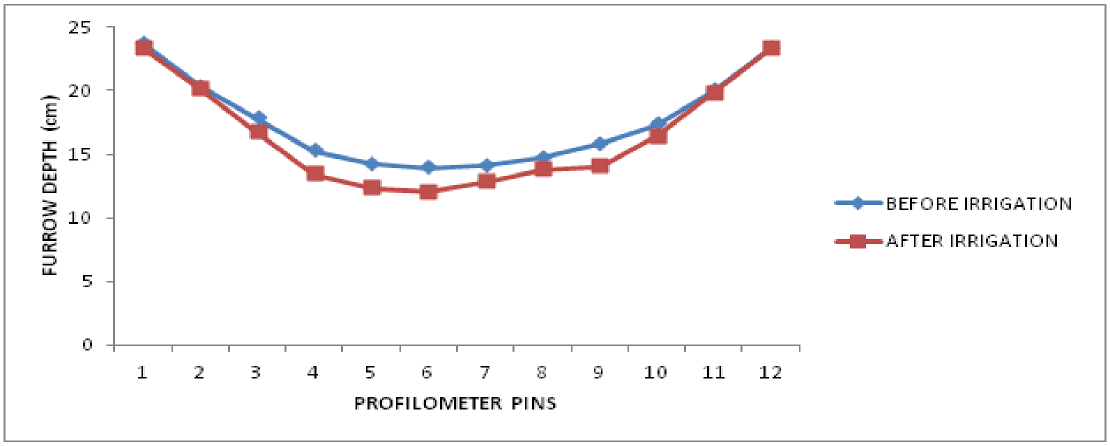

Fig. 2a

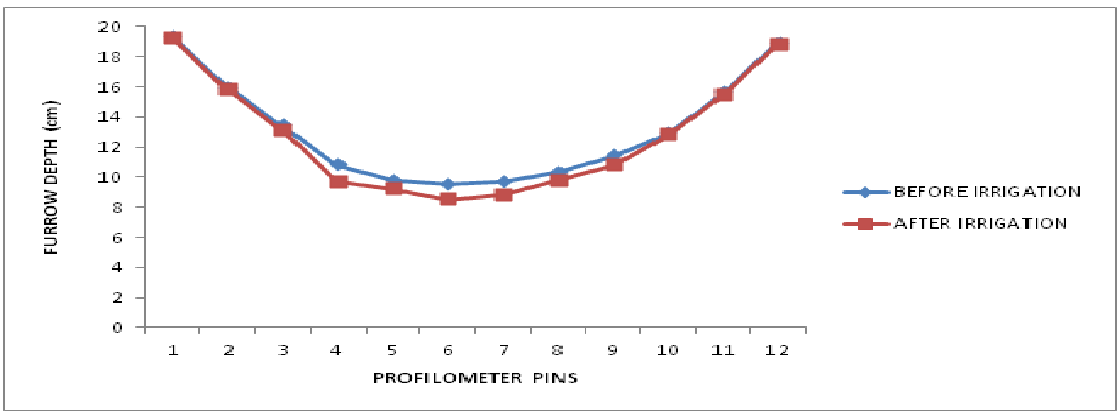

Fig. 2b

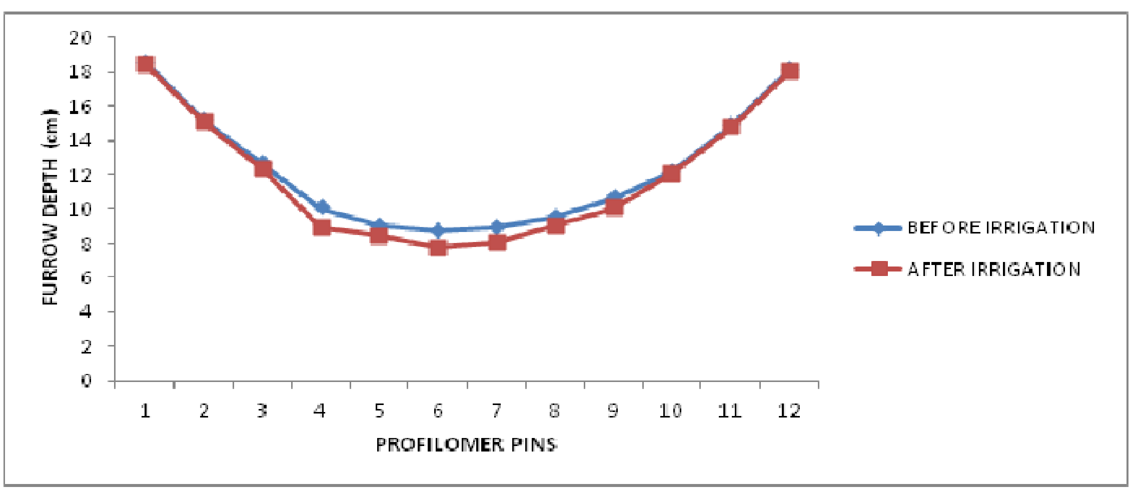

Fig. 2c

Fig. 2. Variations in furrow cross section (a) upstream (b) midway and (c) downstream of the furrow before and after irrigation with 1.5 l/s

