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RESEARCH ARTICLE

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Evaluation of different rainwater harvesting techniques for improved maize productivity in semi-arid regions of Zimbabwe with sandy soils

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Abstract

Background: Maize production in semi-arid areas has been hindered by moisture stress and poor soil fertility. Long frequent droughts and shortening of growing seasons have been causing yield reduction. Limited knowledge of soil water management by farmers is another key contributor to poor maize yields in the smallholder sector. Therefore, the objective of the study was to investigate the effects of contour-based and field-based water harvesting technologies on maize grain yield and rainwater use efficiency under rain-fed conditions on three farms (Jera, Kudzeeta and Manjengwa) with sandy soils in the Marange smallholder farming area of Zimbabwe. The experiment was laid out as a split plot in a randomised complete block design with three replications at each site. Contour-based rainwater harvesting structures were the main treatments comprising tied contour (TC), standard contour (STDC) and infiltration pits (IP). Field-based rainwater harvesting structures were the subplot treatments comprising tied ridges (TR), pot holing (PH) and the flat system (FLAT).

Results: Results showed that the contour-based water harvesting structures significantly influenced ($p < 0.05$) maize grain yields. TCs had the highest maize grain yields compared with infiltration pits and STDCs over two cropping seasons. Maize yields on field-based TR were significantly higher ($p < 0.05$) than on the FLAT but were not different ($p > 0.05$) with what was obtained on PH. The combination of TC and TR water harvesting technologies resulted in significantly higher maize yields ($p < 0.05$) than other combinations. TR and STDC also gave higher maize grain yield at Jera farm which was significantly different from other two farms. Rainwater use efficiency followed the same trend as maize grain yields, with TC having higher values but not significantly different ($p > 0.05$) from STDC.

Conclusion: It can be concluded that farmers in semi-arid areas adopt a combination of TC with either TR or PH to improve rainwater use efficiency and maize yields.

KEYWORDS
contour based, maize productivity, planting basins, rainwater harvesting techniques, semi-arid areas

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1 | INTRODUCTION

The population of Africa is projected to double by 2050, causing food insecurity and poverty across the continent (Bado et al., 2022). This calls for the need to come up with strategies to increase food production to meet household food demand and reduce poverty (Bado et al., 2022). Crop production in semi-arid areas is mainly constrained by water stress due to low and erratic rainfall which is unevenly distributed affecting critical crop growth stages such as flowering and grain filling (Kubiku, Nyamadzawo et al., 2022; Kugedera et al., 2022a; Kugedera et al., 2022b; Nyagumbo et al., 2019). Soils in most smallholder farming environments are sandy characterised with low water retention capacity. In addition, the soils are prone to high surface runoff and soil erosion which removes top soil rich in nutrients. The situation has been worsened by climate changes, which has resulted in increased rainfall variability, long frequent droughts and shorten growing seasons. This critically affects crop production and food security in smallholder farming environments. Hence, there is need to adopt to water conservation practices such as rainwater harvesting techniques.

Crop production under rain-fed conditions in semi-arid areas of sub-Saharan Africa (SSA) is limited by soil moisture stress due to frequent droughts. In addition, smallholder farmers prefer growing staple crops that are not adaptable to the dry conditions (Nyakudya & Stroosnijder, 2011). Maize is one of such staple food crops grown in most parts of SSA under rain-fed conditions. Maize is one of the crops which are heavily affected by drought as it requires large quantities of water during the growing season for high biomass production. Droughts negate water availability to crops resulting in low yields leading to food insecurity. Drought in semi-arid region of Zimbabwe can be a result of either high frequent dry spells or extended dry spells during the cropping season. An increase in dry spell frequency is a proxy of climate variability. Dry spells have been singled out as the major cause of crop failure in rain-fed agricultural systems. The effects of dry spell can be mitigated through restorative systems that are climate smart which include rainwater harvesting at field level (Kubiku, Mandumbu, et al., 2022; Munamati & Nyagumbo, 2010; Mandumbu et al., 2021; Nyakudya et al., 2014).

Rainwater harvesting practices can therefore enhance food security in semi-arid areas by improving soil moisture content and reducing the effects of water stress during critical physiological plant stages (Kugedera et al., 2022b). Field-based water harvesting such as tied ridges (TR) and planting pits are low-cost technologies which can reduce surface runoff, harvest rainwater and recharge groundwater, resulting increased soil moisture content in the plant root zone (Kubiku, Mandumbu, et al., 2022; Nyagumbo et al., 2019). These techniques also improve the capacity of smallholder farmers to adapt to climate change despite the initial high labour requirements involved in making the requisite structures (Nyamadzawo et al., 2013).

Contour-based rainwater harvesting techniques such as infiltration pits and tied contours (TCs) are permanent structures which can have a long-lasting solution in reducing surface runoff and recharging soil moisture during dry spells (Kubiku, Nyamadzawo, et al., 2022; Kugedera et al., 2022b). Adoption of semi-permanent field edge rain water harvesting (RWH) techniques such as TC can be a cheaper option to smallholder farmers when it comes to labour requirements compared with infield RWH practices which are made on an annual basis (Kugedera, Nyamadzawo, Mandumbu, Nyamangara, 2022; Nyamadzawo et al., 2015; Nyagumbo et al., 2019). In Zimbabwe, the STDC were designed to disposed off rainwater from the fields, and not impound water, to combat moisture stress (Kugedera, Nyamadzawo, Mandumbu, Nyamangara, 2022). However, the modification of the STDC, into water-impounding structures can result in improved water retention and crop yields. However, smallholder farmers have limited technical knowledge of the use of these technologies such as infiltration pits (IP), TC and field-based rainwater harvesting practices. This has contributed to the generally low adoption of these technologies by smallholder farmers. In addition, farmers complain about high-labour requirements of putting up these water harvesting structures without considering the benefits of increased crop productivity that will accrued in the long run.

Studies on rainwater harvesting impact on productivity of crops like maize have separately focused on either field-based techniques or contour-based techniques in the semi-arid smallholder sector of Africa (Nyamadzawo et al., 2013). A combination of the two sets of RWH techniques can be hypothesised to complement each other and increase soil water availability to crops thereby combating drought effects. Therefore, the aim of the study was to evaluate the effects of combining in-field and field-edge rainwater harvesting techniques on maize productivity in a semi-arid region of Zimbabwe. The specific objectives were to (i) determine the effects of contour and field-based rainwater harvesting techniques on maize grain yields, and (ii) determine the effects of contour and field-based rainwater harvesting on rainwater use efficiency (RWUE) of maize under smallholder farming environment in semi-arid region of Zimbabwe.

