Evaluating irrigation technologies to improve crop and water productivity of onion in Dangishta watershed during the dry monsoon phase.

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Abstract **Although Ethiopia has abundant rainfall during the monsoon, its agricultural system does not yet fully benefit from the technologies of optimal agricultural water management during the dry season when water supplies are short. Therefore, there is need to investigate the potential of simple water saving irrigation technologies for farmers. In this study two different irrigation scheduling methods were compared: irrigation scheduling by Wetting Front Detector (WFD) and soil water balance by measuring soil moisture using Time Domain Reflectometry (TDR). Eighteen farmers, grew the same onion variety, were randomly assigned to the two irrigation management practices. The experimental plot size varied between 100 m^2 and 230 m^2. Recommended crop management and fertilizer application rates were maintained for all farmers. The average amount of water applied in the WFD plots was 24% lower than for TDR. Larger variability among the TDR farmers was found both in irrigation quantity and yield. Differences in yield, water productivity and water use efficiency between both irrigation treatments were not significant. The study shows that using the WFD tool could guide farmers on how much to irrigate, reducing the amount of water without affecting crop yields.**

Key words: **Wetting Front Detector (WFD), irrigation scheduling, water productivity (WP), Water use efficiency (WUE), soil moisture, soil water balance.**

1 INTRODUCTION

Demographic pressure in the Nile Basin has resulted in tremendous pressure on natural resources to account for the increasing food and energy demand. This results in a rapidly increasing demand to put more land and fresh water for agricultural production. In Ethiopian, the vast majority of agricultural land is under low input- low output rainfed agriculture, highly susceptible to rainfall variability both in magnitude as well as occurrence (Mekonen and Kebede, 2011). Although irrigable land is estimated between 1.5 to 4.3 Mha with an average of 3.5 Mha, only 5 % (~200,000 ha) is currently under irrigation When supplemental irrigation using water from rain water harvesting structures and practices, groundwater use, and water lifting technologies are considered, it is believed that the potential could be more significant. Sustainable development of irrigation within the country requires optimal use of natural resources such as land and water. Efficient water use within irrigation practices covers the water source, water storage, conveying the water to the field and on-farm water management. For individual irrigators outside a scheme the farmer is often responsible for all these aspects.

Crop productivity and overall farm performance is influenced by various factors, e.g. farmer irrigation experience, seed quality, seed and fertilizer access, water access. According to Haileslassie et al. (2016), on-farm water management is relatively poor resulting in low yield and water productivity. In the study of Agide et al. (2016), farmers indicated that the main constraints for poor on-farm management was related to a lack of training on on-farm irrigation practices, seed availability and market access amongst others.

Farmers’ irrigation application is often either more or less than the crop water requirement. Over-irrigation unnecessarily increases the cost of production (e.g. labor, fuel) and might leach macro and micro nutrients out of the root zone. When. On the other hand lack of water during critical stages of the plant life will hamper nutrient uptake, crop development and reduce yield. Improving farmers’ knowledge on on-farm water management, particularly on how much to irrigate and when to irrigate could reduce over-irrigation practices, reduce labor and fuel costs, improve the quality of the product and foster a more equitable water distribution within watersheds throughout the dry season There are a lot of scientific methods developed to irrigate crops based on water requirement and soil moisture status. However, these methods are often complex for small holder farmers to use or are too expensive to purchase in developing countries. Wetting front detectors (WFD), a mechanical irrigation tool has been developed by Stirzaker (2003) to guide farmers in a relatively easy matter on how much to irrigate.

The main aim of the study was to evaluate whether WFD in the local context would be a suitable irrigation tool guiding farmers on how much to irrigate by comparing two irrigation treatments (WFD and soil moisture depletion using TDR) and their effects on: (i) soil moisture and overall soil water balance components throughout the root zone and (ii) onion and water productivity as well as water use efficiency.

2 MATERIAL AND METHODS

2.1 Study area

Dangila woreda is located in Awi zone in the Amhara Region and is one of Agricultural Growth Program (AGP) and USAID feed the future Woredas in the Amhara Regional State. It is located about 80 km south west from Bahir Dar, 36.83° N and 11.25° E and on average 2000 m above sea level. In the woreda, there are 27 rural Kebeles among which 16 of them have access to a perennial river. Average annual rainfall is about 1600 mm, but varies between 1180-2000 mm. The mean annual potential evapotranspiration (PET) is 1250 mm. One of Dangila’s kebeles selected for this study is Dangishta. The population of Dangishta is 5600. Dangishta has two major rivers; Branti river whose watershed covers 2291.49 ha and Kilti river whose watershed covers 1000 ha.

