Rainwater harvesting using dead level contours and infiltration pits under semi-arid conditions in Zimbabwe

W. Mupangwa [1,3], S. Twomlow [2], S. Walker [3]*

[1,3]ICRISAT, Matopos Research Station, P O Box 776, Bulawayo, Zimbabwe E-mail:*
mupangwa@yahoo.com or w.mupangwa@cgiar.org
[2]United Nations Environment Programme, P O Box 30552 (00100), Nairobi, Kenya
[3]Department of Soil, Crop and Climate Sciences, University of Free State, Bloemfontein, South Africa

Abstract

The persistent droughts and in-season dry spells, and chronic food insecurity in semi-arid areas necessitate the introduction of more robust rainwater harvesting and soil water management technologies. It is rare for drought or in-season dry spells not occur during the growing season in semi-arid parts of Zimbabwe. The current study was conducted to assess the influence of dead level contours and infiltration pits on in-field soil water dynamics over two growing seasons. The study was conducted at four farms, two farms having dead level contours only while the other two farms had dead level contours and infiltration pits located along the contour. A transect consisting of six access tubes, spaced at 5 m interval, was established across each dead level contour with or without an infiltration pit before the onset of the rains. Two access tubes were installed upslope of the contour while four tubes were installed on the downslope side. Dead level contours with infiltration pits captured more rainwater than dead level contours only resulting in more lateral soil water movement. Significant lateral soil water movement was detected at 3 m downslope following rainfall events of 60-70 mm. The 0.2-0.6 m soil layer benefited more from the lateral soil water movement at all the farms. Our results suggest

that dead level contours have to be constructed at 3-8 m interval for crops to benefit from the captured rainwater. This is not practical given the high labour demand and the limited crop yield benefits derived from having these structures on the field. It is probably worth exploring strip cropping of food and fodder crops on the downslope of the dead level contours and infiltration pits.

Key words: Dead level contour, infiltration pit, rainwater harvesting, semi-arid, Zimbabwe

1. Introduction

Rainfed crop production plays a pivotal role in the developing countries where the majority of the people depend on agriculture for their livelihoods (Verchot and Cooper, 2008). It is projected that rainfed farming will account for 40% of growth in cereal production by 2021-2025 (Rosegrant *et al*., 2002). In the Southern African Development Community (SADC) region human population is growing at 2.4% per annum while crop output from the smallholder farming sector is declining (Chilonda *et al*., 2007). The decrease in crop output from the smallholder farming sector is related to climatic and socio-economic constraints.

Rainfall is the major climatic factor that influences crop production in the smallholder sector under semi-arid environments (Thomas *et al*., 2007). Rainstorms are often spatially distributed, varying highly even within a few square kilometres (Usman and Reason, 2004; Masvaya, *et al.* 2008; Love, *et al*., 2008). Temporal rainfall distribution is poor

during most growing seasons resulting in soil water deficits at critical stages of crop development. These rainfall characteristics are likely to continue haunting the smallholder agricultural sector of sub-Saharan Africa in the face of climate change. The African continent has been identified as one part of the world to be hit hard by climate change (Jones and Thornton, 2003).

Rainwater harvesting, a method of collecting surface runoff from a catchment area and storing the water in the root zone of a cultivated area for crop growth (Li *et al*., 2004), can play a critical role in reducing production risk in rainfed agriculture. In the semi-arid areas rainwater harvesting could be a source of water for smallholder cropping systems (Falkenmark *et al*., 2001; Irshad *et al*., 2007). Traditionally smallholder farmers in Zimbabwe have been using the graded contour ridge for safely diverting excess water from the field (AGRITEX, undated; Mutekwa and Kusangaya, 2006). A standard graded contour ridge is pegged at a gradient of 1:250 and contour ridges are usually spaced at 20 to 30 m apart on gentle slopes (AGRITEX, undated; Hughes and Venema, 2005).

Dead level contours, pegged at zero gradient, are an appropriate between-field technique for harvesting runoff water for crop production. The purpose of a dead level contour is to retain runoff water in the contour hoping that soil water will move into cropped field by lateral flow (Hughes and Venema, 2005). To improve the ability of the dead level contour in retaining runoff, water infiltration pits are dug along the contour often at 10 m interval (AGRITEX, undated). A standard infiltration pit measures 2 m long, 1 m wide and 0.5 – 1 m deep (AGRITEX undated; Hughes and Venema, 2005).

Efforts by international research organisations, Non-Governmental Organisations (NGOs) and Government Agricultural Departments continue in finding a combination of appropriate technologies that reduce the impact of harsh climatic factors on livelihoods of smallholder farmers. In Gwanda district of southern Zimbabwe dead level contours and infiltration pits are being promoted by Practical Action Southern Africa. The design of the dead level contours includes having an infiltration pit at intervals along the contour. Dead level contours and infiltration pits have been explored in other semi-arid districts of Zimbabwe (Motsi *et al*., 2004; Mugabe, 2004). Results from these studies have shown that dead level contours and infiltration pits can contribute towards soil water status in the cropped field. In a study by Mugabe (2004) rainwater captured by the infiltration pits replenished soil water on the upslope and downslope sides of the infiltration pit.

Our study in Gwanda district was designed to assess the influence of dead level contours and infiltration pits on soil water patterns on the upslope and downslope sides of dead level contours with or without infiltration pits. The specific objectives of the study were (1) to measure the profile soil water content at 7 and 2 m upslope, and at 3, 8, 13 and 18 m downslope of the dead level contours with and without infiltration pits throughout the growing season and (2) to determine the extent to which soil water moves laterally from contours into the cropped field. This paper reports on the soil water changes observed at 2 and 7 m upslope and 3 and 8 m downslope of the dead level contours.

2. Materials and methods

2.1. Site description

Gwanda district is lies in the Mzingwane catchment which is part of the Limpopo river basin and receives annual rainfall of less than 450 mm (Unganai, 1996; FAO, 2004). Rainfall season is unimodal and begins in November/December and ends in March/April. The cropping season experiences periodic dry spells particularly in January and is followed by a dry season that stretches from May to September. The predominant soils in Gwanda district are coarse-grained sands to loamy sands and clay loams to clay with minor occurrences of vertisols (Anderson *et al*., 1993). The soils are classified as Eutric/Dystric Regosols and Chromic Luvisols according to FAO/UNESCO classification, and as Ustalfic Haplargid and Lithic/Ustic Torriorthent according to Soil Taxonomy (Nyamapfene, 1991; FAO, 2006).

2.2. Experimental set up

The experiment was established at four farms located in ward 17 of Gwanda district, southern Zimbabwe. Two farms (Moyo and Ncube) had dead level contours only while the other two (Dube and Siziba) had dead level contours and infiltration pits (Plate 1). In the 2006/07 growing season a single transect of access tubes was set up across the dead level contours and infiltration pits in conventionally ploughed fields which were under maize, sorghum, pearl millet and groundnut crops. In the 2007/08 growing season two transects of access tubes, one along conventionally ploughed field and another along unploughed field, were set up at each farm in order to separate the effect of tillage from that of contours on soil water measured at each distance from the contour. The 15 mm

PVC access tubes were installed at 2 and 7 m from the centre of the dead level contour with/without infiltration pit on the upslope side (Fig. 1). On the downslope side of the dead level contour with/without infiltration pit access tubes were installed at 3, 8, 13 and 18 m from the centre of the contour. The access tubes were sunk to depths varying from 0.5 to 0.8 m across the four farms. Depth of access tubes was restricted by the presence of a stony layer in the profile at three of the four farms. At each farm access tubes were installed in October and maintained for the subsequent seasons. The dead level contours averaged 0.9-1.0 m wide and 0.3 m deep across the four farms. The infiltration pits averaged 1-1.5 m long, 0.5-1.0 m wide and 0.3-0.4 m deep across the two farms (Dube and Siziba).

