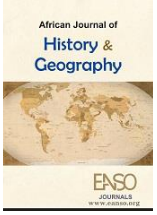

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Original Article

Spatial Patterns of Infiltration on a Bench Terraced Hillslope in Kigezi Highlands, South-Western Uganda

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ABSTRACT

The spatial patterns of infiltration on bench terraced hillslopes are not fully understood. Moreover, these patterns are pivotal for assessing hydrological processes affecting water distribution, surface flow and soil erosion, and groundwater recharge. Our objective was to determine the spatial patterns of steady-state infiltration rates on a bench terraced hillslope; and assess the influence of soil properties on the infiltration process. We employed Geo-Information Science (GIS) to stratify the terraced bench hillslope into three slope position sequences, namely, Upslope, Middle slope, and Downslope. Besides, in each slope position segment, a bench terrace was randomly selected; and later stratified into three plot segments, namely, Upper (A), Middle (B), and Bottom (C), for purposes of conducting infiltration experiments. At each plot segment, three infiltration experiments were replicated to ascertain the intra-bench and inter-bench terrace steady-state infiltration rates. The experimental field design consisted of three slope position sequences, three plot segments, and three replicates, hence, leading to a total of twenty-seven (27) experiments. The infiltration measurements were conducted using a standard double-ring infiltrometer. We sampled soil for two different depths, namely; 0-15 cm and 15-30 cm, at each infiltration experiment to establish its relationship to the infiltration process. Using a Spatial Autocorrelation tool embedded in ArcGIS 10.2, we analysed the spatial patterns of infiltration along the hillslope. Furthermore, a Two-Way analysis of variance (ANOVA) was used to determine differences between the means of the infiltration rates across the hillslope sequences. Descriptive Statistics were used to investigate the Degree of

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Variability in infiltration rates. Results showed that beyond 15 m, infiltration rates vary significantly (P<0.018) from 5 cm hr-1 to 40 cm hr-1 between the bench terraced hillslope sequences, with a mean rate of 21 cm hr-1. Intra-bench steady-state infiltration rates varied higher in the Bottom (C) compared to Upper (A) and Middle (B) segments, especially in the Upslope sequence, where rates varied from 6 cm hr-1 to 20 cm hr-1 with a coefficient of variation (CV) of 45%. The clay content in the soil had a significant influence (P<0.003) on infiltration in the study sites of the hillslope with a correlation coefficient (R, r2 = -0.5). We concluded that the spatial patterns of infiltration on a bench-terraced hillslope are influenced by slope position. Infiltration is higher at the Downslope and Middleslope bench terraces as compared to the Upslope bench terrace. Soil texture and the structural condition of the bench terraces themselves play a cardinal role in the variations in infiltration. Within the bench terraced land parcels, infiltration is higher on the downslope and lower in the upslope positions. Since percent clay content increased with slope, it was noted as a fundamental soil characteristic affecting infiltration within the bench terraces. Our recommendation was that in bench terraces where steady-state infiltration was high such as in downslope and middle slope positions, the terrace bunds should be strengthened with grass and stone embarkments to consolidate them coherently. This strategy may reduce terrace bund breakages and consequently counter surface flow on the bench terraced hillslope. Besides, in areas where low steady-state infiltration rates were recognised, such as the upslope position, agronomic practices should be enhanced.

APA CITATION

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INTRODUCTION

Infiltration is one of the major factors that affect hillslope hydrologic processes (Pratama et al., 2016; Grismer, 2016; Ahmed et al., 2014; Dagadu & Nimbalkar, 2012; Mandal et al., 2005). It is also a crucial process for understanding the hydrological response of agricultural hillslopes, especially under conditions of extreme precipitation (Bronstert et al., 1998), hence impacting crop production. Through water flows on the hillslope, infiltration processes affect the quality of the terrestrial ecosystem and slope stability (Gregory et al., 2005). The velocity or speed at which water enters the soil is referred to as the infiltration rate (Adeniji et al., 2013), which is usually measured by the depth, in units (mm/i/cm), of the water layer that can enter the soil in one hour (Sihag et al., 2017; Ahmed et al., 2014; Gregory et al., 2006). This rate decreases as the soil become saturated. The measure of water into the soil on a hillslope is a vital indication of the efficiency of water for improving the vigour of crops and for minimising erosion by water.

Whereas there is scanty information on hydrological processes, hillslope position and morphology pose as additional for understanding infiltration (Harden & Scruggs, 2003a). The infiltration rates along a hillslope may change with topographic positions, and their trends may also vary over time. For example, Harden and Scruggs (2003) established that infiltration is reduced with the downslope movement of the slope, a view which is widely debated in the literature. Spatial dynamics in infiltration on a hillslope befall when the quantity that is measured in one slope position exhibits values that differ across the other slope sections. Within the slope position, infiltration may also vary across replicates. These variations can be assessed using the data of steady-state infiltration rates. Appropriate soil management, most especially in rural agrarian watersheds, becomes a huge challenge without the knowledge of patterns of soil infiltration behaviour (Ayorinde & Uka, 2012). Moreover, the soil resources on hillslopes of such catchments are usually threatened by huge volumes of infiltration, which in turn, contributes to severe water erosion. The majority of the highland environments in Uganda are evidently being degraded due to this problem. One of the most striking issues is that even where soil and water conservation measures are being emphasised, such as using bench terraces in the fragile highlands of South Western Uganda, soil erosion is still a menace due to a lack of understanding of patterns of water infiltration. In this area, the hillslopes majorly have sloping bench terraces as fields for crop cultivation (Miiro, 1999), which induces rapid infiltration and a consequential increase in water erosion. Therefore, the bench terraces themselves influence hillslope infiltration processes through positioning, angle, cover, tillage, and nature of bands; as well as the variations in the intrinsic properties of the soil (Osuji et al., 2010). The relationship between bench terraces and soil nutrients attracted the interest of many researchers, such as (Siriri et al., 2005), who have demonstrated that bench terraces affect soil properties and water entry into the soil (Wulan Ayu & Prijono, 2013; Yimer et al., 2008). Unfortunately, the positioning of bench terraces along the hillslope limits the technologies of agricultural intensification such as mechanised agriculture and increased use of fertilisers that would increase production without adverse environmental impact and without conversion of additional non-agricultural land in the catchment. Thus resort to arable land expansion, which comes with infiltration varying over small extents in the hillslopes. This makes cultivation entirely controls infiltration on the hillslopes of South Western Uganda making the watershed to be under threat if there is no intervention.