2 | MATERIALS AND METHODS

2.1 | Description of the study area

This study was conducted in three smallholder farmer fields in Mt Zonwe (Kudzeeta (19° 11.616′S; 32°02.871′E, 835 masl), Jera (19° 11.918′S; 32°05.208′E, 842 masl) and Manjengwa, (19° 11.583′S; 32°03.853′E, 839 masl), located in ward 2 of Mutare District, Zimbabwe. The three sites are shown in Figure 1. The experimental sites are located in agroecological region IV (<650 mm rainfall year^{-1}) with a unimodal rainfall distribution pattern (October–March). The area is associated with frequent dry spells which negatively affected the length of growing seasons (Mugandani et al., 2012; Winter-Nelson et al., 2016). The mean annual temperature is 27°C (Kubiku, Nyamadzawo, et al., 2022). These conditions promote high evapotranspiration and prevent accumulation of moisture in the soil, negatively impacting on rainfed crop production. Agricultural systems in the study area are mixed crop-livestock type. The main crops grown include maize (*Zea mays*), pearl millet (*Pennisetum glaucum*),

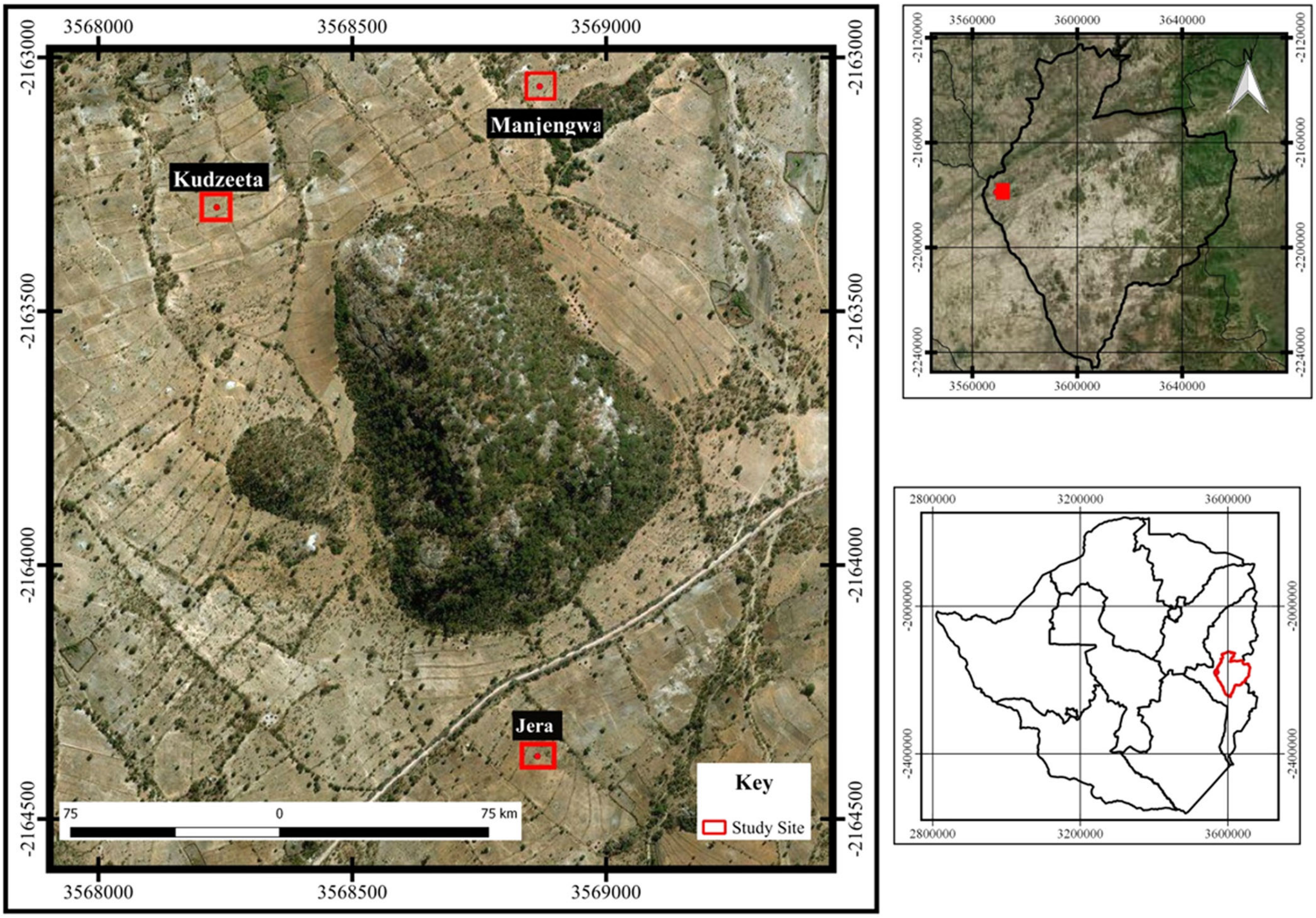

FIGURE 1 Map showing three experimental sites (Jera, Kudzeeta and Manjengwa) in Mt Zonwe, Manicaland

sorghum (*Sorghum bicolor*) and groundnuts (*Arachis hypogea L.*), cowpeas (*Vigna unguiculata (L.*), sugar beans (*Phaseolus vulgaris L.*), pumpkins (*Curcubita* spp) and sweet potatoes (*Ipomoea batatas L*). Cattle are the main livestock and an important source of draught power and organic manure.

2.2 | Soil characterisation and analysis

Soil samples were collected from 0 to 0.15 m depth (plough layer) in 2016 at the three study sites for baseline characterisation. Composite soil samples (constituted from 10 subsamples) were air dried, sieved (<0.002 m) and analysed at Africa University Soil Laboratory for pH, exchangeable Ca, Mg, K, mineral N and available P_2O_5. The results from these soil fertility assessments were combined with regional pedological analytical results available for soils in the area.

2.3 | Experimental layout

The experiment was laid out as a randomised complete block design (RCBD) arranged in split plot with treatments replicated three times at each site. Contour-based rainwater harvesting was used as the main treatment factor with three levels (TC, IP and standard contour [STDC] as a control). Field-based rainwater harvesting was the subplot factor at three levels, (TR, potholing [PH] and flat system [FLAT] as a control). The study was carried out at three farms, namely Jera, Kudzeeta and Manjengwa. Treatments were all replicated three times at each farm, and the study was carried out over two cropping seasons, (2016/17 and 2017/18).

The dimensions for a STDC were: 1.7 m for the channel; 1.7 m for the ridge and 0.25 m high (Nyagumbo et al., 2019). The TCs were made up of cross ties, 0.5 m wide, which were placed at an interval of 5 m along the channels to create mini dams that captured water for improved moisture conservation (Figure 2). Infiltration pits along contour ridges measured: 2.0 m (long) x 0.5 m (wide) x 0.5 m (deep) and were 0.5 m apart along the contour ridge. The STDC was the control contour-based structure. A 2.0 m distance was left between contour-based water harvesting structures which were 32 m long each. The field-based rainwater harvesting structures comprised PH and TR, while the FLAT system was the control. Pot holes were dug between the inter row space at 2 m intervals, 0.15 m (length) x 0.15 m (width) x 0.15 m (depth). The TR comprised of long ridges constructed on the interrow space parallel to the planting lines. Tied were then

FIGURE 2 Layout of tied contour in the field (Photo by G. Nyamadzawo)

FIGURE 3 Infiltration pits used in Marange, (right)

constricted across the furrows to make TR. The ridges were made using hand hoes (Figure 3). Cross ties at 2.0 m intervals were erected between the ridges to retain water. The flat system represented the practice by the smallholder farmers. General experimental lay out for a complete replication is shown in Figure 4.