Plate 1. Dead level contour with (a) and without (b) infiltration pit in ward 17 of Gwanda district, southern Zimbabwe
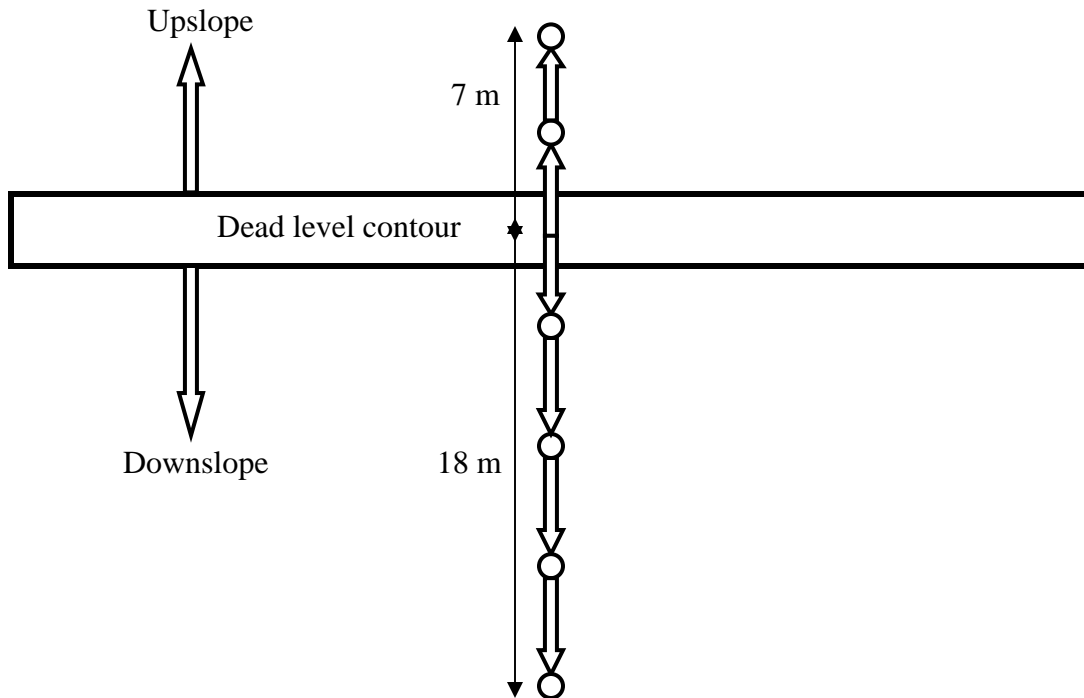
Figure 1. Schematic diagram of the set up of access tubes across dead level contours at each farm in Gwanda district

2.3. Soil water measurements

During the 2006/07 and 2007/08 growing seasons volumetric soil water content was measured using a capacitance probe (MGPHR *microgopher sensor,* *http://www.odysseydatarecording.com*). Soil water was measured fortnightly at 0.1 m depth intervals during both 2006/07 and 2007/08 seasons. Six to eight readings were taken from each access tube depending on the depth of the access tubes. Soil water content in millimetres was determined by multiplying volumetric water content by the thickness of each layer where the soil water was measured. The soil water content in the 0-0.6 m profile at each farm was calculated during the two growing seasons. Soil samples were collected at 0.15 m depth interval up to 0.60 m for texture determination. Soil

texture for each farm was determined by the hydrometer method as outlined by Anderson and Ingram (1993).

2.4. Soil water data analysis

Soil water data were analyzed using the method of residual maximum likelihood (REML) in Genstat version 9. Each season was analysed separately because of differences in the rainfall patterns experienced during the 2006/07 and 2007/08 growing seasons. In the analysis of soil water data the following model was applied;

2.4.1. 2006/07 growing season

Fixed model: Constant + Contour type + Distance + Date + Depth + Contour type.Distance + Contour type.Date + Contour type.Depth + Distance.Date + Distance.Depth + Date.Depth + Contour type.Distance.Date.Depth

Random model: Farm

2.4.2. 2007/08 growing season

Fixed model: Constant + Contour type + Distance + Date + Depth + Tillage + Contour type.Distance + Contour type.Date + Contour type.Depth + Contour type.Tillage + Distance.Date + Distance.Depth + Distance.Tillage + Date.Depth + Date.Tillage + Contour type.Distance.Date.Depth.Tillage

Random model: Farm

3. Results and Discussion

3.1. Soil physical properties at the four farms

The physical properties of the soils at the four farms used in this study are summarized in Table 1. Coincidentally the farms that had a dead level contour with infiltration pits had higher clay content in the soil profile than those with dead level contours only. The soil types at the four farms ranged from sand to loamy sand.

Table 1. Soil physical properties at the four farms used for quantifying soil water supply from dead level contours and infiltration pits in Gwanda district, southern Zimbabwe

Farm	Contour type	Depth (cm)	Clay (%)	Silt (%)	Sand (%)
Moyo	Only dead level contour	0-15	5	3	92
		15-30	6	4	90
		30-45	8	4	88
		45-60	7	8	85
Ncube	Only dead level contour	0-15	4	6	90
		15-30	3	5	92
		30-45	2	8	90
		45-60	4	7	89
Dube	Dead level contour and infiltration pit	0-15	10	4	86
		15-30	11	3	86
		30-45	16	6	78
		45-60	18	6	76
Siziba	Dead level contour and infiltration pit	0-15	6	13	81
		15-30	12	7	81
		30-45	18	6	76
		45-60	20	7	73

3.2. Seasonal rainfall at the farms

3.2.1. 2006/07 growing season

The four farms received different amounts of rainfall during the 2006/07 growing season (Fig. 2). The number of rainfall events recorded at the four farms ranged from eight to 17 during the 2006/07 season. The highest daily rainfall event during the 2006/07 season