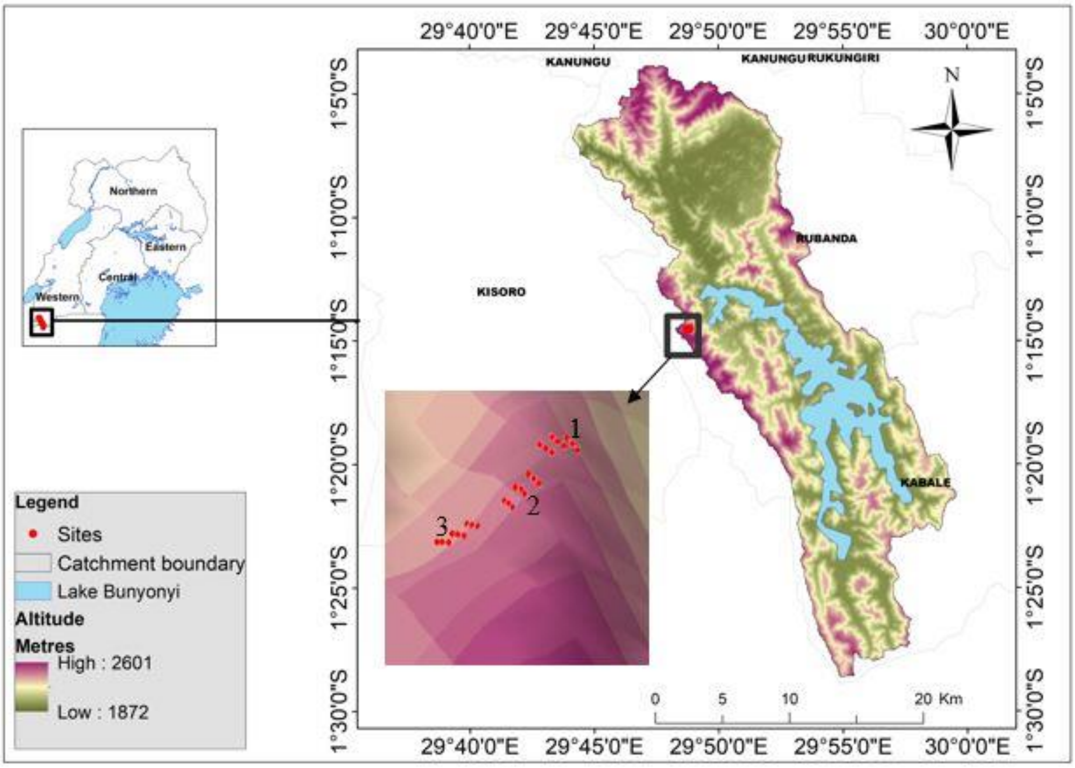
Quantitative research on infiltrating in the bench terraces is dismal, yet it is important for soil and water conservation in the cultivated highlands of South Western Uganda. Furthermore, variations in the properties of soil, especially soil texture and structure on the hillslope, strongly control hillslope infiltration processes (Pratama et al., 2016; Siriri et al., 2005). Soil texture consequently affects the hydraulic conductivity of the soil, which controls hillslope infiltration (Casanova, 1998), but there is no systematic research in this regard to address the question of spatial patterns of infiltration on bench terraced hill slopes. In light of this, our objective was to determine the spatial patterns of steady-state infiltration rates on a bench terraced hillslope; and assess the influence of soil properties on the infiltration process.

MATERIAL AND METHODS

Study Site

The study was conducted on a victimised north-facing bench terraced hillslope in the Bunyonyi catchment of Kigezi highlands (*Figure 1*). Bunyonyi catchment was delineated using ArcGIS 10.2 software. It covers areas of Rubunda and Kabale districts in Southwestern Uganda. Bunyonyi sub-catchment geographically lies between Latitudes 1^{0}13’0’’ S and 1^{0}14’0’ S and Longitudes 29^{0}48’30’ E and 29^{0}50’0 E. It covers an area of six square kilometres (6 Km^{2}). The relief is dominated by gentle and steep hillslopes with hills of elevations between 1872 and 2,495 meters above sea level. The area receives an annual rainfall of between 1000 and 1500 mm of rain, with a bimodal rainfall pattern. The first main rain is from March to May, and the second short rains are from August to December. The dominant land use in the area is agriculture. Crop cultivation is mostly done on the middle and lower slopes, while animal grazing is found on the upslope. The crops cultivated are mostly Irish potatoes, cowpeas, onions, and sorghum, among others. Bunyonyi sub-catchment is dominantly known for Irish potato production and is a source of food to Uganda and neighbouring countries like Rwanda, Burundi, and the Democratic Republic of Congo. Bench terraces and grass stripes are the dominant land management practice on the hill slopes of Bunyonyi Sub catchment. The bench terracing system is practically known for controlling overland flow on an arable hillslope. However, conserving these bench terraces with the front edge perfectly on a uniform surface so that runoff is effectively controlled to infiltration is difficult, making these bench terraces to becoming sloping bench terraces since they have been overgrown.

Figure 1:Location of the study site



Bench-terraces are used to increase infiltration as well as reduce soil loss on these sloping crop fields (Widomski, 2009; Juo & Thurow, 1980). Due to the large volumes of infiltrated water in them during rainy seasons, the soil at the terrace bunds becomes highly saturated and heavy. This has caused several to wear downslope in these areas (Siriri et al., 2005; Dorren & Rey, 2004; Miiro, 1999). This has made it hard to maintain them and thus abandonment by some people in the catchment, thus severe runoff and erosion, perhaps landslides and mudflow (Dorren & Rey, 2004; Miiro, 1999). Therefore, an understanding of the hydrological functioning of the cultivated hill slopes (with bench terraces) is key in developing management interventions that increase the efficiency and sustainability of the highland hill slopes.

Infiltration Experimental Design

The study was conducted on a bench terraced hillslope with Irish potato parcels. The hillslope was approximately 250 m long, from the upslope to the downslope in the Southwestern areas of the Bunyonyi sub-catchment of Kigezi highlands. The study was based on randomised block and matched pair experimental designs (Jones & Bartlett, 2014). Hillslope sequences, bench terraces, and bench terrace segments were the key variables. The bench terrace was considered the central unit for investigating the intra-infiltration patterns on the hillslope. Three bench terraces were selected, picking one from each of the three hillslope positions, following slope gradients of 0-15%, 15-30%, and >30% (Figure 2). Twenty-seven (27) experiments, taking 9 from each bench terrace. Each bench terrace had the upper, middle, and bottom segments, denoted as A, B, and C, respectively. Based on the width of the bench terraces, water infiltration measurement was conducted at an interval distance of 5 m between replicates of the same segment across the sloping bench terrace. Five to ten meters were considered between the segments based on the length of the bench terraces. There was a distance of approximately 50 meters between these bench terraces. The steady-state infiltration rates were measured following the standard procedures of measuring infiltration by Gregory (2005).

Soil Sampling

Composite soil samples at 0-15 cm and 15-30 cm deep on the soil surface were picked from every infiltration replicate, making a total of 54 samples. The following soil properties were obtained, namely; soil texture, and soil chemical properties of Phosphorous (P), Calcium (Ca), Potassium (K), Sodium (Na), Nitrogen (N), and Soil organic matter (SOC). These soil parameters could best explain the infiltration dynamics on the hillslope.