2.3.1 | Field experiment management

A total of 27 experimental plots measuring 10 m x 4 m were set up on the downslope of contour ridges for contour-based and field-based rainwater harvesting treatment combinations replicated three times at each site. Distance between each treatment was 1.0 m and between each RWH technique was 1.5 m. Treatment effects on other treatments was controlled by growing buffer lines at the edge of each treatment plot and the use of middle rows for evaluation to counter these effects. A commercial maize variety (SC 403, which takes 127 days to maturity) recommended for dry areas was planted on 11 December 2016 and 16 December 2017 in the 2016/17 and 2017/18 seasons, respectively. Three maize seeds were hand sown into basins and planting stations marked on the flat system and TR at a spacing of 0.90 m x 0.50 m. Maize plants were thinned to one plant per station giving a plant density of 22,000 plants ha^{-1}. At planting, 300 kg ha^{-1} compound D (7% N: 14% P_2O_5: 7% K_2O) basal fertiliser was applied and ammonium nitrate (34.5%N) was side dressed 4–6 weeks after planting at a rate of 250 kg ha^{-1}. The experimental plots were kept weed free by weeding using hand held hoes throughout the growing seasons.

2.4 | Data collection

2.4.1 | Rainfall season quality assessment

Conical standard rain gauges were installed at three sites and daily rainfall was recorded throughout the duration of the experiment. Rainfall data were evaluated using pentad approach for each maize growing season (December–April) to determine the distribution quality. Using this approach, a rainy pentad was defined as the centre one of three 5-day periods (pentad) which together received at least 40 mm of rainfall and two of the pentads received a minimum of 8 mm of rainfall (DMS, 1981; Kodzwa et al., 2020). Pentads were then matched with the phenological growth stages of maize to ascertain moisture stress levels during the course of each growing season. According to FAO (1977), the durations of the maize phenological stages are: Establishment-e (25 days); vegetative-v (40 days); flowering-v (20 days), grain filling-g (20 days) and ripening-r (20 days).

2.5 | Maize grain yields

Maize was harvested manually at maturity from a net plot (9 m^2) from central rows in each experimental plots and all grain yield data were standardised to 12.5% grain moisture content according to Kugedera, Nyamadzawo, Mandumbu, (2022)

$$\text{Adjusted yield} = \text{Actual yield x} \frac{(100 - A)}{(100 - U)}, \tag{1}$$

where; A = grain moisture content and, U = grain moisture content of 12.5%.

2.6 | Rain water use efficiency (RWUE)

RWUE is the ratio of total grain yield harvested (kg ha^{-1}) to total rain fall received during the season (mm). It was calculated using equation 2 (Kugedera, Nyamadzawo, Mandumbu, 2022);

$$\text{RWUE}(\text{kg Grain mm}^{-1}\,\text{rainfall}) = \frac{\text{Total grain yield}\,(\text{kg ha}^{-1})}{\text{Total rainfall}\,(\text{mm})}. \tag{2}$$

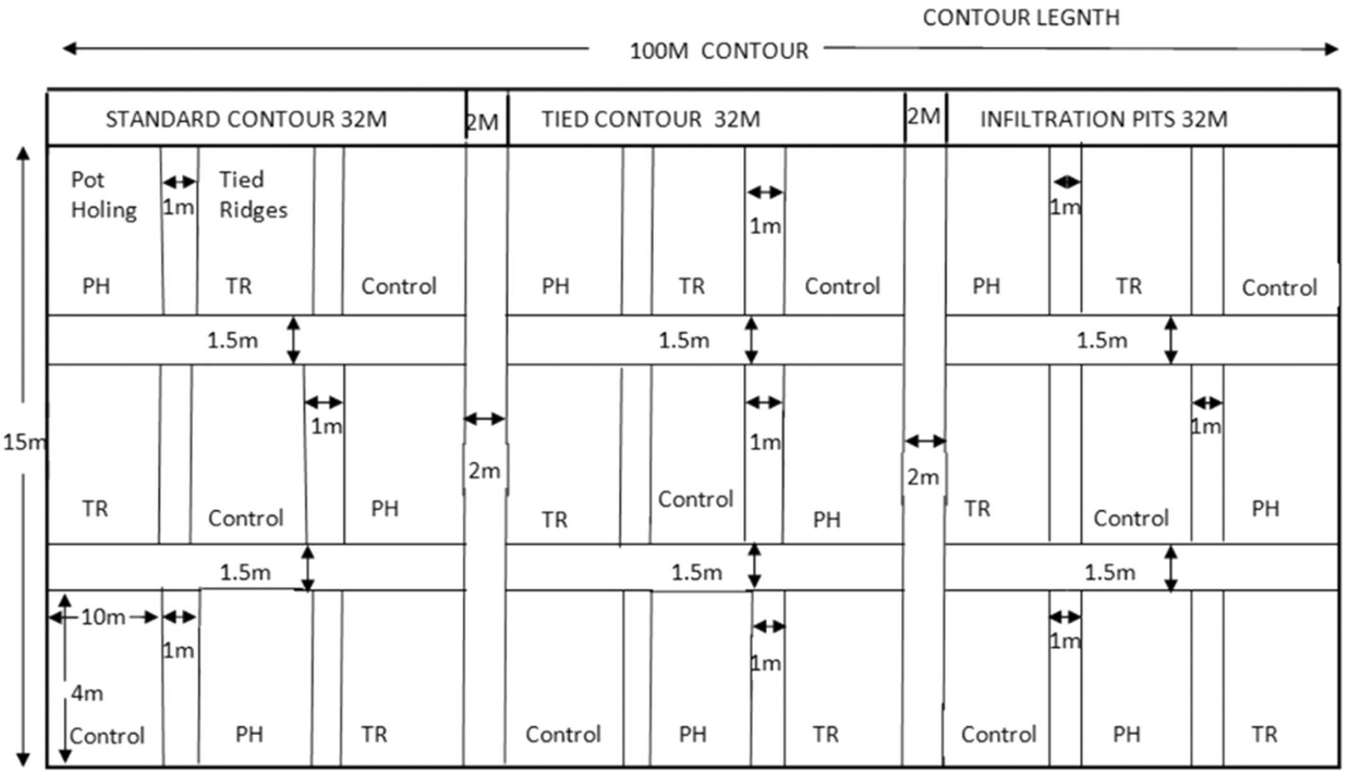

FIGURE 4 Experimental field layout used at the farms. Contuor-based rainwater harvesting techniques were: CONTROL = standard contour (STDC), tied contour (TC) and infiltration pits (IP); Field-based techniques were: control = FLAT, pot holing (PH) and tied ridge (TR).

2.7 | Statistical analyses

Data were tested for normality using Shapiro–Wilk test which showed that the data were normal. Maize grain yield and RWUE data were then subjected to analysis of variance (ANOVA) using Genstat 14th Edition 200 to determine treatment effects. The factorial treatment structure was adopted in the ANOVA with contour-based structure, field-based structure and site as factors. The least significance difference (LSD) of means was computed and used for mean separation when treatment effects were significant at $p < 0.05$.

3 | RESULTS

3.1 | Rainfall

Rainfall totals received in 2016/17 season ranged from 774.3 mm at Kudzeeta to 935.5 mm at Jera. In the 2017/18, rainfall ranged from 810.5 mm (Jera) to 786 mm (Kudzeeta). These rainfall totals were above the long-term average of 650 mm per season for the area in both growing seasons. However, the rainfall distribution in the two seasons was different. Only a single dry spell was observed at the end of 2016/17 season at all sites (Supporting Information: Figure S1). In 2017/18 season, up to four mid-season dry spells were observed at the sites showing relatively poor rainfall distribution compared with the 2016/17 season. Supporting Information: Figure S1 shows that maize crops were subjected to water stress at grain filling and ripening stages in March 2017 and April 2017 of the 2016/17 seasons at all the sites. Higher rainfall was received in January and February for three sites in 2016/17 and 2017/18, respectively (Supporting Information: Figure S1). However, the 2017/18 season had dry spell occurrences of up to 20 days according to pentad analysis (Supporting Information: Table S1). The dry spells in 2017/18 season coincided with the following maize phenological growth stages: vegetative (all sites), flowering (Kudzeeta; Jera), grain filling (Kudzeeta, Manjengwa) and ripening (all sites).