was 38 mm recorded at Moyo farm on 26 February 2007 (day 149). The total seasonal rainfall recorded during the 2006/07 growing season ranged from 145 mm to 242 mm. The total seasonal rainfall recorded at each farm during the 2006/07 season was below the 50 year average of 376 mm for Beitbridge district (NR V) which has similar climatic characteristics with the southern part of Gwanda district (Mupangwa, 2008). A 54-day dry spell was experienced from 2 January 2007 (day 94) to 26 February 2007 (day 149) when 22 mm of rain was received. The dry spell coincided with the vegetative and flowering stages of the major cereal crops (maize, sorghum and pearl millet) resulting in complete crop failure on most smallholder farms in Gwanda district. Dry spells occurring during the cropping period are a characteristic feature of semi-arid areas of East Africa (Barron *et al.*, 2003), West Africa (Graef and Haigis, 2001) and Southern Africa (Usman and Reason, 2004).
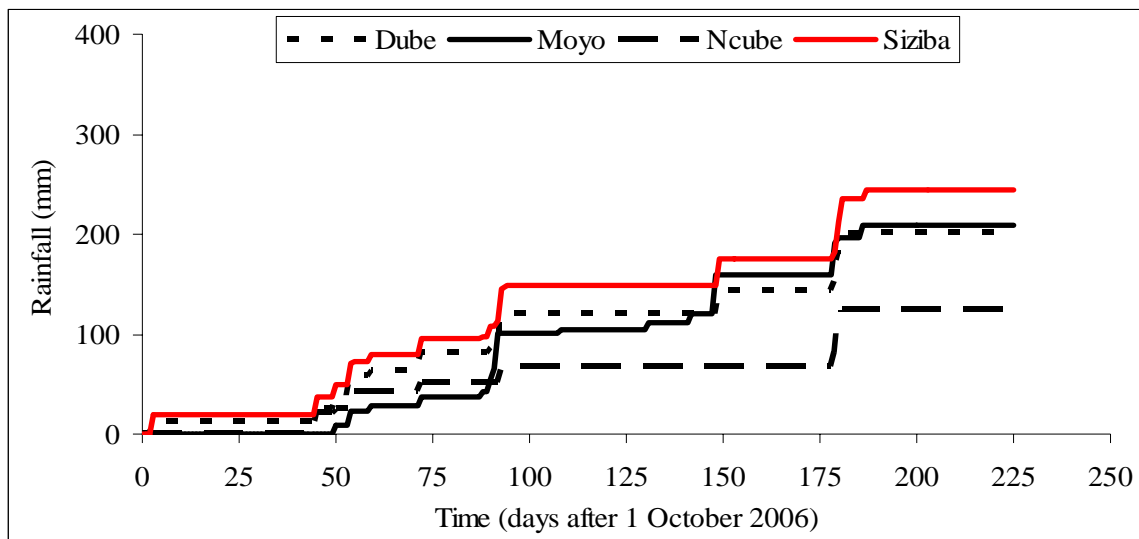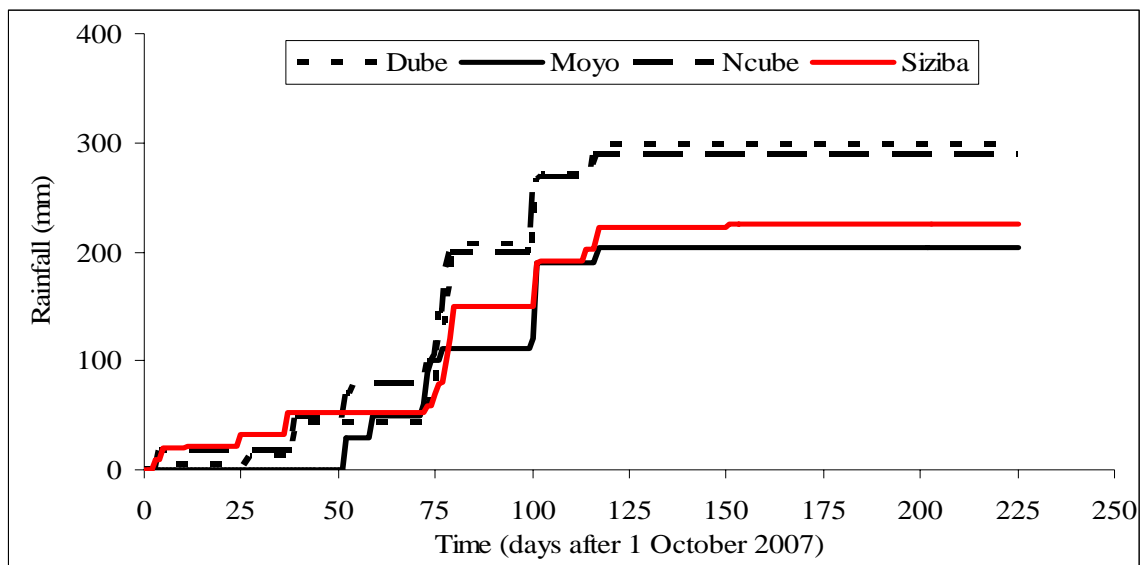

Figure 2. Daily rainfall distribution at Moyo, Ncube, Dube and Siziba farms of ward 17 in Gwanda district during 2006/07 growing season

3.2.2. 2007/08 growing season

Total seasonal rainfall recorded during the 2007/08 season ranged from 204 mm to 298 mm (Fig. 3). Most of the rainfall events were concentrated in the October to December period with just five events occurring during the January to April period. The highest daily rainfall event was 70 mm recorded on 8 January (day 100) at Dube, Moyo and Ncube farms. The last rainfall event was recorded on 24 January 2008 (day 116) with 18 to 20 mm being received across the four farms. As observed in the 2006/07 season, total seasonal rainfall at all farms was below 376 mm which is the 50 year average for Beitbridge district (NR V) of southern Zimbabwe.

Figure 3. Daily rainfall distribution at Moyo, Ncube, Dube and Siziba farms of ward 17 in Gwanda district during 2007/08 growing season

3.3. Soil water changes in fields with dead level contours only

3.3.1. 2006/07 growing season

The distance from the dead level contour had no significant (P>0.05) influence on profile water content recorded along the ploughed transect during the 2006/07 growing season

(Fig. 4). The lowest profile water content was recorded at 7 m upslope of the dead level contour throughout the season. Soil water content recorded in the profile differed significantly (P<0.001) between the dates when soil water measurements were made indicating the occurrence of wetting and drying cycles during the growing season. Profile soil water content decreased (P<0.001) from 25 January (day 117) to 19 February (day 142) at all distances from the dead level contour (Fig. 4). The decrease in profile water content between these two dates is attributed to soil water uptake by crops growing around the access tubes as well soil evaporation. In the 0-0.60 m profile, soil water content decreased by 52 to 53% upslope of the dead level contour and 49 to 51% downslope of the contour between days 117 and 142. A 7 mm rainfall event was recorded at Moyo farm between 25 January (day 117) and 19 February (day 142) and this amount was negligible to cause any notable changes in profile soil water content. The soil profiles at Moyo and Ncube farms were recharged by 49-57 mm of rain that was received between 28 March (days 179) and 13 April (194) (Figs. 2 and 4).

On 12 January 2007 (day 104), the wettest day when soil water measurements were made, there was no significant difference (P>0.05) in soil water content measured at each depth at all the distances from the dead level contour along the ploughed transect (Fig. 5). The 0–0.15 m layer had more (P<0.001) soil water than the deeper layers at each distance from the dead level contour (Fig. 5). There was higher soil water content at 8 m from the dead level contour than other distances suggesting the contribution of conventional ploughing to the measured soil water. In the top 0.5 m soil layer the lowest soil water

content was recorded at 7 m upslope of the contour, further confirming negligible lateral movement of soil water from the dead level contour.
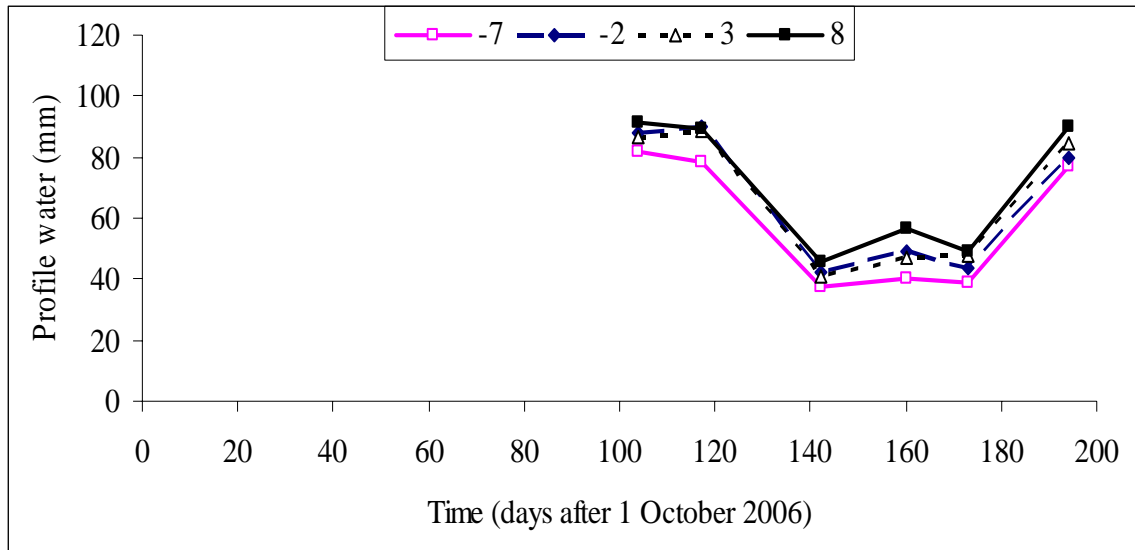