Plate 1: Old and enduring sloping bench terraces in Kigezi Highlands

Methods of Data Analysis

Spatial Analysis of Steady-state Infiltration Rates

The spatial autocorrelation tool embedded in ArcGIS was used to analyse the spatial patterns of infiltration, looking at how the infiltration rates varied with distance on the top sequence bench terraced hillslope. Global Moran’s Index statistic gives the minimum distance at which steady-state infiltration rates cluster and disperse on the bench terraced hillslope. The tool computes the mean and variance for the attribute being evaluated. The Spatial Autocorrelation (Global Moran's I) tool is an inferential statistic whose analysis is always interpreted within the milieu of its null hypothesis. According to Chen (2021)**,** autocorrelation reveals deep geographical information and performs the spatial dynamic analysis. In ArcGIS**, t**he Moran's I statistic for spatial autocorrelation is given as;

$$\mathrm{I} = \frac{\mathrm{n}}{S_O} \frac{\sum_{\mathrm{i}=1}^{\mathrm{n}} \sum_{j=1}^{n} w_{i,j}\, z_i z_j}{\sum_{i=0}^{n} z_i^2} \qquad [\mathrm{i}]$$

Where Z_i is the deviation of the attribute value (steady-state infiltration rate) for feature location i from its mean, $w_{i,j}$ is the spatial weight between feature i and j, n is the total number of features, and S_O is the aggregate of all spatial weights computed as;

$$S_O = \sum_{\mathrm{i}=1}^{\mathrm{n}} \sum_{j=1}^{n} w_{i,j} \qquad [\mathrm{ii}]$$

The z_I- score for the statistic can be computed as;

$$z_I = \frac{\boldsymbol{I} - \boldsymbol{E}[\boldsymbol{I}]}{\sqrt{V[I]}} \qquad [\mathrm{iii}]$$

where

$$\mathrm{E}[\boldsymbol{I}] = -1/(\mathrm{n}-1) \qquad [\mathrm{iv}]$$

$$\mathrm{V}[\boldsymbol{I}] = \mathrm{E}[\boldsymbol{I}^2] - \mathrm{E}[\boldsymbol{I}]^2 \qquad [\mathrm{v}]$$

The Analysis of Variance (ANOVA-one way) in Excel was further used to determine the mean differences in the measured steady-state infiltration rates within and between bench terrace segments and hillslope sections.

Spearman's correlations coefficient was used to determine the relationship between infiltration rates and the effect of soil properties. This is because the data had a monotonic relationship. Spearman's rank-order correlation also investigated the degree of strength of the relationship between the steady-state infiltration rates and controlling soil physical properties. Spearman's rank-order correlation was used because the infiltration data had a monotonic relationship (i.e. infiltration has no perfect collinearity with soil, the analysed soil parameters as depicted on the scatter plots). These two conditions make the Spearman rank-order suitable for investigating the correlation between infiltration and soil parameters. The Spearman's rank-order correlation coefficient formula is given as follows;

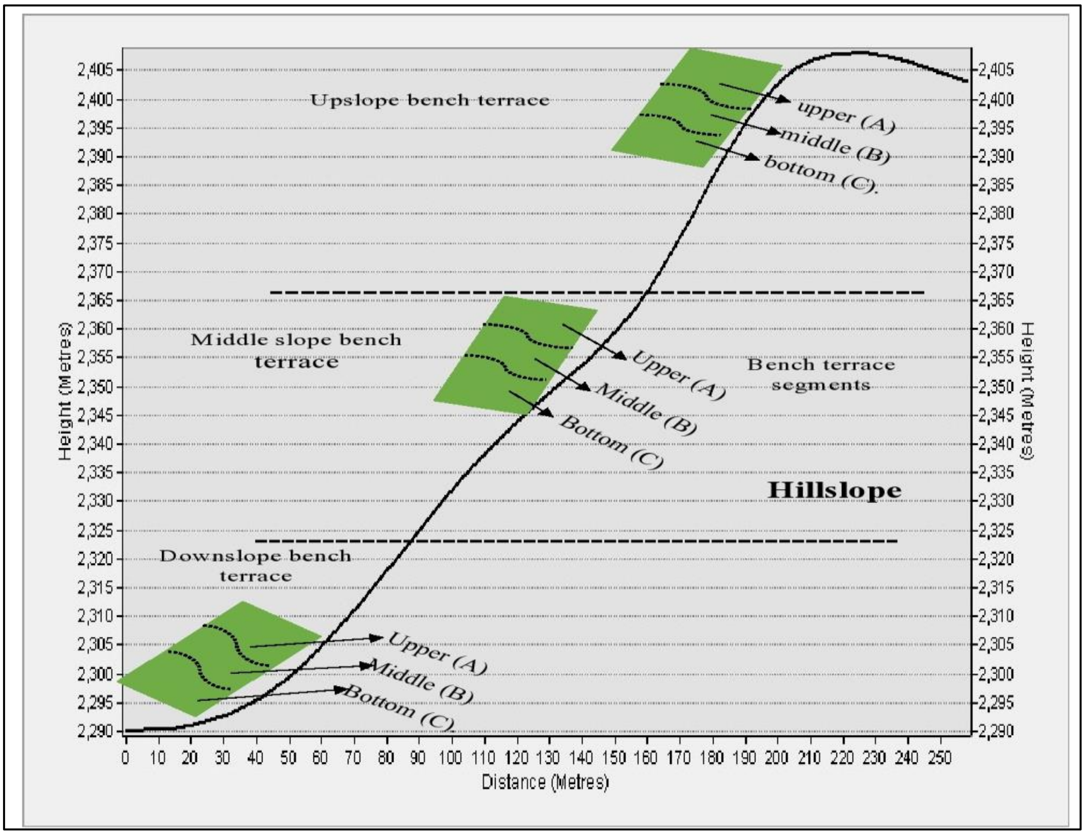
$$\mathrm{p} = 1 - \frac{6 \sum_{I=1}^{N} d^2 i}{N(N^2-1)} \qquad [\mathrm{vi}]$$

p = is the spearman's rank correlation coefficient; d_i= the difference between the ranks of X (soil properties, slope gradient) and Y (measured steady-state infiltration rates) for each observation/experiment and N is the number of experiments/sample size.

Soil Analysis

Soil samples were analysed routinely in the Laboratory at Makerere University to test for chemical and physical properties based on methods by Okalebo et al. (2002). The soil parameters analysed included the Soil texture and soil chemical properties such as Phosphorous (P), Calcium (Ca), Potassium (K), Sodium (Na), Nitrogen (N), and Soil organic matter (SOC).

Figure 2: Layout of infiltration experiments on the bench terraces of the hillslope



RESULTS AND DISCUSSION

Infiltration Processes

The infiltration processes for experiments on the Downslope, Middle, and Upper hillslope sections are depicted in *Figures 3*, *4*, and *5*, respectively. The overall time taken to reach the steady-state infiltration rates varied from 90 minutes to 6 hours, with an average time of 4 hours. The average duration for the steady-state infiltration rates on the hillslope implies deeper soils with more sand particles for the Middle and Downslope bench terraces and although there is high clay content causing crusted soil surface in the upslope sections resulting to slow infiltration based on the field observations. These observations were not surprising since the findings confirm those of Siriri et al. (2006), who found out that soils in the upslope bench terraces have soils with less hydraulic conductivity and finer clay particles that cause slow infiltration. The slow infiltration processes at the upslope bench terraces cause intra runoff that makes soil particles of sand and silt of size ranging between 0.002 mm to 0.05 mm as indicated by Bagoora (1997) to be eroded from upslope and deposited to the middle and downslope as also found out by Gardner and Gerrard (2003) in the hills of Nepal on his study on runoff and erosion.

The deposited sand and silt on the middle and downslope explains the faster and longer infiltration processes at the sites in *Figure 3* and *Figure 4*, especially the experiment for site 17 downslope. The deposition materials accumulate and make soils deeper, hence, leading to higher steady-state infiltration rates as observed in the middle and downslope positions. The time intervals taken before refilling the infiltrometer during the measurements were also observed as frequent for the down and middle slope bench terrace as compared to the longer intervals of water refill on the upslope. Major implications associated with these long durations of time taken by the soil in the middle and downslope bench terraces to get the steady-state infiltration rates tend to cause the wearing of terrace bunds. This condition results in higher volumes of water infiltrating them, and the lateral infiltration downslope tends to create small pores at the bund step. This observation complies with the findings by Miiro (1999) during his study on the challenges in the conservation of bench terrace use in Kigezi highlands.