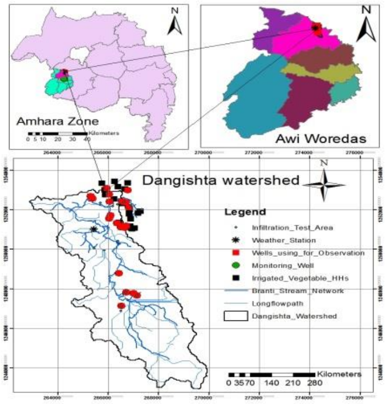

Figure 1 Location of the study area (top) and the location of farmer households within the Danghista watershed (below)

2.2 Experimental design

Within the village, 18 smallholder farmers were selected and randomly assigned to one of the two irrigation treatments: (i) WFD or (ii) Soil moisture deficit based on TDR measurements. The same onion variety was planted in for all farmers. The field size ranged between 100 m² and 230 m². The bed width (1.2 m) and length (6 m) were similar for all farmers and onions were planted at a spacing of 20 by 30 cm. Fertilizer was applied under the form of DAP and urea. Farmers in both treatment groups were trained on best agronomic practices for onion to reduce variability in the results due to crop management.

Wetting Front Detectors were installed in pairs shortly after planting within one onion bed at 4 m distance. When field capacity (FC) is reached and soils gravitationally start draining, the water is collected within the reservoir below the funnel (Figure 2). Depending on the amount of water collected in the reservoir (i.e. suction > 3kPa) the float will be activated. Each pair consists out of a yellow and a red indicator. The detectors were installed in pairs at a specific depth below the soil surface in function of the root zone (Stirzaker et al., 2004). Assuming an effective root zone of 40 cm (Allen et al., 1998), the yellow indicator was installed half (i.e. 20 cm) whereas the red indicator was installed at the end of the effective rootzone (i.e. 40 cm) below the soil surface. Irrigation is assumed to be optimal when the yellow indicator is activated during irrigation with minimal activation of the red one. If the red indicator is activated continuously during irrigation, a high likelihood of over irrigation exists. More detailed information on the functioning and installation can be found in Stirzaker et al. (2004).

Figure 2 Installation of wetting front detector and access tube.

2.3 Irrigation quantity and scheduling

2.3.1 Soil moisture based (TDR)

The Time Domain Reflectometer was used before each irrigation event to obtain average soil moisture readings in the selected plots. The TDR had 20 cm rods giving the average soil moisture content in the first 20 cm of the soil profile. Soil moisture readings were taken from five places in each plot and the average was calculated. Based on the readings the calculation of irrigation quantity to be applied in the field was calculated for each farmer as shown in equations 2-1 to 2-5.

$$\mathbf{TAW} = (\mathbf{FC} - \mathbf{WP}) * \mathbf{RD} \qquad \textbf{Eq. 2-1}$$

$$\mathbf{WH} = \mathbf{FC} - \mathbf{PWP} \qquad \textbf{Eq. 2-2}$$

$$\textbf{Irrigation interval} = \frac{(\mathbf{AWA})}{\mathbf{MAD}} \qquad \textbf{Eq. 2-3}$$

$$\mathbf{MAD} = (\mathbf{WH} * \mathbf{AD}) \qquad \textbf{Eq. 2-4}$$

$$\mathbf{AWA} = (\mathbf{FC} - \mathbf{i}) * \mathbf{RD} \qquad \textbf{Eq. 2-5}$$

where, FC=Field capacity (%); i =actual soil moisture content (using TDR)(%); PWP = permanent wilting point (%); AD=allowable depletion of onion (%); RD= effective root depth of the onion (cm); WH=water holding capacity (%); TAW = total available water (mm) and AWA=Amount of water should be applied (mm/day).

To know the total available water in the root zone of onion, field capacity, permanent wilting point and a root depth of 40 cm was used (Allen et al., 1998). Onion, as common with most vegetable crops, is sensitive to water deficit. For high yield, soil water depletion should not exceed 25 percent of available soil water (Allen et al., 1998).

2.3.2 Wetting front detector based (WFD)

The scheduling was fixed at a 1 to 2 day interval whereas the amount of water was dependent on the signaling of the shallow detector.