Figure 4. Profile soil water changes along ploughed transects averaged across two farms with dead level contours only (Moyo and Ncube) during the 2006/07 growing season
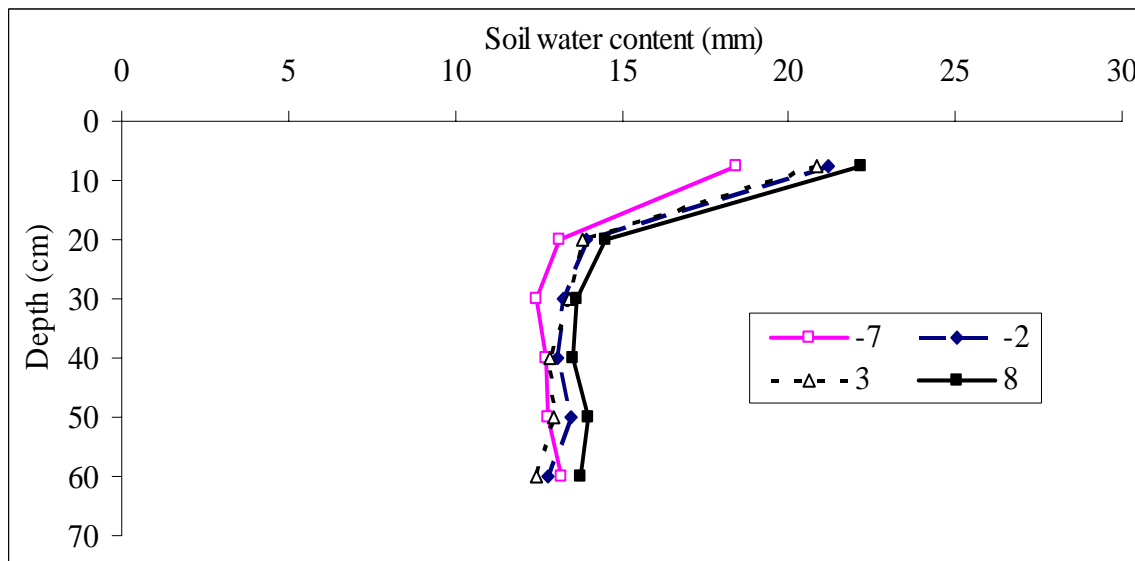

Figure 5. Soil water distribution with respect to depth at different distances from the dead level contour only averaged across two farms (Moyo and Ncube) on the wettest day (12 January 2007) along ploughed transect during 2006/07 growing season

3.3.2. 2007/08 growing season

There was no significant (P>0.05) difference in profile water content recorded along the unploughed and ploughed transects between 14 November 2007 (day 45) and 9 January 2008 (day 101) (Fig. 6). After receiving 70 mm of rain on 8 January 2008, the measured profile water content at 8 m was 15% less than at 3 m downslope along the unploughed transect. On the upslope side of the contour, the recorded profile water content at 2 m was 14% less than at 3 m. There was 20% more soil water in the profile at 3 m downslope than at 7 m upslope. After receiving 70 mm of rain, the highest profile water content along the ploughed transect was recorded at 3 m downslope, suggesting that water had moved laterally from the dead level contour. Conventional ploughing further increased profile water content along the ploughed transect. Ploughing loosens the soil and creates surface depressions that collect rainwater giving it more time to infiltrate (Van der Meer, 2000; Sasal *et al*., 2006).

Along the unploughed and ploughed transects the 0–0.15 m soil layer had significantly (P<0.001) higher soil water content than the deeper layers at each distance from the contour following the 70 mm rainfall event (Fig. 7). The distance from the dead level contour had a significant (P<0.001) influence on soil water content measured at each depth along the unploughed and ploughed transects. The highest soil water content at each soil depth was recorded at 3 m along the unploughed transect (Fig. 7). Along the ploughed transect, soil layers below 0.2 m depth were wettest at 3 m (Fig. 7). This further confirms that there was lateral soil water movement following the 70 mm rainfall event along both the unploughed and ploughed transects. There was better lateral soil water

movement between 0.3 and 0.4 m depths along the ploughed transect. This could be attributed to the influence of soil physical properties on the lateral movement of water in the profile. The 0-0.15 m soil layer had more soil water at 2, 7 and 8 m than at 3 m from the contour, confirming the contribution of conventional tillage on the soil water content measured along the ploughed transect.
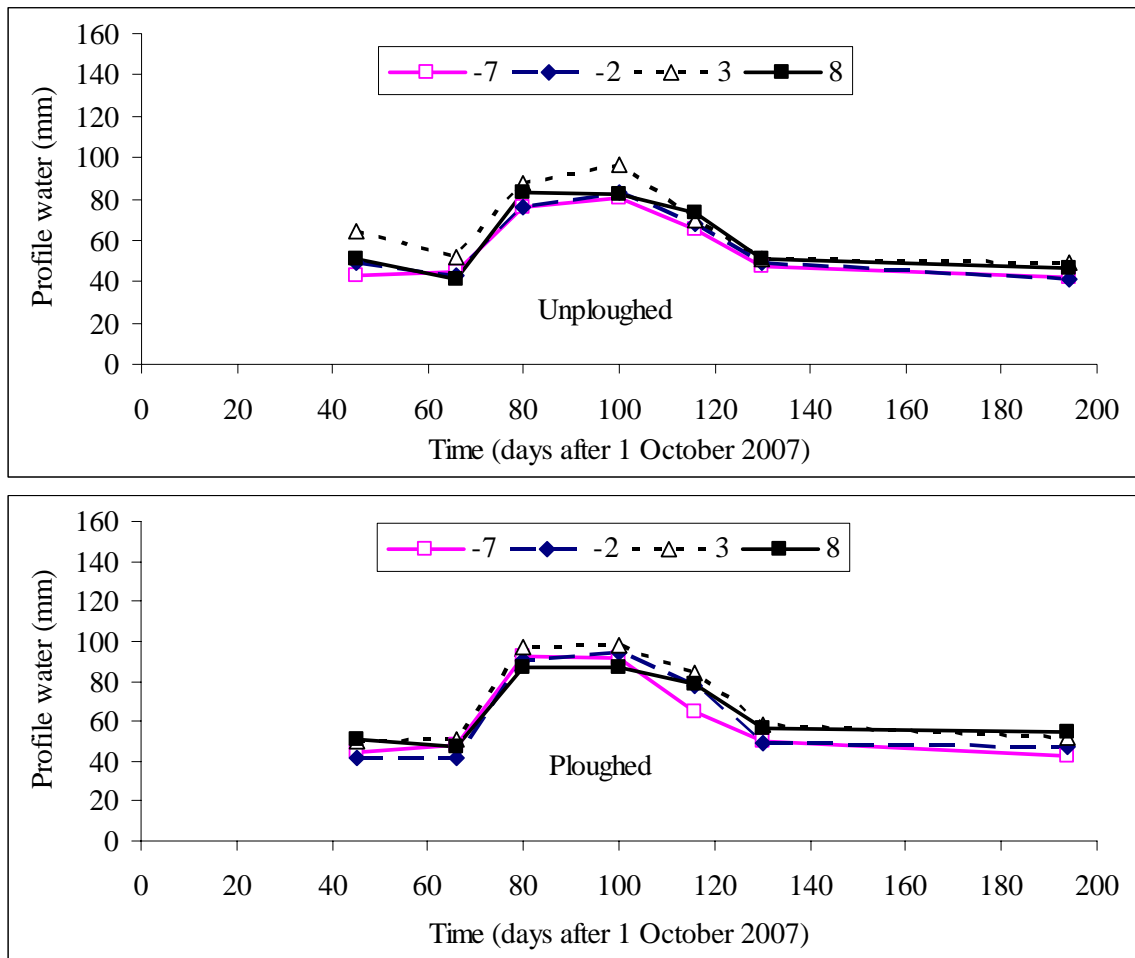