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Figure 3: Infiltration process in the Downslope bench terrace

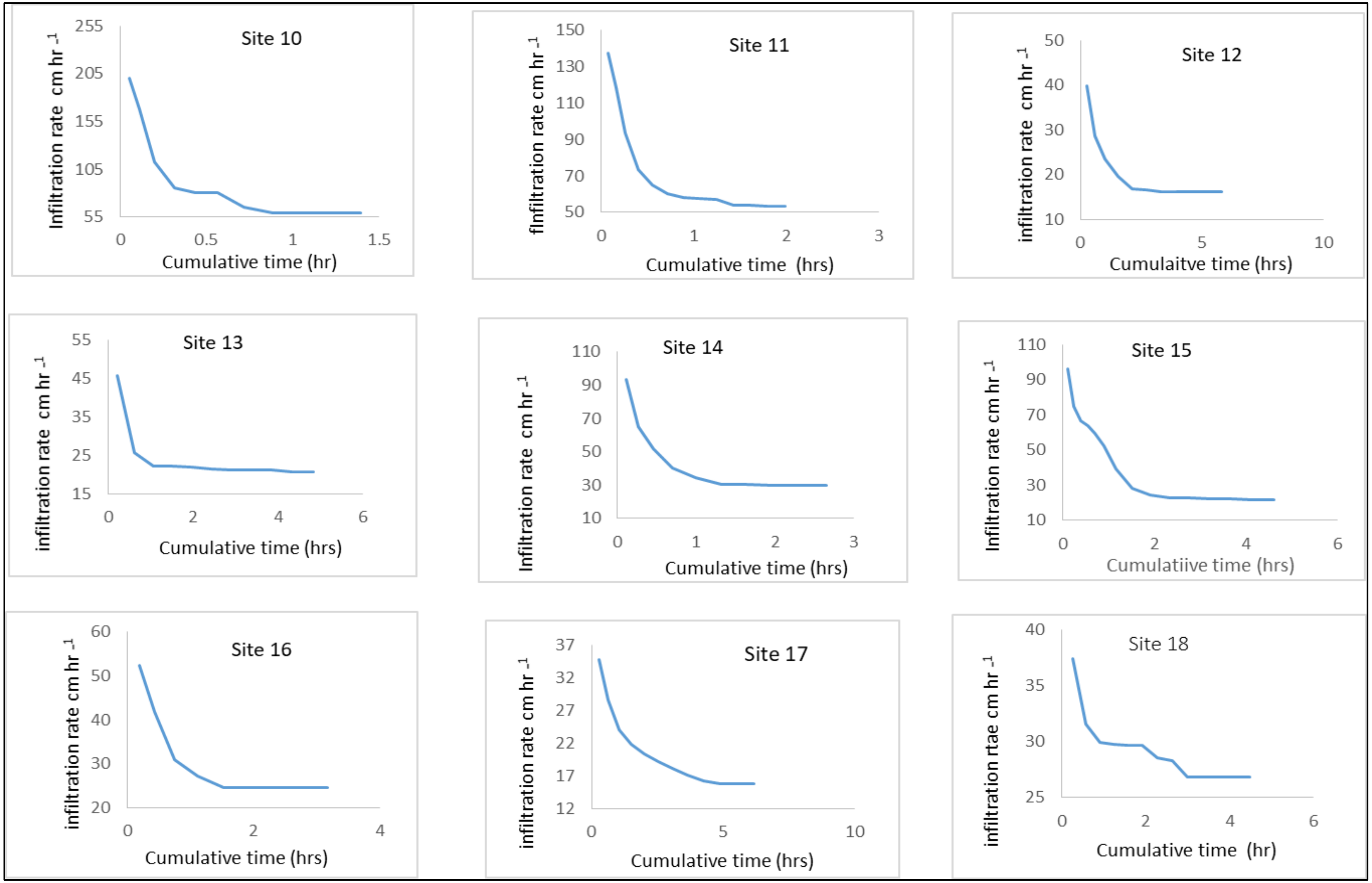


Figure 4: Infiltration process in the Middle slope bench terrace

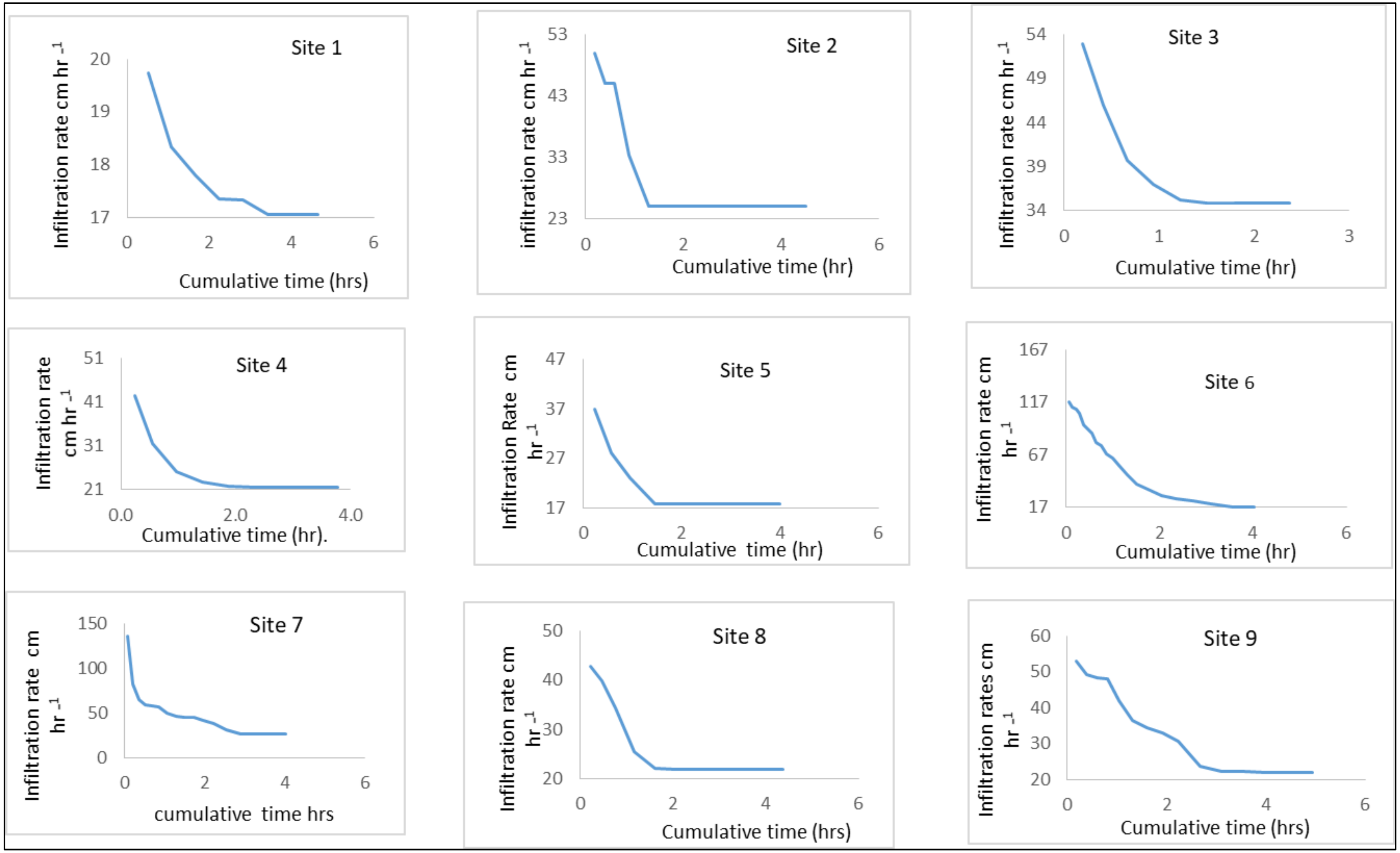
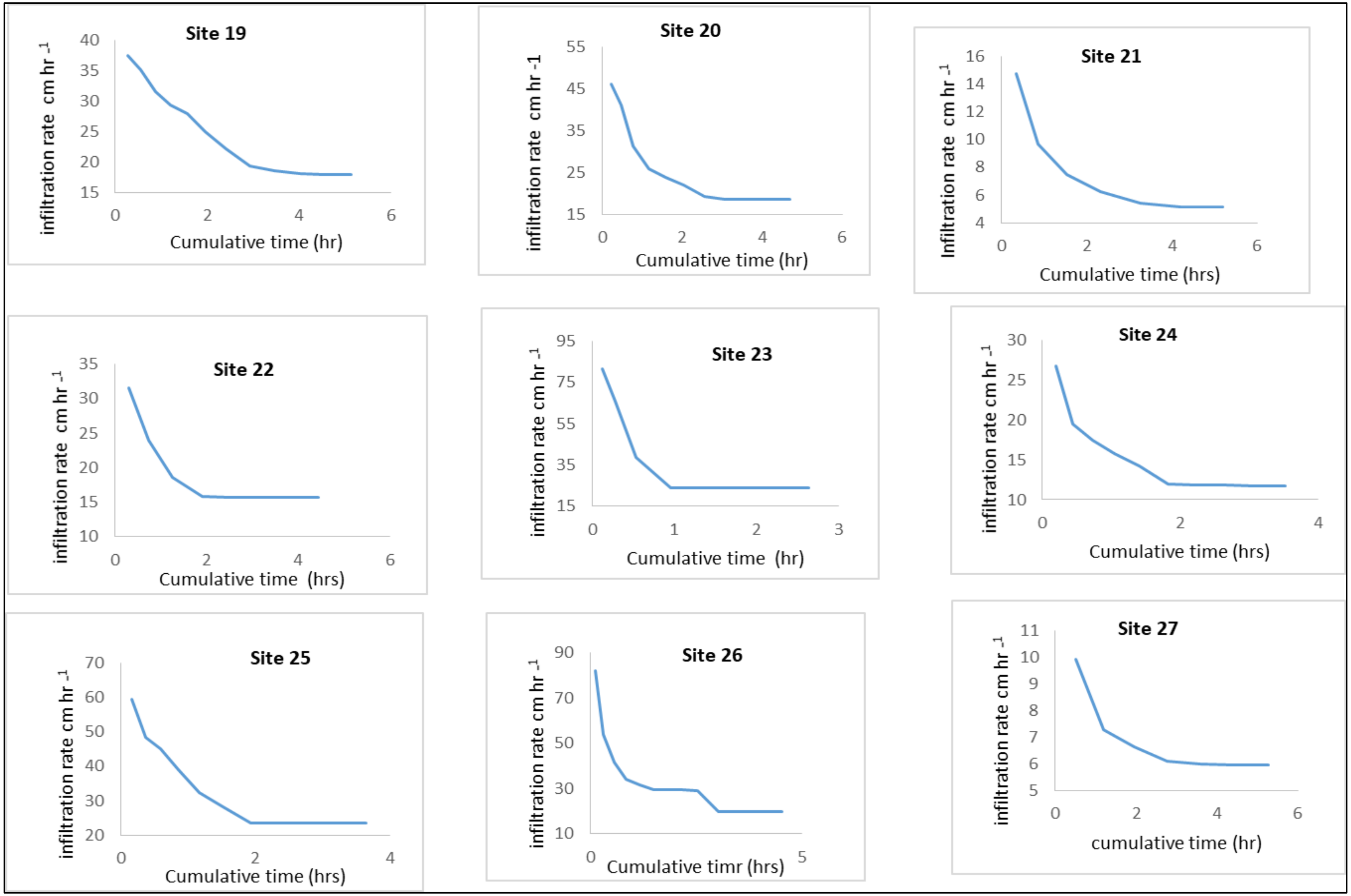


Figure 5: Infiltration process in the Upslope bench terrace



Spatial Variation in Steady-state Infiltration Rates

The results of the variation of the steady-state infiltration rates on the studied hillslope are given in *Table 1*. Across the hillslope, a large variation between the lowest and highest steady-state infiltration rate to the tune of 35 cm hr^{-1} was detected. The measured infiltration rates varied from 5 to 40 cm hr^{-1} across the hillslope. The computed coefficient of variation (CV%) for the steady-state infiltration rates of the studied locations on the hillslope was 36%. This variation