3.2 | Soil characteristics

The soils at the study sites were moderately deep to deep (>80 cm) reddish brown coarse-grained sands over strong brown similar sands and loamy sands. The clay content of the soils ranged from 4% to 8% (Supporting Information: Table S2). The soil was strongly acidic with mean pH values ($CaCl_2$) of 4.6. Mineral soil nitrogen content was low (<7 mg kg^{-1}) as well as available phosphate (Supporting Information: Table S2). The soil organic carbon concentrations were also low (<0.03%) across the sites. These moderately weathered soils derived from granitic rocks were classified as Fersialitics (5 G) according to the Zimbabwean system (Nyamapfene, 1991) or Haplic Arenosols (IUSS Working Group WRB, 2014). In addition, the soils were immature and did not exhibit clearly defined toposequences on gently undulating terrain (Anderson et al., 1993). The soils were therefore inherently infertile due to acidity, low water retention capacity, low cation exchange capacity, low organic matter content and poor structural stability (Supporting Information: Table S2; Nyamangara et al., 2000).

3.3 | Contour-based rainwater harvesting effects on maize grain yield

Results show that main treatment factors significantly affected ($p < 0.05$) maize grain yields (Table 1). Maize grain yields were averaging at 1698 kg ha^{-1} in 2016/17 season and were 24% higher ($p < 0.05$) compared with grain yields observed in 2017/18 season (Table 1). Contour-based rainwater harvesting structure had no significant effect ($p > 0.05$) on maize grain yields in 2016/17 cropping season. Average maize grain yields were 25% and 34% higher under IP and TC, respectively, compared with the STDC (control) but were statistically similar ($p > 0.05$, Table 1). In the drier 2017/18 season, the two contour-based structures had contrasting but significantly influenced ($p < 0.05$) maize grain yields when compared with STDC. The RWH method significantly reduced ($p < 0.05$) maize yield compared with the STDC in 2017/18 (Table 1). Results also show no significant differences ($p > 0.05$) between grain yields from TC and STDC in 2017/18 cropping season.

TABLE 1 Maize grain yield (kg ha^{-1}) response to contour-based and field-based rainwater harvesting structures in 2016/17 and 2017/18 seasons at Jera, Kudzeeta, Manjengwa site sites in Mutare District, Zimbabwe

	Maize grain yield in:	
Treatment/factor	**2016/17**	**2017/18**
Contour-based structure		
Infiltration pit	1775^a	920^a
Standard contour	1416^a	1522^b
Tied contour	1903^a	1655^b
p value	*0.164*	*<0.001*
LSD	523	277.8
Field-based structure		
Flat system	511^a	453^a
Pot holing	2199^b	1692^b
Tied ridge	2385^b	1951^b
p value	*<0.001*	*<0.001*
LSD	494	277.8
Site		
Jera	1259^a	1767^b
Kudzeeta	1999^b	1516^b
Manjengwa	1837^b	814^a
p value	*0.016*	*<0.001*
LSD	523	277.8
Grand mean	1698	1366

Note: Means in the same column followed by different superscripts and italics under each treatment factor are significantly different at $p < 0.05$.
Abbreviation: LSD, least significant difference.

3.4 | Effects of infield-based rainwater harvesting on maize grain yield

In the wet 2016/17 cropping season, PH and TR statistically increased ($p < 0.05$) maize grain yields by 4.3 and 4.7 times compared with the farmer's flat system which had a mean grain yield of 511 kg ha^{-1} (Table 1). Results also show that PH and TR had statistically similar effects ($p > 0.05$) on maize grain yields. In the drier 2017/18 seasons, mean maize yield of 453 kg ha^{-1} on the FLAT system was 3.7 and 4.3 times significantly lower ($p < 0.05$) than that from PH and TR, respectively (Table 1).

3.5 | Site effects on maize grain yield

Maize grain yields were significantly ($p < 0.05$) affected by experimental sites (Table 1). In 2016/17 season, Jera had the lowest mean grain yields of 1259 kg ha^{-1} which increased by 1.5 folds at Manjengwa and 1.6 folds at Kudzeeta site (Table 1). However, maize grain yields observed at Manjengwa and Kudzeeta sites were not significantly different ($p > 0.05$). The sequence was different in 2017/18 cropping season where maize grain yields were lowest at Manjengwa (814 kg ha^{-1}) and significantly lower ($p < 0.05$) by 702 and 953 kg ha^{-1} compared with yields at Kudzeeta and Jera respectively site.

3.6 | Interactions between site, contour-based and field-based rainwater harvesting structures on maize grain yields

Maize grain yields were not statistically influenced ($p > 0.05$) by interaction of RWH techniques and sites. In the 2016/17 season, the interaction between site and contour-based structure significantly affected ($p < 0.05$) maize grain yields (Figure 5b).

The effects of site x field-based structure and site x contour-based structure significantly influenced ($p < 0.05$) maize grain yields in 2017/18 cropping season (Figure 6b). In this drier season, contour-based and field-based rainwater harvesting structures had no significant interactive effects ($p > 0.05$) on maize grain yields. TC and STDC significantly ($p < 0.05$) out-yielded IP at Jera. The least grain yield response to contour-based structure were observed at Manjengwa site (Figure 6c). Results also show significant ($p < 0.001$) grain yield response under TR and PH compared with the FLAT system was observed at Jera and Kudzeeta sites (Figure 6b).

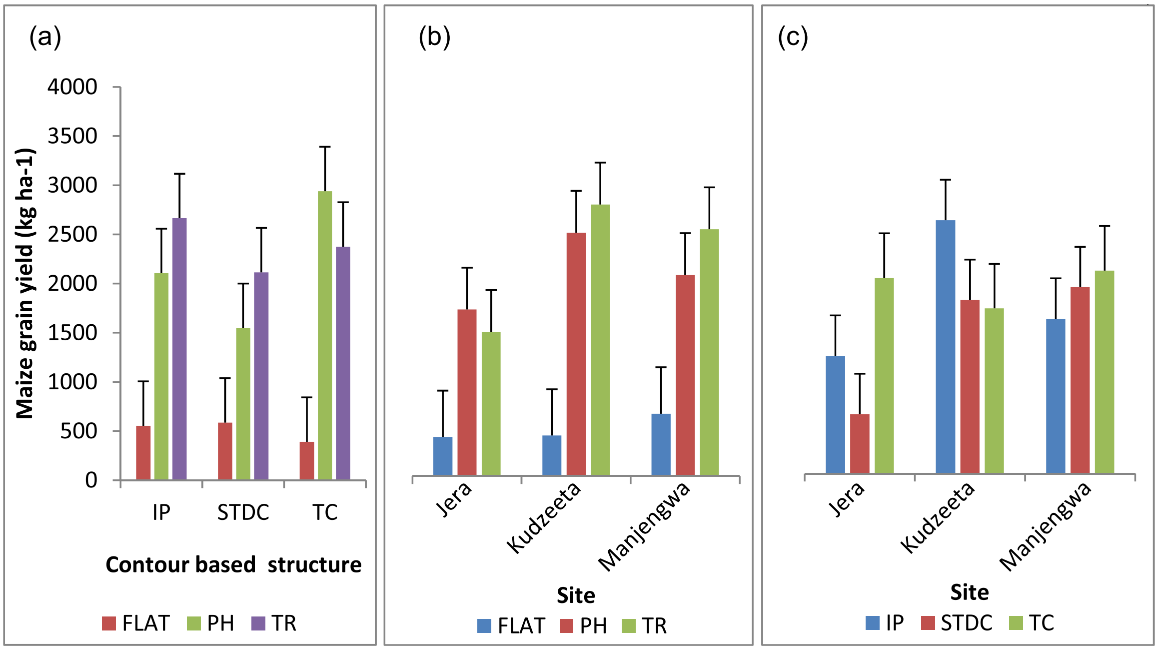

FIGURE 5 Interactive effects of: (a) Contour-based structure x field-based structure ($p = 0.183$); (b) site x field-based rainwater harvesting structure ($p = 0.272$); (c) site x in- contuour water harvesting structure ($p = 0.030$) on maize grain yield in the 2016/17 season. FLAT is the flat system; PH is pot holing; TR is tied ridges; IP is infiltration pit; STDC is the standard contour and TC is the tied contour.