Figure 6. Profile soil water changes averaged across two farms (Moyo and Ncube) with dead level contours only along unploughed and ploughed transects during 2007/08 growing season
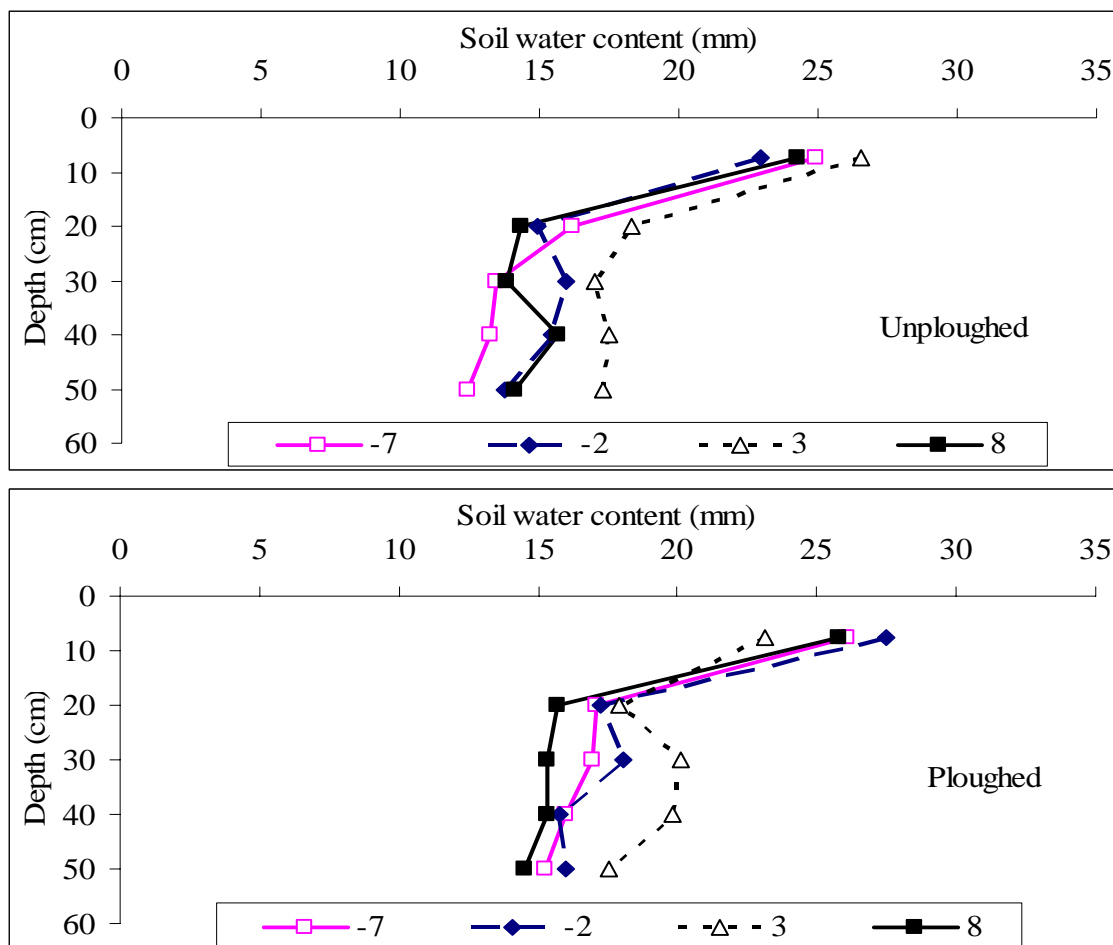
Figure 7. Soil water distribution with respect to depth at different distances from the dead level contour only averaged across two farms (Moyo and Ncube) on wettest day along unploughed and ploughed transects during 2007/08 growing season

3.4. Farms with dead level contours and infiltration pits

3.4.1. 2006/07 growing season

As observed at farms with dead level contours only, distance from the contour had no significant ($P>0.05$) influence on profile soil water content measured on each day soil water measurements were taken (Fig. 8). Profile water content decreased significantly ($P<0.001$) between 25 January (day 117) and 19 February (day 142) at all distances from the dead level contour and infiltration pit. Profile water content decreased by 52 to 54%

upslope of the contour and 51% downslope of the dead level contour and infiltration pit. The soil profiles at the two farms were recharged following 22 and 26 mm of rainfall recorded on 24 February (day 149) (Fig. 2). The rainfall events that occurred between 28 March (day 179) and 13 April (day 194) also recharged the soil profiles at Dube and Siziba farms. Dube farm received 60 mm of rain over a nine day period while Siziba farm accumulated 69 mm during the same period (Fig. 2).
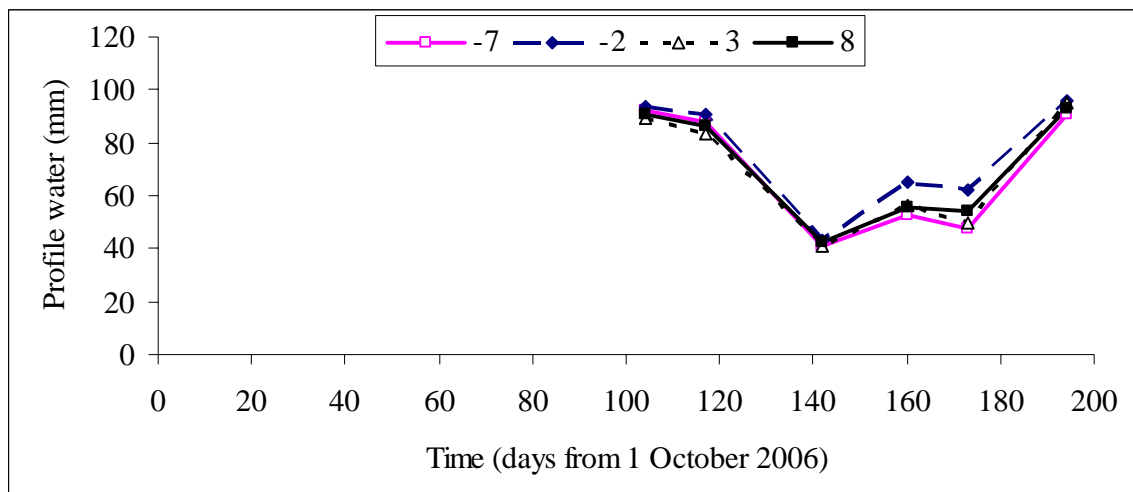