is high following the CV classification system of Couto et al. (2017). The high variation observed corroborates with that reported by Siriri et al. (2006), who observed variations of 38% for their studies in the Kigezi highlands.

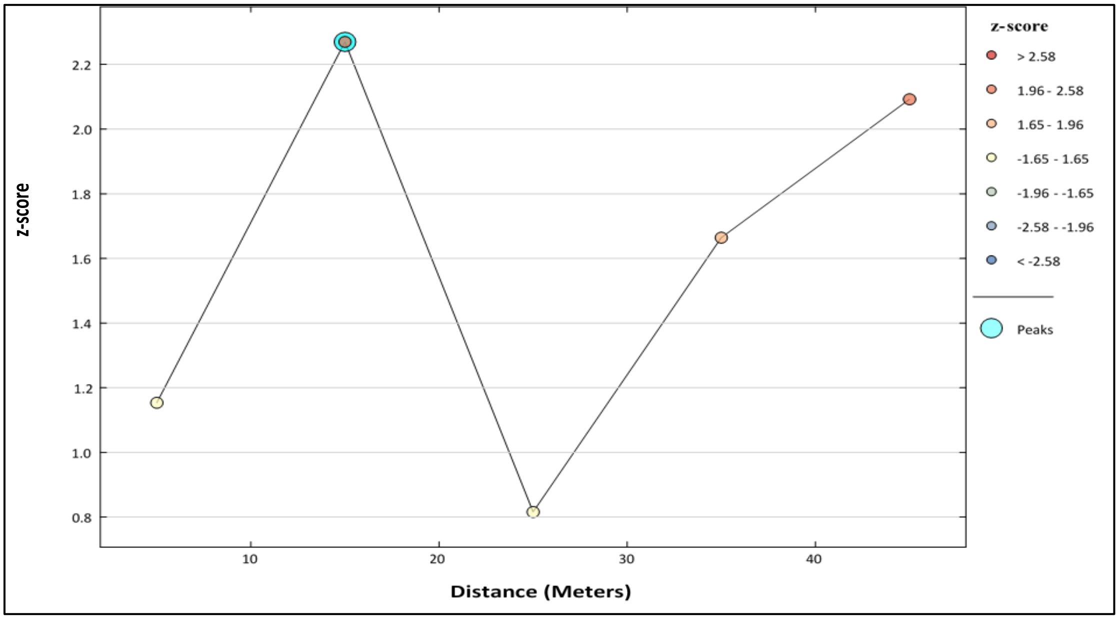
The mean steady-state infiltration rate recorded was 21cm hr^{-1} for the bench terraced hillslope. The observed mean steady-state is higher than 12.7 cm hr^{-1} recorded by Siriri et al. (2006). The mean steady-state infiltration rate indicates higher infiltration, as recorded by Mangala et al. (2016), where the applicable infiltration rates on the sandy loam soils lay between 1cm hr^{-1} to 3 cm hr^{-1}. The higher steady-state infiltration rate recorded here is attributed to the similar treatments of bench terraces across the hillslope where a given annual crop may affect pore size uniformly (Bodner et al., 2014; Dorren & Rey, 2004).