2.3.3 Guiding irrigation at farm level

Farmers were trained on how and when to irrigate in both treatment groups and used buckets to apply the necessary. For the WFD group, farmers received training on how to use the irrigation tool and instructed to irrigate at a 1 to 2 day interval and stop when the shallow detector (i.e. yellow flag) responded within one bed. Subsequently, the amount of buckets used for the bed where the pair of WFD was installed were calculated and the same amount of buckets were applied for the other beds within the same plot.

For the TDR farmers, the irrigation interval dependent on the soil moisture content measured and the amount of water needed to bring the moisture content back to field capacity (see section 2.3.1).

2.4 Data collection

2.4.1 Soil physico-chemical properties

In each plot, 10 disturbed soil samples were collected at 0- 20 cm depth using an auger, uniformly mixed and a bulk sample of 500-1000 gram was taken. Additionally an undisturbed sample was taken to determine wilting point and field capacity? Analysis of the physio-chemical parameters were performed using standard procedures by Amhara Design and Water Work Supervision Laboratory.

Soil texture was determined in the laboratory using the Hydrometer method. The water content at field capacity (FC) (-0.33 bar) was determined in the laboratory by using a pressure (porous) plate apparatus. Permanent wilting point (PWP) was also determined by using pressure membrane apparatus by applying -15 bar to a saturated soil sample. When water is no longer leaving the soil sample, the soil moisture is taken as permanent wilting point. Electrometric method with the suspension of soil-water ratio of 1 to 2.5 stirred for 30 minute was used to determine the pH of soil. Kjeldahl method was used to determine total N. Plant available phosphorus P (mg P kg^{-1} soil) was obtained from extraction of acid-soluble and adsorbed phosphorus with fluoride-containing solution according Bray I test (acid soil). Electrical Conductivity Bridge was used to determine the EC (dS m^{-1}) of a 60 min stirred suspended soil solution (1:5 H_2O ratio).

2.4.2 Soil water balance

The soil water equation according to Allen et al. (1998) (Figure 3) was used:

$$\mathbf{ET_c = I + P - D - R - Cr \pm \Delta S} \quad \textbf{Eq. 2-6}$$

with ET_c =crop evapotranspiration (mm); I = amount of irrigation (mm); P = precipitation (mm); R= Runoff (mm); D = drainage (mm); Cr= Capillary rise (mm) and ΔS= is the change in soil water storage (mm).

Within the equation runoff (R), deep percolation (D) and capillary rise (Cr) were neglected, given that irrigation in both methods were applied using a bucket according to crop water requirement and no runoff or deep percolation was observed, groundwater tables are at 5 to 10 m.

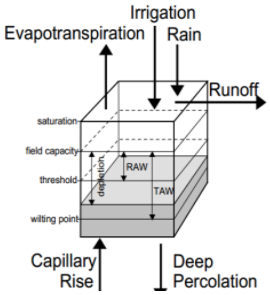

Figure 3 Soil water balance in the root zone (Allen et al., 1998)

In order to calculate ET, irrigation quantity, precipitation and the change in soil moisture needed to be determined.

Precipitation

Rainfall data during irrigation season was collected from the Dangila weather station, from the first week of February to the end of May (during the irrigation season).

Soil moisture change

The TDR was used to measure soil moisture changes at a weekly interval in all experimental plots. This was used to calculate the change in soil moisture throughout the irrigation season (Eq. 2-6).

Additionally, in three WFD and three TDR plots soil moisture access tubes were installed to understand the effect of both scheduling methods on soil moisture changes up to 1 m depth of the soil profile and quantify potential deep percolation losses below the root zone. The Soil Moisture Profiler Probe (SMPP) measures the volumetric soil moisture content at 10, 20, 30, 40, 60, and 100 cm depths within the soil profile. It consists of a sealed polycarbonate rod, 25 mm diameter, with electronic sensors attached at fixed intervals along its length. The access tubes are specially constructed, thin-wall tubes which maximize the electromagnetic field into the surrounding soil. The probe is inserted into an access tube while taking a reading. Measurements were taken regularly during the various growth stages at a weekly interval. Additionally specific readings were taken at the onset of the irrigation and continued at 2, 5, 10, 15, 30, 60 and 180 minutes interval to understand the movement of the wetting front under both irrigation methods.

Irrigation

The irrigation quantity was recorded on data sheets by the farmers. The total irrigation depth applied in the WFD plots was recorded by counting the total number of buckets applied per bed as well as for the overall field while for the TDR plots the total amount of water was calculated according to equations 2.1 to 2.5 and applied by the farmer accordingly.