Figure 8. Profile soil water changes at different distances from the dead level contour with infiltration pit averaged across two farms (Dube and Siziba) during 2006/07 growing season

Soil water distribution with respect to depth measured on the wettest day (12 January) during the 2006/07 season is given in Figure 9. The top layer had more (P<0.001) soil water than the deeper layers on 12 January, nine days after a 35 mm rainfall event. The 0–0.15 m soil layer had more soil water at 2 m upslope on 12 January (day 104) than at the other distances nine days after the last rainfall event. The higher soil water content in the top layer at 2 m upslope can be attributed to the fact that more rainwater was captured

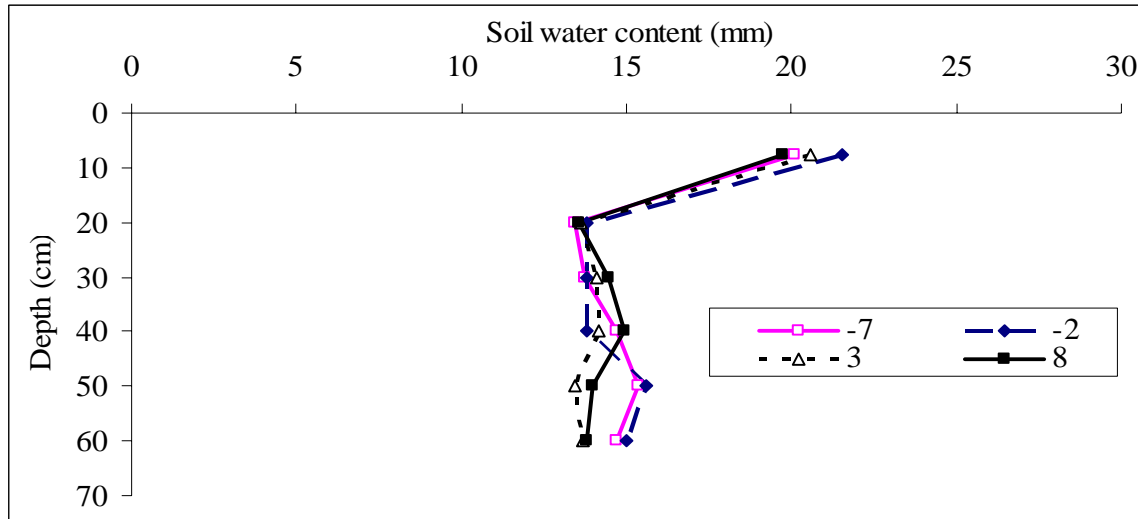in the surface depressions around the access tube since the transect was conventionally ploughed.

Figure 9. Soil water distribution with respect to depth at different distances from the dead level contour and infiltration pits averaged across two farms (Dube and Siziba) on wettest day during 2006/07 season

3.4.2. 2007/08 growing season

The soil profile along the ploughed transect had more soil water than the unploughed transect. The unploughed transect had the highest profile water content at 8 m from the contour after receiving 60 mm of rainfall on 8 January 2008 (Fig. 10). There could have been some surface depressions near the access tube at 8 m that were created by conventional ploughing in previous seasons. These depressions collected rainwater during the rainfall event of 8 January (day 100) resulting in the higher soil water observed than at the other distances from the contour. Contrary to the ploughed transect, the lowest soil water content along the unploughed transect on 9 January 2008 was recorded at 7 m upslope. Profile soil water content at 7 m upslope was 5% less than at 2 m upslope and 8% less than at 3 and 8 m downslope along the unploughed transect.

18

Along the ploughed transect the highest soil water content in the profile was recorded at 3 m between 14 November 2007 (day 45) and 12 April 2008 (day 194) (Fig. 10). Following the 70 mm rainfall event of 8 January 2008, profile soil water content recorded at 3 m downslope was 7 and 10% more than at 2 and 7 m upslope, and 5% more than at 8 m downslope.
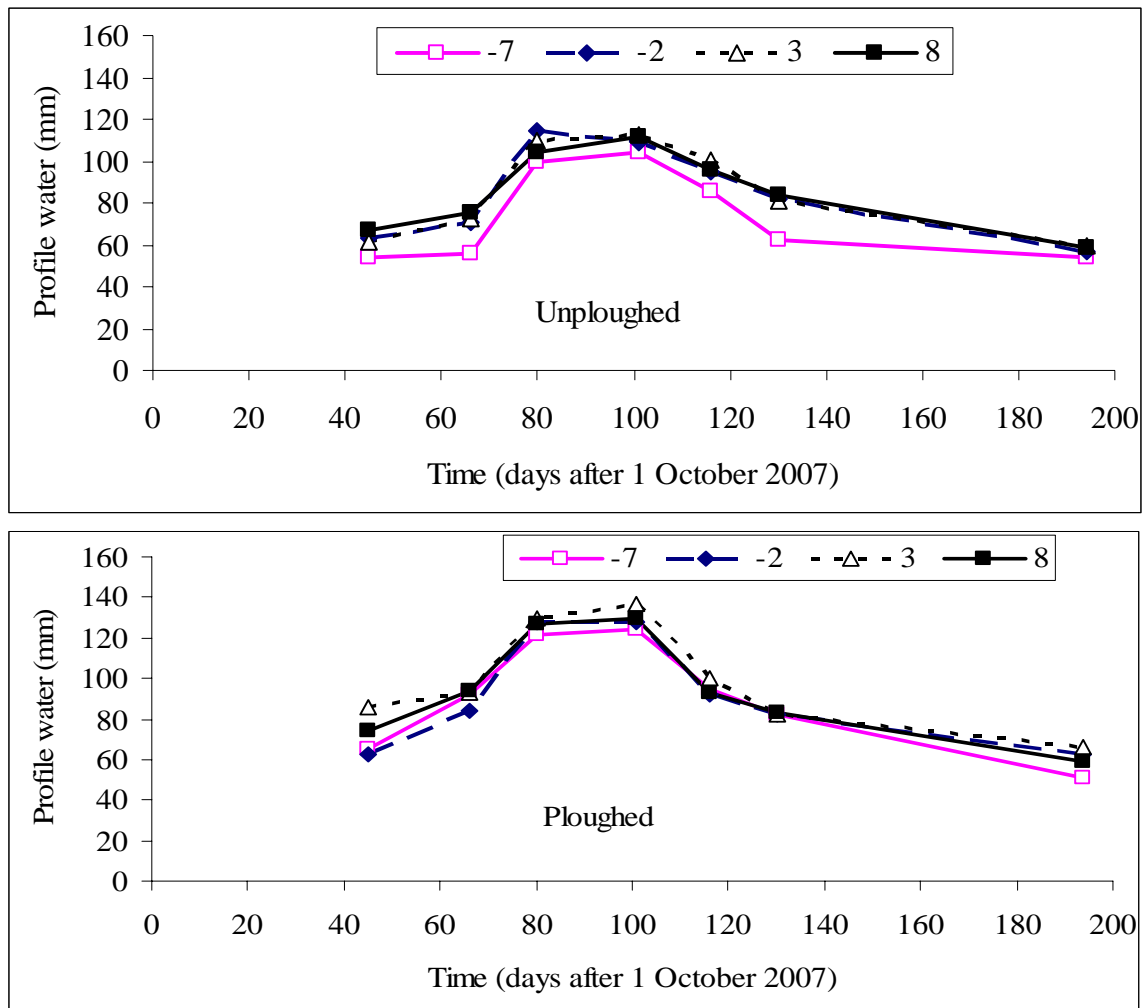