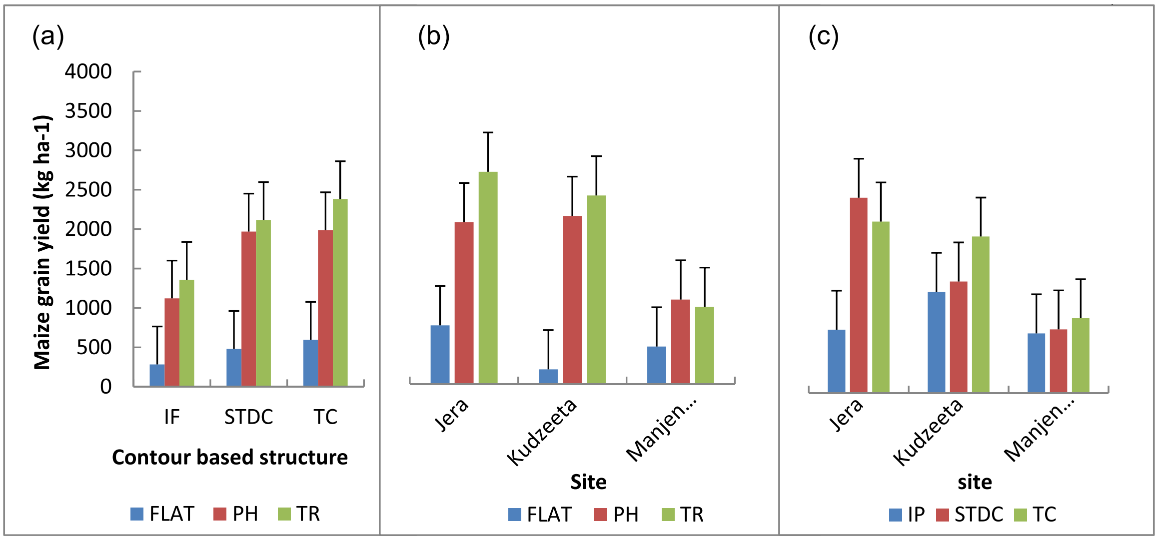

FIGURE 6 Interactive effects of: (a) Contour-based x field-based rainwater harvesting structure ($p = 0.183$); (b) Site x field-based rainwater harvesting structure ($p < 0.001$) (c) Site x contour-based water harvesting structure ($p < 0.001$) on maize grain yield in the 2017/18 season. FLAT is the flat system; PH is pot holing; TR is tied ridges; IP is infiltration pit; STDC is the standard contour and TC is the tied contour.

3.7 | RWUE

Table 2 shows that contour-based structures had no significant effects ($p > 0.05$) on RWUE in the wet 2016/17 season. RWUE observed from TC and IP indicates positive improvement compared with the control STDC (1.7 kg ha^{-1} mm^{-1}), although not significant ($p > 0.05$, Table 2). In the drier 2017/18 season, IP had significantly low ($p < 0.05$) RWUE which was 75% lower compared with STDC (Table 2).

The field-based rainwater harvesting structures significantly ($p < 0.05$) increased RWUE by 4.3 folds for PH and 4.8 folds for TR compared with flat system which had RWUE of 0.6 kg ha^{-1} mm^{-1} in 2016/17 cropping season (Table 2). However, TR and PH had statistically similar RWUE in both seasons but significantly different ($p < 0.05$) to FLAT system in 2017/18 cropping season.

Results in Table 2 show that RWUE was lowest at Jera (1.2 kg ha^{-1} mm^{-1}) which was significantly lower ($p < 0.05$) by

TABLE 2 Response of rainwater use efficiency (kg ha^{-1} mm^{-1}) to contour-based and field-based RWH structures in 2016/17 and 2017/18 seasons at Jera, Kudzeeta, Manjengwa sites in Mutare District, Zimbabwe

Treatment/factor	Rainwater use efficiency in: 2016/17 season	2017/18 season
Contour-based structure		
Infiltration pit	2.1^a	1.2^a
Standard contour	1.7^a	2.1^b
Tied contour	2.2^a	2.2^b
P value	0.242	<0.001
LSD	0.3	0.38
Field-based structure		
Flat system	0.6^a	0.6^a
Pot holing	2.6^b	2.3^b
Tied ridge	2.9^b	2.6^b
P value	<0.001	<0.001
LSD	0.3	0.38
Site		
Jera	1.2^a	2.5^c
Kudzeeta	2.6^b	1.9^b
Manjengwa	2.3^b	1.1^a
p value	<0.001	<0.001
LSD	0.3	0.38
Grand mean	2.0	1.8

Note: Means in the same column followed by different superscripts under each treatment factor are significantly different at $p < 0.05$.

Abbreviation: LSD, least significant difference.

117% and 92% to that observed at Kudzeeta and Manjengwa sites in 2016/17 season, respectively. Jera site had the highest RWUE in the drier 2017/18 season which was significantly different ($p < 0.05$) from results observed from Manjengwa and Kudzeeta (Table 2).

The effects of site x contour-based water harvesting structures had significant effects ($p < 0.05$) on RWUE in 2016/17 cropping season (Figure 7b). RWUE was significantly higher ($p < 0.05$) under IP and TC compared with STDC. Rainwater harvesting method of IP had significantly higher ($p < 0.05$) RWUE at Kudzeeta (Figure 7b). TR had the highest RWUE from Kudzeeta and this was significantly higher ($p < 0.05$) compared with other sites (Figure 7c).

In the 2017/18 season, signficant ($p < 0.05$) interactive effects of site and contour-based structure on RWUE were observed (Figure 8b). Manjengwa site had the lowest RWUE which show no significant effects across contour-based structures ($p > 0.05$). At Jera site, IP had signficantly lower ($p < 0.05$) RWUE compared with the control (STDC). The TC had no significant effect ($p > 0.05$) on RWUE. At Kudzeeta site, IP had no significant effect on RWUE ($p > 0.05$) in the drier 2017/18 season. However, the TC had significant effects ($p < 0.05$) on RWUE compared with the STDC.

Interaction of site and field-based water harvesting structures show significant effects ($p < 0.05$) on RWUE in the 2017/18 season (Figure 8c). At Jera site, planting basins and TR significantly ($p < 0.05$) increased RWUE by 1.8 and 2.7 kg ha^{-1} mm^{-1}, respectively. In addition, PH and TR significantly increased ($p < 0.05$) RWUE by 2.4 and 2.7 kg ha^{-1} mm^{-1}, respectively. Field-based structures had no significant effects ($p > 0.05$) on RWUE were observed at Manjengwa in the drier 2017/18 season.