Table 1: Overall variation in steady-state infiltration rates (cm hr^{1}) on entire hillslope (n=27)

Measure of variation	Infiltration rate (cm hr^{-1})
Minimum	5
Maximum	40
Mean	21
Standard deviation	7.6
Coefficient of Variation (CV%)	36

The spatial structure of the steady-state infiltration rates for the hillslope is depicted in Fig. 7. The spatial distribution of steady-state infiltration rates shows a clustered pattern. A significant variation with a z-score of 2.58 ($P<0.023$) is noted after 15 metres. However, clustering steady-state infiltration rates were found high within a distance limit of 15 metres. This thus makes a target of 15 metres appropriate length and width for a bench terrace. This distance could control uniform infiltration rates within the bench terraces, thus upscaling soil and water conservation on these hillslopes. Beyond that, the steady-state infiltration rates tend to spatially disperse significantly with a severe accumulation of runoff downslope breaking terrace bunds.

Figure 6: The spatial pattern of steady-state infiltration rates across the bench terraced hillslope



Variation of Steady-state Infiltration Rates between the Bench Terraces

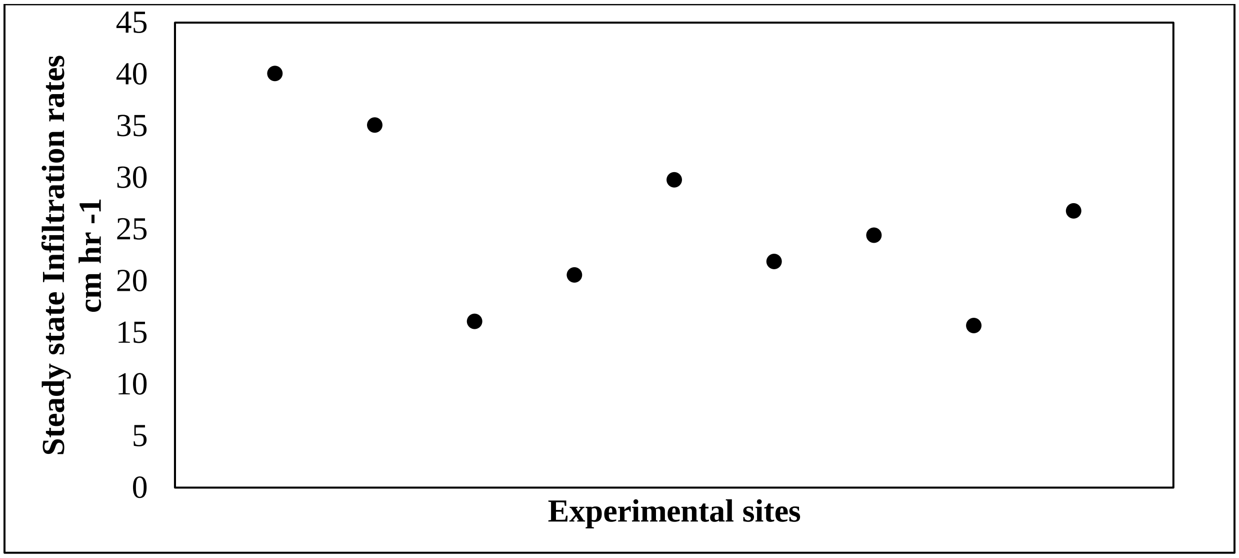
Results on variation in steady-state infiltration rates between the three bench terraces, i.e. the Downslope, Middle and Upslope sections, are given in *Table 2*. Steady-state infiltration rates varied significantly (ANOVA-P<0.018) between the bench terraces on these slope positions. In the downslope bench terrace, infiltration rates varied from 16 cm hr $^{-1}$ to 40 cm hr $^{-1}$ with CV=31%. In the upslope bench terrace, infiltration rates varied from 5 cm hr $^{-1}$ to 24 cm hr $^{-1}$ with CV=41%. Infiltration rates varied from 16 cm hr $^{-1}$ to 32 cm hr $^{-1}$ with CV=21% in the middle slope bench terrace. Therefore, there was high variation (CV=21%) in the steady-state infiltration for the middle slope bench terrace and very high for the upslope bench terrace according to the coefficient of variation classification according to Costa et al. (2002).

Table 2: Variations in steady-state infiltration rates between bench terraces/hillslope sequences

	Position of a bench terrace on a hillslope		
Statistics	**Downslope**	**Middle slope**	**Upslope**
Mean cm hr $^{-1}$	26	22	16
Minimum cm hr $^{-1}$	16	16	5
Maximum cm hr $^{-1}$	40	32	24
Standard deviation	7.80	4.72	6.49
CV%	30.5	21.2	41.1
P-Value		(P<0.018)	

As indicated in *Table 2*, higher steady-state infiltration rates on the hillslope were recorded on the downslope bench terrace and middle slope, as illustrated in the spatial distribution of the steady-state infiltration rates in *Figure 7* and *Figure 8*; mean infiltration rates of 26 cm hr $^{-1}$ and 22 cm hr $^{-1}$. The higher infiltration rates were due to the increase in the sand content in the soils and low clay content at these sites. The coarse particles are deposited down and in the middle slope making infiltration higher given higher porosity and hydraulic conductivity compared to other sites, as also found by Siriri et al. (2006) during his study on infiltration and hydraulic conductivity on sloping terraces in Kigezi highlands. There were moderately high variations (CV=31% and CV=21%) in the steady-state infiltration rates on the downslope and middle slope bench terrace, respectively. This is attributed to the uniformity in textural soil conditions on the bench terraces lying in the middle and downslope slope sections. These slope sections have thick and deeper soils, as also reported by Bagoora (1997) as a result of deposition and sedimentation with coarse particles that cause higher steady-state infiltration rates.

Figure 7: Distribution of the steady-state infiltration rates in the downslope bench terrace



The upslope section registered the lowest minimum and maximum steady-state infiltration rate of 5 cm hr^{-1} and 24 cm hr^{-1}, with a mean steady-state infiltration rate of 16 cm hr^{-1}. This bench terrace also had the greatest variations in the steady-state infiltration rates (CV=41%). The low steady-state infiltration rates of the upslope bench terraces are in line with that of Siriri et al. (2006), who also found out that the upslope position has low hydraulic conductivity due to the existing thin and shallow soils as a result of runoff downslope as again observed by Bagoora (1997).