Figure 10. Profile soil water changes along unploughed and ploughed transects at farms with dead level contours and infiltration pits averaged across two farms (Dube and Siziba) during 2007/08 growing season

On 9 January 2008 (day 101) the soil profile along the ploughed transect had more (P<0.001) water than the unploughed transect (Fig. 11). This indicates that conventional ploughing increased soil water content through collecting rainwater in the surface depressions created during the tillage operation. The distance from the dead level contour and infiltration pit had no significant (P>0.05) influence on soil water content measured at each soil depth along the unploughed transect throughout the 2007/08 growing season (Fig. 11). The 0–0.15 m soil layer had higher (P<0.05) soil water content than the deeper layers along the unploughed and ploughed transects (Fig. 11). Along the ploughed transect the wettest 0–0.15 m layer was at 3 m while the same layer was driest at 2 m upslope (Fig. 11). More profile water was gained downslope at farms with dead level contours and infiltration pits than at those farms with dead level contours only following the 60-70 mm rainfall event (Figs 7 and 11). This indicates that the dead level contours and infiltration pits at Dube and Siziba farms captured more rainwater that moved laterally into the field than the dead level contours at Moyo and Ncube farms. Our observation at Dube and Siziba farms are consistent with the findings of Mugabe (2004) that also indicated lateral soil water movement upslope and downslope of an infiltration pit measuring 7m long and 1m deep.
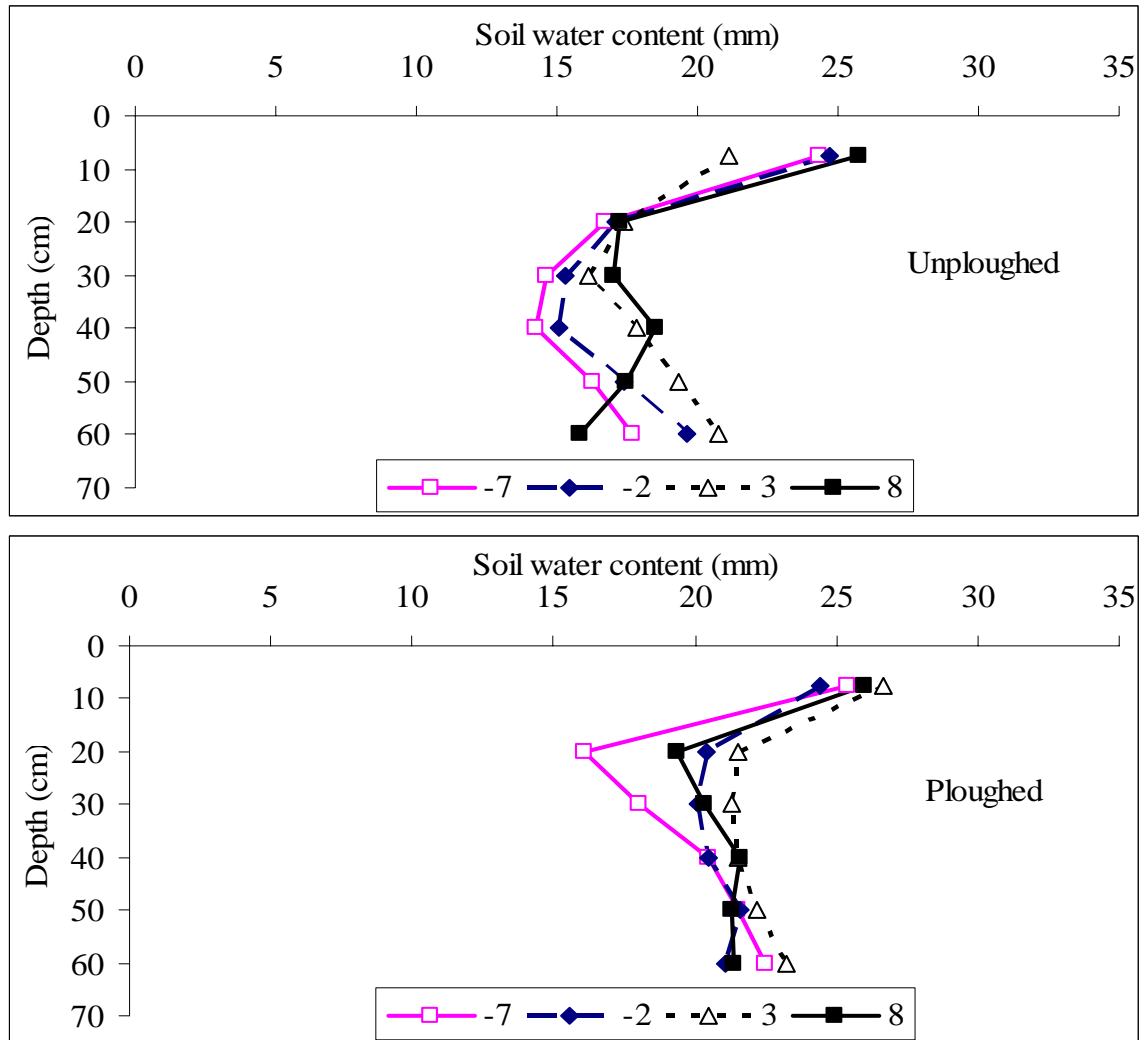
Figure 11. Soil water distribution with respect to depth at different distances from the dead level contour and infiltration pits averaged across two farms (Dube and Siziba) on wettest day along unploughed and ploughed transects during 2007/08 season

4. Conclusions and recommendations

As expected the upward side of the dead level contour with or without infiltration pit was drier than downslope on most occasions when soil water was measured. The dead level contours with infiltration pits captured more rainwater following heavy rainfall events (60-70 mm). After the contours and infiltration pits had filled with rainwater following rainfall events of 60 and 70 mm on 8 January 2008, the wettest parts of the field were at -2 and 3 m from the contour. The soil layers that benefited most from the rainwater

captured by the dead level contours with/without infiltration pit were in the middle (0.2-0.5 m) of the 0-0.6 m soil profile. Crops such as maize, sorghum, pearl millet and legumes commonly grown in semi-arid areas can access soil water from these soil layers. The bulk of the active maize roots have been observed in the 0-0.8 m soil layer (Amato and Ritchie, 2002) although roots can reach 1.5 m deep depending on the soil type. For sorghum and pearl millet most of the roots are concentrated in 0-0.50 m soil layer (Zaongo *et al.,* 1997). Roots for grain legumes such as cowpea are also concentrated in the 0-0.50 m soil layer (Moroke *et al*., 2005).

Results from this study suggest that the dead level contours have to be constructed at between 3-8 m spacing if they are to supply soil water to crops in the field. However, given the labour and time requirements for the construction of these structures and the limited soil water benefits observed so far, it is not worthwhile investing in these rainwater harvesting structures using the current design in areas such as Gwanda district with a <1% slope and light textured soils. There are limited or unclear short term benefits (e.g. grain for human consumption and stover for livestock feeding) derived from the labour, equipment such as shovels, picks and wheelbarrows, and time invested in constructing dead level contours and infiltration pits on smallholder farms in Gwanda district. Low producer prices for small grains (<US$250/tonne), poor marketing and transport systems leave smallholder farmers in Gwanda with no incentive to invest in the construction and maintenance of the dead level contours on their farms. The labour constraint is further exacerbated by the migration of able-bodied household members to urban centres or South Africa and Botswana in search of employment and better life.