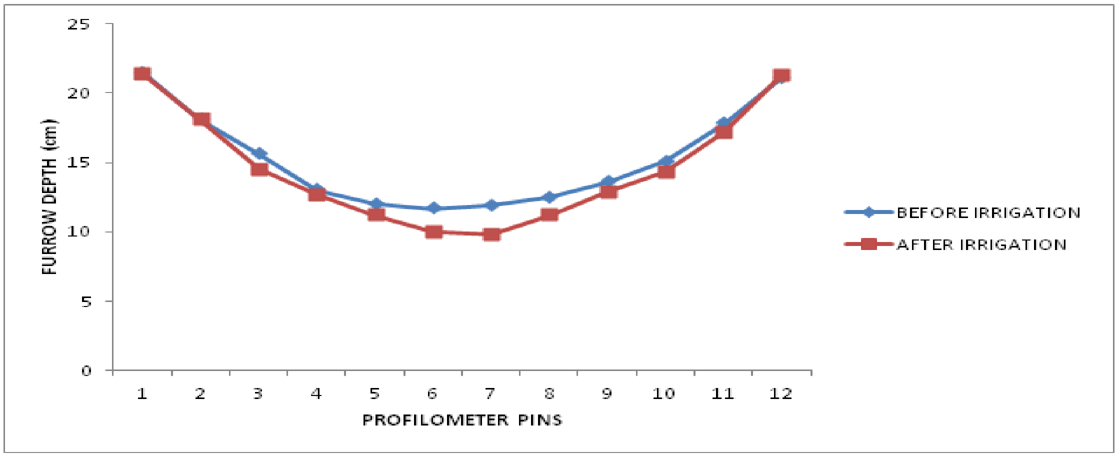

Fig. 3a

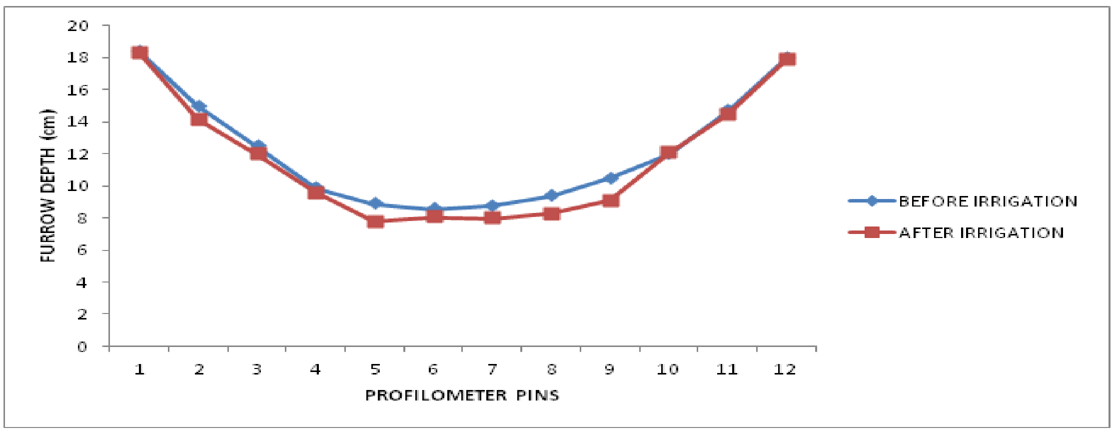

Fig. 3b

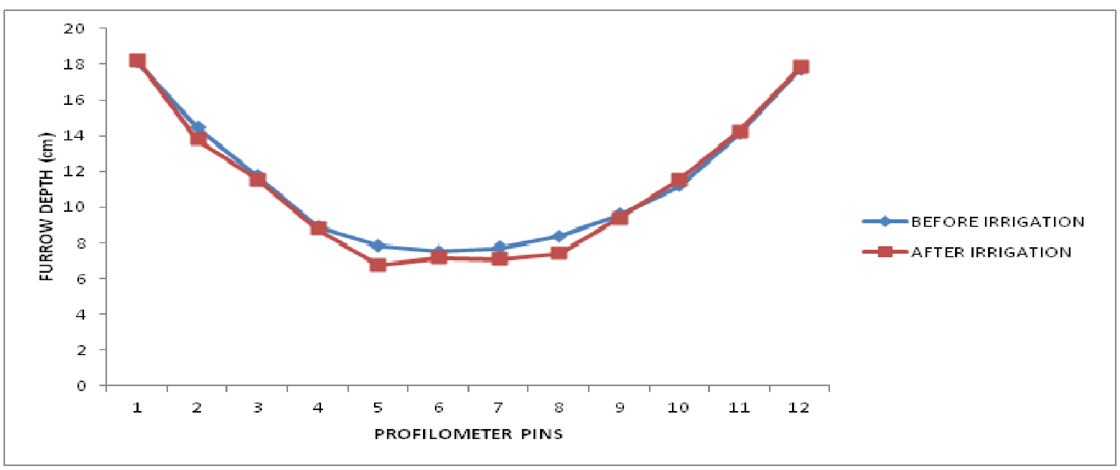

Fig. 3c

Fig. 3. Variations in furrow cross section (a) upstream (b) midway and (c) downstream of the furrow before and after irrigation with 0.5 l/s

Soil erosion and depositions that were measured with the profilometer (Figs. 1, 2 and 3) were estimated and presented in Tables 4 and 5 respectively.

The trend of soil erosion in Table 4 shows that soil erosion is highest at the first upper segment of the furrows. For example, in furrows irrigated with 2.5 l/s, about 50% of earth movement occurred in the first one-third segment of the furrow. Soil erosion that was estimated at the last one-third segment was only about 18% of the total soil erosion that occurred in the furrow. Similar trends were observed with the other two stream sizes. Trout et al. [20] found that soil erosion was greatest in the upper one-quarter of furrows. This could be attributed to the initial large inflow of water into the furrow and the gradual decrease in the sediment transport capacity of the flow as it runs down the furrow due to infiltration action. This confirmed the earlier observation that soil erosion was highest at furrow upstream and least at the downstream. In Figs. 2 and 3, sediment depositions were noted (Table 5). There were more depositions in furrows irrigated with 0.5 l/s. Similarly, more depositions had occurred at the downstream of the furrow than other positions studied.

Table 4. Estimates of volume of soil scoured (m^3) in irrigated furrows made from Figs. 1, 2 and 3