Figure 8: Distribution of the steady-state infiltration rates in the middle slope bench terrace

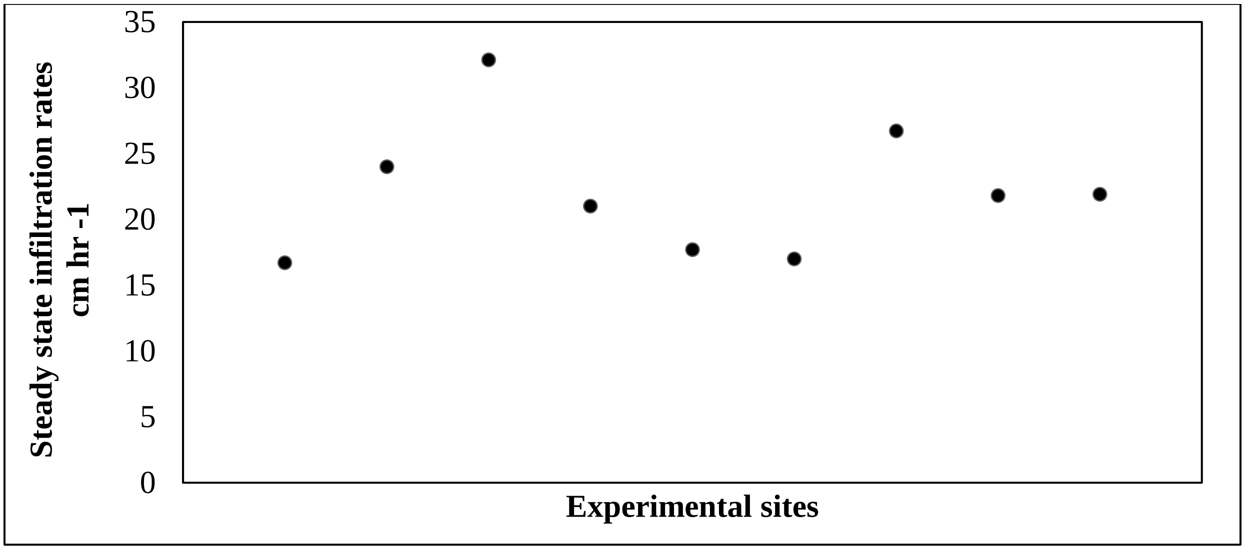
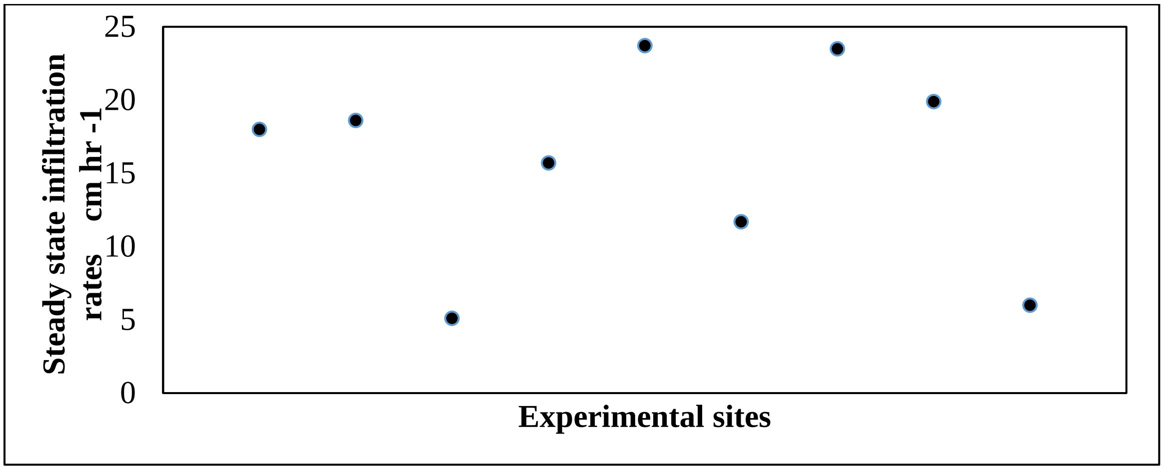


Figure 9: Distribution of the steady-state infiltration rates in the upslope bench terrace



There exist high soil clay content, as indicated in *Table 4*, with some sections of the surface observed crusted as a result of footpaths and animal trails. There is also more continued tillage compared to the other slope positions whose bench terraces are continuously used for crop growing.

Wide variations in the distribution patterns of steady-state infiltration rates were recognised on the hillslope position (downslope, middle and upslope), as shown in *Figures 7, 8* and *9*, respectively. For instance, this is highly noted on the upslope bench terrace as compared to the middle and downslope positions. This variation was largely attributed to the differences in the soil texture at the sites within the upslope bench terrace.

Variation of the Steady-state Infiltration Rates Within Bench Terraces

Intra bench results on steady-state infiltration rates were based on bench terrace segments, namely, upper (A), middle (B), and bottom (C). *Table 3* presents these results. The steady-state infiltration rates varied, especially with segments of the upslope bench terrace. Ordinarily, infiltration would be low, with limited variations as the terrace position was upslope and under a pure stand of the crop. This was not the case though culminating in the need for further pragmatic scientific investigations. But among the notable observation was that variation in the steady-state infiltration rates within the bench terrace segments showed no statistically significant difference for downslope, middle and upslope positions, respectively.

The variation of the steady-state infiltration rates within the segments of the downslope bench terrace indicated a moderately higher variation (CV=34%) in the bottom C segment. These varied from 16 cm hr $^{-1}$ to 40 cm hr $^{-1}$ with a mean of 30 cm hr $^{-1}$. The great variation on the bottom segment C of the bench terrace is due to the dissimilarity in the deposition of the sediments downslope, as also found by Twagiramaria and Tolo (2016). The lowest variation of (CV=17%) was in the middle segment (B). Here with second-highest infiltration with a mean of 24 cm hr $^{-1}$. The upper segment (A) had the lowest steady-state infiltration rates with a mean of 22 cm hr $^{-1}$. Here variations of steady-state infiltration rates were intermediate (CV=21%).

Table 3: Variation of the steady-state infiltration rates within the bench terraces (between the segments).

Hillslope Position	Bench Terrace		Mean Infiltration rates of Bench Terrace Segments		
			A	B	C
	1	Mean cm hr $^{-1}$	22	24	30
Downslope		Stdev	4.78	4.07	10.34

Hillslope Position	Bench Terrace		Mean Infiltration rates of Bench Terrace Segments		
			A	B	C
		CV%	21	17	34
		P-Value	>0.51		
	2	Mean cm hr $^{-1}$	23	19	24
		Stdev	2.29	1.74	6.29
		CV%	9.7	9.1	26
Middle slope		P-Value	>0.37		
	3	Mean cm hr $^{-1}$	14	17	16
		Stdev	7.55	4.99	6.23
		CV%	46	29	45
Upslope		P-Value		>0.87	

Stdev = Standard deviation; A = upper segment; B = middle segment; C = a bottom segment on the bench terraces; and P-Values = ANOVA for means of steady-state infiltration rates of the three replicates at each segment.