4 | DISCUSSION

4.1 | Grain yield

Higher maize grain yields in 2016/17 season were attributed to higher rainfall and better rainfall distribution during the season in all experimental sites. Least significant differences (LSD) were used to separate means which show significant differences. The contour-based structures had varying effects on maize yields in smallholder farming environments because these areas experience climate variability since they are mainly located in semi-arid regions. In this study, the rainwater harvesting structures significantly affected maize grain yield in the drier season only. The lack of yield and RWUE response to contour-based structures in the wet 2016/17 season indicate water adequacy that masked treatment effects. However, IP significantly reduced maize grain yield and RWUE in the 2017/18 season (Table 1). This could be attributed to the fact IP did not impound and release enough water to cushion maize crop against dry spells that coincided with critical flowering and grain-filling stages in February and March 2018 leading to lower grain yields (Table 1). Infiltration pit had a dimension of 2(L) x 0.5 (W) x 0.5 (D), and two IPs could hold a maximum of 1.0 m^3 per 5 m distance along the contour, compared with TCs which could approximately hold 1.75 m^3 of water (5 (L) x 1.4 (W) x 0.25 (H)). This makes IPs a less reliable climate change adaptation strategy in the smallholder sector on sandy soils in comparison to TCs. Results from this study were supporting results by Kubiku, Nyamadzawo, et al. (2022) and Kugedera et al. (2022b) who reported higher sorghum grain yields from TCs compared with IP and STDC.

Maize grain yields from contour-based rainwater harvesting techniques did not show any significant differences in 2016/17 cropping season although TCs had the highest grain yields. This was attributed to high rainfall received during this cropping season which stimulated physiological processes such as grain filling. TC harvested surface runoff and availed it to crops during dry spells to improve plant growth and development (Kugedera et al., 2022a). Availability of moisture reduces effects of drought stress through improvement in the key biochemical processes such as photosynthesis and translocation of carbohydrates and proteins to grains. These results concur with findings by Fahad et al. (2021) and Haider et al. (2021) who reported that drought stress can be alleviated by the availability

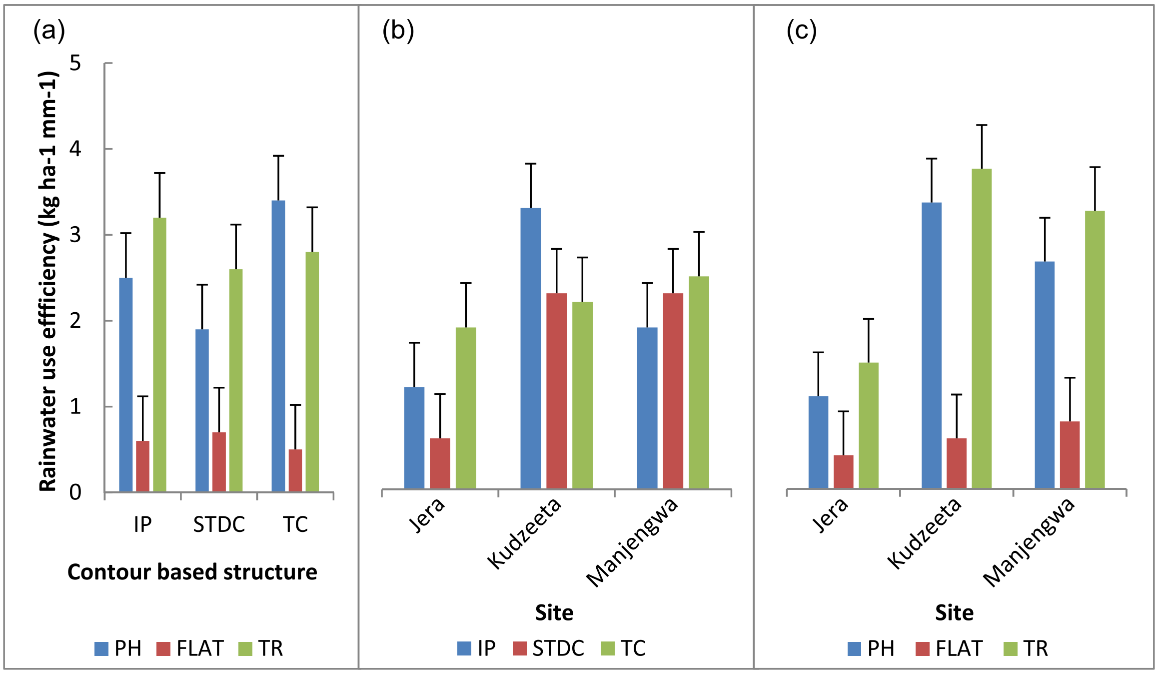

FIGURE 7 Interactive effects of: (a) Contour-based structure x field-based structure ($p = 0.150$);); (b) site x in- contour water harvesting structure ($p = 0.037$); (c) site x field-based rainwater harvesting structure ($p = 0.063$) on maize rain water use efficiency (RWUE) in the 2016/17 season. FLAT is the flat system; PH is pot holing; TR is tied ridges; IP is infiltration pit; STDC is the standard contour and TC is the tied contour.

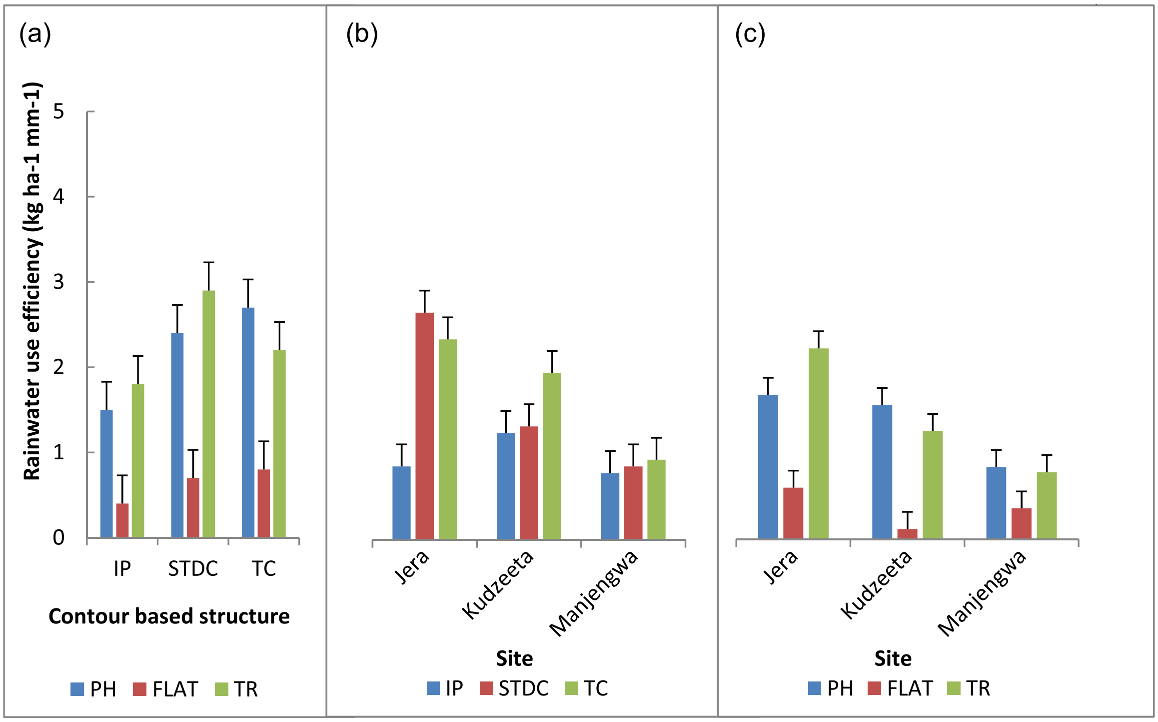

FIGURE 8 a-c: Interactive effects of: (a) Contour-based structure x field-based structure ($p = 0.191$); (b) site x field-based rainwater harvesting structure ($p < 0.001$); (c) site x in- contuour water harvesting structure ($p < 0.001$) on maize rain water use efficiency (RWUE) in the 2017/18 season. FLAT = the flat system; PH is = pot holing; TR = tied ridges; IP = infiltration pit; STDC = standard contour and TC = tied contour.