Stream sizes (l/s)	Measurement positions along the furrows		
	Upstream	Mid way	Down stream
2.5	50.7	32.73	17.73
1.5	23.25	14.73	11.49
0.5	18.48	9.24	5.49

Table 5. Estimates of soil depositions (t/ha) in irrigated furrows made from Figs. 1, 2 and 3

Stream sizes (l/s)	Measurement positions along the furrows		
	Upstream	Mid way	Down stream
2.5	0	0	0
1.5	0	0	0.249
0.5	0	1.002	2.001

4. CONCLUSION

The study also established that larger fraction of the soil erosion occurred at the upstream segment of the furrows. This implies the need for the review of the customary practices where a large initial stream of water is released on to the hitherto dry soil. Generally, an improvement in on-farm water management, particularly in determining the correct amount of water to apply, using the appropriate range of stream sizes/inflow times for effective application is advocated. This could be achieved by extending to the farmers the appropriate design recommendations of the ranges of furrow stream sizes and their corresponding furrow lengths and widths such as avoiding irrigation in short and narrow furrows. Such improvement would go a long way in controlling furrow irrigation erosion. Social-economic, institutional and technical constraints to improved furrow irrigation system designs and management alternatives need to be fully explored to identify the most feasible combination of stream sizes and furrow geometry toward improving the irrigation practices and averting soil erosion.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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