The variations of steady-state infiltration rates had no significant difference in the segments (P>0.05) of the downslope bench terrace, as shown in *Table 3*. This can also be explained by the short distance of 5 m that was considered between the experiments within a bench terrace, which does not give significant differences in the soil water infiltration, especially within a bench terrace. In the Middle slope bench terrace, the highest variation in the steady-state infiltration rates was also found on bottom segment C, with (CV = 26%). These varied from 21 cm hr $^{-1}$ to 27cm hr $^{-1}$ on segment C with a mean of 24 cm hr $^{-1}$. The higher variation in the Bottom segment is attributed to the observed paths on the terrace bund, making some sites become crusted on soil surfaces. The upper segment was recorded second with varying steady-state infiltration rates with a mean of 23 cm hr $^{-1}$ and with (CV = 10%). The middle segment had the lowest steady-state infiltration rate with a mean of 19 cm hr $^{-1}$ and low variations of (CV = 9%). Although there are observable differences (P>0.05), indicated no statistical significance in the variations of steady-state infiltration rates of the middle bench terrace segments.

Results on the variation of steady-state infiltration rates within the upslope bench terrace presented the highest variation of (CV = 46%) in the upper (A) and Bottom C segments recorded with the lowest infiltration mean value of 14cm hr $^{-1}$ and a (CV = 45%) with a mean steady-state infiltration rate of 16 cm hr $^{-1}$ respectively. Middle segment (B) records high infiltration of 17cm hr $^{-1}$ mean value with less variation of (CV = 30%). Although the coefficients of variation indicate high variations within the replicates of the segment, the differences in the mean steady-state infiltration rates have no statistical significance (P>0.05). The greater variations in the bottom (C) and upper (A) segments are due to the crusting of the soil surface due to footpaths and continued tillage on the upslope, as also observed by (Siriri et al., 2006). Therefore, the observed intra-variations in the steady-state infiltration rates of the segments on the bench terraces can be attributed to the intra-variation of soil properties and soil surface conditions across the bench terrace. It was observed that the bottom segment (C) lies on terrace bunds/steps, thus dominant, registering higher steady-state infiltration rates on the Bench terraces.

The low steady-state infiltration rates were mostly in the middle (B) segments of these bench terraces, thus cumulating intra-runoff. This is later trapped at the terrace bunds causing them to saturate, and if the surfaces are found conserved with grass, then soil loss is reduced. In case the terrace bund/step is not conserved well, the highly infiltrated soils at bunds tend to collapse due to low clay content. This makes it hard to manage these bench terraces in the area as also observed by Critchley and Brommer (2003) and Miiro (1999). Infiltration in the upper (A) segments of the bench terraces also contributes to the collapse of the terrace bunds through the sub-surface runoff downslope. Lateral infiltrated water tends to come out at the lower steps of terrace bunds downslope through small pore spaces on the slope.

This was observed especially on bench terraces whose bunds are not well conserved.

Influence of Soil Properties on the Steady-state Infiltration Rates

The results on the effects of soil properties on steady-state infiltration rates are presented in Table 4. The slope gradient was not significant ($R,r^2 = -0.5$; $P > 0.05$) in determining the steady-state infiltration rates on the bench terraced hillslope. These results reveal the complex relationship of the infiltration process with slope gradient, as presented by Morbidelli et al. (2018). He presented different scholars who have found contrasting results on the influence of the slope gradient on infiltration. The results of steady-state infiltration rates on the hillslope in Table 4 depict increasing infiltration with a decrease in slope gradient. This trend infiltration with slope gradient is certainly approving those of Wang et al. (2018) and Morbidelli et al. (2016).

On a hillslope, steady-state infiltration rates were most influenced by soil texture of the soil especially the content of clay on the hillslope with ($R, r^2 = -0.5$; $P < 0.05$) for topsoil; ($R,r^2 = -0.44$; $P < 0.05$) as indicated in Table 4. Many have found similar results, such as Adeniji et al. (2013) and Siriri et al. (2006), where infiltration was significantly influenced by soil texture. A minimal difference in the mean steady-state infiltration rates on the middle and downslope was observed, implying the less distinguishing difference in the textural conditions of these slope positions compared to the upslope.

Table 4: Effect of the physical soil properties on steady-state infiltration rates

Variables		**R, r^2**	**p-value**
Vegetation (Constant) Slope gradient		-0.50	0.67
Soil elements			
Soil depth (0-15 cm)	Soil pH	0.29	0.15
	Soil Organic Carbon	0.04	0.422
	N	0.04	0.86
	P	0.50	<0.008
	K	-0.14	0.502
	Na	-0.15	0.44
	Ca	-0.22	0.133
	Mg	-0.40	<0.02
	Sand	0.34	0.41
	Clay	-0.51	<0.003
	Silt	-0.01	0.979
Soil Depth (15 -30 cm)	Soil pH	0.35	0.075
	Soil Organic Carbon	0.06	0.774
	N	0.04	0.861
	P	0.42	<0.030
	K	0.24	0.22
	Na	-0.03	0.868
	Ca	-0.01	0.484
	Mg	-0.12	0.281
	Sand	0.25	0.104
	Clay	-0.44	<0.01
	Silt	-0.21	0.303

R, r^2 correlation coefficient

Bagoora (1997) noted that in the Rukiga highlands, which are part of the highlands of Kigezi, the eroded soil particles of sand and silt from the upslope are also deposited on the middle slope, creating almost similar soil conditions. The insignificant influence of the slope gradient on the steady-state infiltration rates is due to the irregular landscape caused by the sloping bench terraces and bunds. These landforms reduce the impact of the slope gradient on soil infiltration rates depending on the management of these terraces (Miiro, 1999). These make the inherent soil properties explain the patterns of infiltration along the hillslope, as seen in *Table 4.* The soil clay was the most significant soil property to determine infiltration on the bench terraced hill slope (R, r^2 = -0.509 for topsoil; R, r^2= -0.44, $P<0.05$, for the subsoil). Phosphorus (P) was observed significantly influence the process of infiltration on the hillslope, although it is less considered a factor in determining infiltration rates.

Steady-state infiltration rates increased with phosphorus with (R, r^2= 0.5, $P<0.05$*)* in the topsoil and (R, r^2=0.42, $P<0.05$) in the subsoil on the hillslope. Based on the results on the variation of soil properties in Table 4, phosphorus was found higher in the middle and downslope at a level of 25 ppm than in the upslope with 15 ppm. Steady-state infiltration rate was recorded higher on the downslope with an average of 26 cm hr $^{-1,}$ followed by the middle slope with 22 cm hr$^{-1,}$ and lowest on the upslope with an average of 16 cm hr^{-1}. The higher amounts of phosphorus in the middle and downslope is as a result of erosion that carries with it tiny organic materials to the middle and downslope from the upslope, according to Singh et al. (2015).

CONCLUSION

The spatial patterns of infiltration on a terraced bench hillslope are influenced by slope position. Infiltration is higher at the Downslope and Middleslope bench terraces as compared to the Upslope bench terrace. Soil texture and the structural condition of the bench terraces themselves play a cardinal role in the variations in infiltration. Within the bench terraced land parcels, infiltration is higher on the downslope and lower in the upslope positions. Since the percentage of clay content increased with slope, it was noted as a fundamental soil characteristic affecting infiltration within the bench terraces.

Recommendation

We recommend that in bench terraces where steady-state infiltration was high such as in downslope and middle slope positions, the terrace bunds should be strengthened with grass and stone embarkments to consolidate them coherently. This strategy may reduce terrace bund breakages and consequently counter surface flow on the bench terraced hillslope. Besides, in areas where low steady-state infiltration rates were recognised, such as the upslope position, agronomic practices should be enhanced.

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