of moisture and this increases photosynthetic area and yields. This leads to higher maize grain yields even from STDCs which were designed to dispose-off most runoff water from the fields. These results also corroborates to results by Kubiku, Nyamadzawo, et al. (2022) and Kugedera et al. (2022b) who reported higher grain yields from TCs. Higher maize grain yields from STDC in 2017/18 cropping season compared with infiltration pits were different from findings by Nyamadzawo et al. (2015), Nyagumbo et al. (2019), Kubiku, Mandumbu, et al. (2022) and Kugedera et al. (2022a) who all reported better yields from infiltration pits than STDC.

Infield-based rainwater harvesting techniques had significant effects on maize grain yields. Higher yields from TR were attributed to higher soil moisture since TR harvest water and recharge the root zone (Mandumbu et al., 2021). The availability of water facilitates plant physiological processes such as flowering and grain filling. This also lengthens the growing season, allowing all plant physiological processes to be fulfilled (Chilagane et al., 2020; Mahinda et al., 2018; Tapiwa et al., 2020). Semi-arid areas are associated high evapotranspiration rates which can only be solved by the availability of water to counteract the effects of moisture stress (Fahad et al., 2021). Availability of water results in healthier crops with higher leaf area index and photosynthetic area. TR and PH proved to have the potential to mitigate the moisture stress at critical growth stages by availing more moisture in the plant root zone (Mahinda et al., 2018; Tapiwa et al., 2020). These results also proved that TR and PH can be used by farmers in areas which receive rainfall ranging from 650 to 900 mm to store water which can be used by crops during dry spells to improve growth and yields. Maize grown on the flat system had the lowest grain yields despite high rainfall received.

Maize grain yields were improved by integrating contour-based and infield RWH techniques. This could have been linked to the availability of more soil moisture in the plant root zone which was effectively utilised by maize crops. Integrating TC and PH resulted in the collection of more water which was efficiently used by maize crop during the wetter season (2016/17) and this reduce drought stress especially during critical stages such as grain filling (Kugedera et al., 2022a; Mahinda et al., 2018; Nyagumbo et al., 2019; Sher et al., 2022). Infiltration pits combined with TR and PH performed better than STDC integrated with PH and TR. This may have been caused by poor water harvesting of STDC which disposed-off runoff from the field resulting in moisture stress which deliberately affected grain filling stage and movement of photosynthetic carbohydrates from leaves to grain hence lower yields (Kubiku, Mandumbu, et al., 2022; Kugedera, Nyamadzawo, Mandumbu, Nyamangara, 2022; Kugedera et al., 2022a). Nyamadzawo et al. (2015) reported that TC can be the cheapest option for farmers which if combined by other cheaper options like TR can boost maize grain yields since the construction of BAS is labour intensive (Masaka et al., 2019; Marumbi et al., 2020).

TR gave higher grain yields at Kudzeeta and Manjengwa sites. This can be linked to better management and better construction of the structures which were able to store more harvested rainwater for a longer period and recharge plant root zone to keep it moist even during the dry period. This allows the crop to have better photosynthesis and other physiological processes which needs a lot of moisture. Leaf area index was also improved by the availability of moisture and this was linked to higher yields (Mahinda et al., 2018; Chilagane et al., 2020).

Pot holing and TR have the potential of harvesting a lot of runoff water and recharge the soil increasing water in the plant root zone. This increase plant growth and even nutrient uptake promoting growth and development. When integrated with STDC and TC, maize grain yields were boosted. This may be linked to high moisture availability in the plant root zone throughout the growing season which reduces moisture stress and mitigate drought stress (Mahinda et al., 2018).

The effects of the field-based rainwater harvesting were greater in the wet 2016/17 than in drier 2017/18 season. The PH and TR field-based water harvesting structures significantly improved maize grain yield and RWUE in both seasons. This can be attributed to the fact that the water harvesting was done closer to the maize crop where it was readily available for uptake. There was less lateral water conveyance distance from the basins or TRs to the maize crop. The PH and TR were indifferent in improving maize yields in the dry and wet seasons. Smallholder sites could opt for both structures and their choice is guided by their level of preparedness.

The lack of significant interactions between the two sets of water harvesting structures shows a lack of synchronisation in water provision to the root zone. In theory, the rainwater harvested by contour-based structures is more exposed to losses (deep percolation and evaporation) and would get to the crop root zone well after the infield-based harvested water. The water provisions to the maize crop did not gel well resulting in inadequacy and lack of interactions.

4.2 | Performance of water harvesting structures at different sites

Results from this study had shown significant interactive effects of the water harvesting structures and sites. Contour-based structures significantly increased maize yield at Kudzeeta site (IP) and RWUE at Jera site (IP and TC) in the wet season. This is attributed to high rainfall where rainwater harvesting structures increased water availability towards an ideal scenario for crop growth. Field-based water harvesting was particularly important at Jera and Kudzeeta sites unlike at Manjengwa. This could be attributed to differences in location, sources of collected water and technical management at the sites. However, inaccuracy in the construction of the water harvesting structures may also contribute to the disparities observed in this study. Although grain yield and RWUE increased with the use of contour and field-based rainwater harvesting techniques, the yields and RWUEs were lower than those observed from the use of irrigation techniques such as drip irrigation. Drip irrigation supply enough water in the plant root zone which become available to crops during crucial growth stages, this improves ear development and grain filling leading to higher yields (Gadédjisso-Tossou et al., 2020). Contour and field-based rainwater harvesting improve water availability to crops but this depends on the distance from the structure (Kubiku, Nyamadzawo, et al., 2022) compared with drip irrigation which provide water directly to the plant, boost crop growth and yields. The major challenge is high investment needed to establish irrigation which is beyond the reach of many farmers in semi-arid regions (Kugedera, Nyamadzawo, Mandumbu, Nyamangara, 2022; Nyamadzawo et al., 2013). Maize grain yields were also low from sites which had low rainfall and this rainfall variation also affected the amount of water harvested by contour and field-based rainwater harvesting structures.

4.3 | RWUE

RWUE was higher from TCs compared with infiltration pits and STDCs. This may be linked to better water collection and higher volume of entrapment from TCs than infiltration pits and STDCs. Construction of TCs made them more effective in collecting rainwater and this was transformed to higher RWUE. These results agree with results by Kugedera et al. (2022b) and Kugedera, Nyamadzawo, Mandumbu, (2022) who reported higher RWUE from TCs. TR had higher RWUE compared with planting basins and flat system. TR have the ability to hold water for long period and allow it to recharge plant root zone and hence used effectively by plants (Mandumbu et al., 2021). These results were corroborating results by Itabari (1999), Fatondji et al. (2006), Chiroma et al. (2008) and Coulibaly (2015) who all reported higher RWUE in the same range with this experiment after using TR and Zai pits.