Most of the farming activities are therefore left in the hands of the elderly, women and children.

Given the crop-livestock systems of Gwanda district, it is probably worth exploring strip cropping of food and fodder crops on the downslope side of the dead level contours and infiltration pits. Deep rooted fodder crops or drought tolerant agroforestry tree species would benefit more from the soil water supply derived from dead level contours and infiltration pits. Combining structures such as dead level contours and infiltration pits with in-field rainwater harvesting techniques such as planting basins and tine ripping could be explored to assess if it will bring better returns to smallholder farms where dead level contours and infiltration pits are being promoted and used. New designs of dead level contours and infiltration pits for different soil types and slopes could be explored as a way forward in the use of inter-field rainwater harvesting structures.

References

AGRITEX (undated). A guide for farmers on good land husbandry. 64pp. www.uz.ac.zw/agriculture/cropscience/CD/gff/handplanting.pdf.

Amato, M. and Ritchie, J.T. 2002. Spatial distribution of roots and water uptake of maize (*Zea mays* L.) as affected by soil structure. Crop Science, 42: 773-780.

Anderson, I.P., Brinn, P.J., Moyo, M. and Nyamwanza, B. 1993. Physical Resource Inventory of Communal Lands of Zimbabwe. Natural Resources Institute Bulletin 60, London. 186pp.

Anderson, J.M. and Ingram, J.S.I. 1993. Tropical Soil Biology and Fertility. A Handbook of Methods. 2nd Edition. C.A.B. International, Wallingford, UK, 221pp.

Barron, J., Rockström, J., Gichuki, F. and Hatibu, N. 2003. Dry spell analysis and maize yields for two semi-arid locations in east Africa. Journal of Agricultural and Forest Meteorology, 117: 23-37.

Chilonda, P., Machethe, C. and Minde, I. 2007. Poverty, food security and agricultural trends in Southern Africa. Regional Strategic Analysis and Knowledge Support System for Southern Africa (ReSAKSS-SA), Discussion Paper N$^{\underline{o}}$1. ReSAKSS-SA, IWMI and ICRISAT, Pretoria, South Africa. 40pp.

Falkenmark, M., Fox, P., Persson, G. and Rockström, J. 2001. Water harvesting for upgrading of rainfed agriculture – Problem Analysis and Research Needs. SIWI Report N°11. Stockholm International Water Institute, Stockholm, Sweden. 94pp.

FAO, 2004. Drought impact mitigation and prevention in the Limpopo River Basin. Land and Water Discussion Paper 4. Food and Agriculture Organisation of the United Nations, Rome. http://www.fao.org/docrep/008/y5744e/y5744e00.HTM

Graef, F. and Haigis, J. 2001. Spatial and temporal rainfall variability in the Sahel and its effects on farmers' management strategies. Journal of Arid Environments, 48: 1-11.

Hughes, O. and Venema, J.H. (eds.). 2005. Intergrated soil, water and fertility management in semi-arid Zimbabwe. Farmer Field Schools Manual, vol. 1. Harare, Zimbabwe:FAO. ftp://ftp.fao.org/agl/agll/docs/ffsfm_zim.pdf.

Irshad, M., Inoue, M., Ashraf, M. and Al-Busaidi, A. 2007. The management options of water for the development of agriculture in dry areas. Journal of Applied Sciences, 7(11): 1551-1557.

Jones, P.G. and Thornton, P.K. 2003. The potential impacts of climate change on maize production in Africa and Latin America in 2055. Global Environmental Change, 13: 51-59.

Lie, X.K., Xie, Z.K. and Yan, X.K. 2004. Runoff characteristics of artificial catchment materials for rainwater harvesting in the semi-arid regions of China. Agricultural Water Management, 65: 211-224.

Love, D., Uhlenbrook, S., Twomlow, S. and van der Zaag, P. 2008. Changing rainfall and discharge patterns in the northern Limpopo Basin, Zimbabwe. European Geophysical Union General Assembly, Viena, Austria, April 2008. http://www.worldwaterweek/stockholmwatersymposium/Abstract_volume_06/workshop_9.htm.

Masvaya, E., Mupangwa, W. and Twomlow, S. 2008. Rainfall variability impacts on farmers' management strategies and crop yields. Water and sustainable

development for improved livelihoods. 9th WaterNet/WARFSA/GWP-SA symposium, 29-31 October 2008, Johannesburg, South Africa.

Moroke, T.S., Schwartz, R.C., Brown, K.W. and Juo, A.S.R. 2005. Soil water depletion and root distribution of three dryland crops. Soil Science Society of America Journal, 69: 197-205.

Motsi, K.E., Chuma, E. and Mukamuri, B.B. 2004. Rainwater harvesting for sustainable agriculture in communal lands of Zimbabwe. Physics and Chemistry of the Earth, 29: 1069-1073.

Mugabe, F. 2004. Evaluation of the benefits of infiltration pits on soil moisture in semi-arid Zimbabwe. Journal of Agronomy, 3: 188-190.

Mupangwa, W. 2008. Water and nitrogen management for risk mitigation in semi-arid cropping systems. PhD Thesis (unpublished). University of Free State, South Africa. 357pp.

Mutekwa, V. and Kusangaya, S. 2006. Contribution of rainwater harvesting technologies to rural livelihoods in Zimbabwe: The case of Ngundu ward in Chivi district. Water SA, 32(2): 437-444. http://www.wrc.org.za.

Nyamapfene, K. 1991. Soils of Zimbabwe, NeHanda Publishers, Harare, Zimbabwe.179pp.

Rosegrant, M., Cai, X., Cline, S. And Nakagawa, N. 2002. The role of rainfed agriculture in the future of global food production. ETPD Discussion Paper $N^{\underline{o}}$ 90. Environment and Production Technology Division, International Food Policy Research Institute, Washington, D.C. 20006, USA. February 2002.

Sasal, M. C., Andriulo, A. E. and Taboada, M. A. 2006. Soil porosity characteristics and water movement under zero tillage in silty soils in Argentinean Pampas. Soil and Tillage Research, 87: 9-18.

Thomas, D.S.G., Twyman, C., Osbahr, H. and Hewitson, B. 2007. Adaptation to climate change and variability: farmer responses to intra-seasonal precipitation trends in South Africa. Climate Change, 83: 301-322.

Unganai, S.L. 1996. Historic and future climatic changes in Zimbabwe. Climate Research., 6: 137-145.

Usman, M.T. and Reason, C.J.C. 2004. Dry spell frequencies and their variability over southern Africa. Climate Research, 26: 199-211.

Van der Meer, F.W., 2000. Modeling tropical soil water regimes in semi-arid environments. Ph.D. Thesis, Loughborough University. 270pp.

Verchot, L.V. and Cooper, P. 2008. International agricultural research and climate change: A focus on tropical systems. Agriculture, Ecosystems and Environment, 126:1-3.

Zaongo, C.G.L., Wendt, C.W., Lascano, R.J. and Juo, A.S.R. 1997. Interactions of water, mulch and nitrogen on sorghum in Niger. Plant and Soil, 197: 119-126.