The lack of RWUE response to contour-based structures in the wet 2016/17 season indicates water adequacy that masked treatment effects. However, in 2017/18 season RWUE was low in IP. This can be attributed to little water released by IPs to cushion maize crop against dry spells that coincided with critical flowering and grain-filling stages in February and March 2018 leading to low grain yields. This makes IPs as a less reliable climate change adaptation strategy in the smallholder sector of Marange on sandy soils in comparison to TCs. The TCs marginally increased maize grain yield compared with the STDC. Despite high rainfall from three sites, RWUE was very low compared with what other semi-arid areas with low rainfall for example 2.1–309 kg ha^{-1} mm^{-1} from infiltration pits and TCs (Kugedera, Nyamadzawo, Mandumbu, 2022), 2.83–3.38 kg ha^{-1} mm^{-1} by Chiroma et al. (2008) and 13–26 kg ha^{-1} mm^{-1} from maize under infiltration pits in Zimbabwe (Nyakudya et al., 2014). This could have been attributed to more rainwater lost after infiltration pits and TCs were full after heavy downpours.

RWUE also showed a consistently similar trend to yields, implying the lack of prowess of the two contour-based water harvesting structures as climate change adaptation strategies. Contour-based water harvesting entails the need for lateral conveyance of the harvested water across the contour bound to the maize crop grown on the downslope side (Kugedera, Nyamadzawo, Mandumbu, Nyamangara, 2022; Nyagumbo et al., 2019). This process can be inefficient due to several factors, among them deep percolation water losses and high evaporation losses from sandy soils which have low water retention capacity to combat these processes. This inefficiency in RWUE was attributed by Lovenstein (1994) to a mismatching between water availability and crop water requirements. This calls for the need to fine tune water uptake under such fluctuating conditions created by rainwater harvesting to optimise the efficiency of water use, for example, increasing plant density. However, the use of irrigation system such as drip irrigation in semi-arid areas has higher water use efficiency (15–22 kg ha^{-1} mm^{-1}), (Gadédjisso-Tossou et al., 2020) compared with 1.2–2.6 kg ha^{-1} mm^{-1} from the use of contour and field-based rainwater harvesting techniques from this study. This is because drip irrigation is associated with low evaporation losses compared with water harvested in IP, TC and PH where evaporation is high due to large surface area.

The use of RWH techniques has the potential to increase soil moisture, crop growth and yields. Most smallholder farmer had preferred the use of contour ridges because of poor information dissemination about infiltration pits and TCs. Most farmers had labelled the use of IP as techniques suitable in drier regions (receive rainfall less than 300 mm per year). Adoption of RWH techniques have been affected by high labour demand especially TR and PH which need to be constructed every cropping season. The study was limited by climate change which caused tropical cyclone in 2017/18 cropping season which destroyed parts of RWH structures and reduced crop growth due to water logging. The use of TC and IP can be cheaper options for smallholder farmers because they are constructed one and require little labour in preceding seasons. TC and IP can be used to prepare compost which is economically cheaper for farmers since transport cost is reduced. Economically, TC and IP have higher benefit-cost ratio and net returns compared with STDC, PH and TR (Kugedera et al., 2022a). TC and IP have better agronomic efficiencies which translate to increased farm profitability and net profit. This can increase their adoption by smallholder farmers. Field edge rainwater harvesting techniques also promote sustainable agriculture in semi-arid region through reduced soil erosion, surface runoff, increased soil health and promoting vegetation due to increased soil moisture content. Using results from this study, farmers in the study area now prefer the use of TCs and infiltration pits because these techniques harvest runoff, reduce land degradation and increase soil moisture which boost crop production (Kubiku, Nyamadzawo, et al., 2022). TC technique was welcomed by several farmers in the region basing on findings from other researchers in Zimbabwe by Nyamadzawo et al. (2015), Kubiku, Mandumbu, et al. (2022) and Kugedera et al. (2022b) who all reported higher results from TC in semi-arid regions of Zimbabwe.

To increase the adoption of RWH techniques there is a need to improve agricultural extension services where extension officers are trained on how to peg and construct TCs and infiltration pits. This will help information dissemination and increase adoption of these techniques by smallholder farmers. These structures need to be evaluated on a small piece of land so that farmers enjoy the benefits and willing to expand. Water harvesting can be combined with soil fertility management strategies such as the use of compost, animal manure and agroforestry biomass to improve soil fertility in semi-arid areas (Kilasara et al., 2015; Kubiku, Mandumbu, et al., 2022; Kugedera, Nyamadzawo, Mandumbu, 2022). The use of organic nutrient sources also help RWH techniques to achieve sustainable agriculture making it climate smart in smallholder farming environments to boost food security and soil health. Training farmers on the importance of soil and water conservation explaining their benefits in achieving sustainable agriculture and environment may increase the adoption of RWH and nutrient management in semi-arid regions of Zimbabwe.

5 | CONCLUSIONS

Maize production in semi-arid areas can be improved with the use of infield and field edge rainwater harvesting techniques. These structures harvest water and recharge groundwater, increasing water use efficiency by maize plants and improve yields. Combining TR with TCs proved to be one of the best options for smallholder farmers in semi-arid areas of Zimbabwe in improving maize grain yields. These structures are labour intensive and there is need for farmers to use mechanised implements to construct TR and maintain them in future to reduce labour cost and increase return on investment. Further evaluation of these techniques is needed since results were affected by tropical cyclones which were received during the study period. Combining infield + field edge rainwater harvesting structures with nutrient management can be a solution to improve the productivity of sandy soils in smallholder areas exposed to climate change. The use TR + TC have the potential to reduce land degradation through reduced soil erosion and surface runoff. Integrating TC and PH gave higher maize grain yields of 2940 kg ha^{-1} which is more than enough per year for a household. TR show better RWUE of 3.8 $\text{kg ha}^{-1}\ \text{mm}^{-1}$ which make it suitable for improving crop yields in semi-arid regions. The combination increase food security, reduce poverty and increase human income through selling of surpluses. However, the combination creates breeding sites of mosquito which may increase the outbreak of malaria. Farmers can add plant residues or any other mulching source in TR and TCs to reduce evaporation of water. These two rainwater harvesting techniques can be applied in any region or country with similar meteorological conditions to increase crop production. Economic evaluations need to be done integration of field edge and field-based rainwater harvesting to see if the combinations are profitable and recommend the most profitable combination to farmers.

AUTHOR CONTRIBUTIONS

Pasipanodya Chiturike, George Nyamadzawo and Jephta Gotosa developed the conceptual framework. Pasipanodya Chiturike, George Nyamadzawo, Ronald Mandumbu, Jephta Gotosa and Innocent Wadzanayi Nyakudya designed the experiment. Pasipanodya Chiturike, Jephta Gotosa, Andrew Tapiwa Kugedera and Friday Nguvayasvika Mudondo Kubiku wrote the paper. All authors corrected the paper. All authors contributed to manuscript writing which was led by Pasipanodya Chiturike and George Nyamadzawo.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article.

ETHICS STATEMENT

The authors confirm that they have adhered to the ethical policies of the journal.

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SUPPORTING INFORMATION

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