2.4.3 Onion yield

Onion yield was measured at plot level for all farmers and converted to kg ha^{-1} using the harvested area.

2.4.4 Water productivity and water use efficiency

Water productivity is the total yield per quantity of water applied. Several factors affect water productivity such as: crop management, soil preparation, soil type, irrigation scheduling, crop variety and climate (Zwart and Bastiaanssen, 2004). The irrigation experiment was conducted using similar onion seed variety, similar crop management, and similar climate condition and irrigation application method (i.e. bucket) for all treatments.

As such the water productivity based on the water management was calculated according to:

$$\boldsymbol{WP = \frac{Yield}{I+R}} \qquad \textbf{Eq. 2-7}$$

where WP= water productivity (kg m^{-3}), Y= yield is (kg ha^{-1}), I=irrigation water applied ($m^3 ha^{-1}$) and R= rainfall ($m^3 ha^{-1}$).

The water use efficiency was calculated based on:

$$\boldsymbol{WUE = \frac{Y}{ET_c}} \qquad \textbf{Eq. 2-8}$$

where ET_c, is the crop evapotranspiration (Eq. 2-6) ($m^3 ha^{-1}$) and Y, is yield (kg ha^{-1})

2.5 Data analysis

The collected data such as irrigation amount, crop water use, crop yield and water use efficiency was checked on normality and transformed where necessary. Afterwards a one way analysis of variance (ANOVA) test at the 5% probability level (P<0.05) was conducted using SPSS 16.0 version software.

3 RESULT AND DISCUSSION

3.1 Soil physico-chemical property

Mean and standard deviation (SD) results for pH, EC, OM, TN, Av P, Fe, FC and PWP are shown in Table 1. The comparison was carried out to test whether fields between the treatments differed significantly, which might partially influence the crop and water productivity results obtained within the experiment. No significant differences between both irrigation treatments for all measured soil properties were found.

The average pH of 6 is suitable for onion production. The soil texture of most of the experimental plots is clay and clay loam, a medium textured soil, suitable for onion is growing (FAO, 2002). In both treatments similar field capacity (FC) and permanent wilting point (PWP) of 32.5% and 20.5%, respectively were obtained.

Table 1: Overview of soil physio-chemical analysis result as per treatment

Parameter	***Water Management***			
	WFD		**TDR**	
	Mean	**SD***	**Mean**	**SD***
pH (1:2.5)	5.9	0.3	5.9	0.6
ECE(ds m^{-1})	0.1	0.1	0.2	0.2
OM (%)	4.4	1.1	4.8	1.4
TN (%)	0.2	0.1	0.2	0.1
Av P (ppm)	14.8	9.1	11.0	4.7
Fe (ppm)	18.3	3.8	17.2	4.3
FC (%)	32.5	1.8	32.5	3.1
PWP (%)	20.6	1.4	21.0	1.1

* with SD being the standard deviation.

Electric conductivity ranged between 0.12 dS m^{-1} and 0.26 dS m^{-1} respectively and the average value is 0.17dS/m. The onion crop is sensitive to soil salinity and yield decrease at varying levels of EC is 0% at EC .2dSm^{-1}, 10% at EC1.8dSm^{-1}, 25% at EC2.8dSm^{-1}, 50% at EC4.3 dS m^{-1} and 100% according.

3.2 Effect of irrigation treatment on soil moisture changes

The temporal evaluation of the soil moisture along the 1 m soil profile allows for the understanding of soil moisture increases during and after irrigation as function of water management. Specific attention was paid to the soil moisture change at 20 cm (depth of the yellow WFD) and at 40 cm (depth of the red WFD) for both the WFD as well as the TDR group.

The measured field capacity of the top soil (0-20 cm) was 31.7 % and 33.67 % for the WFD and TDR treatment, respectively while the permanent wilting point was 20.6 % for both treatments. The soil is relatively homogenous and therefore similar field capacity was assumed at 20 and 40 cm within the soil profile. The shallow detector (i.e. 20 cm) responded 15 min after irrigation started and corresponded to a soil moisture reading of 31.6 % which is close to field capacity. Three hours after irrigation the soil slowly drained and reached 27.6 % remaining below field capacity. The deeper detector was not activated. Weekly measurements supported that deep percolation beyond 60 cm did not occur in the WFD plots.

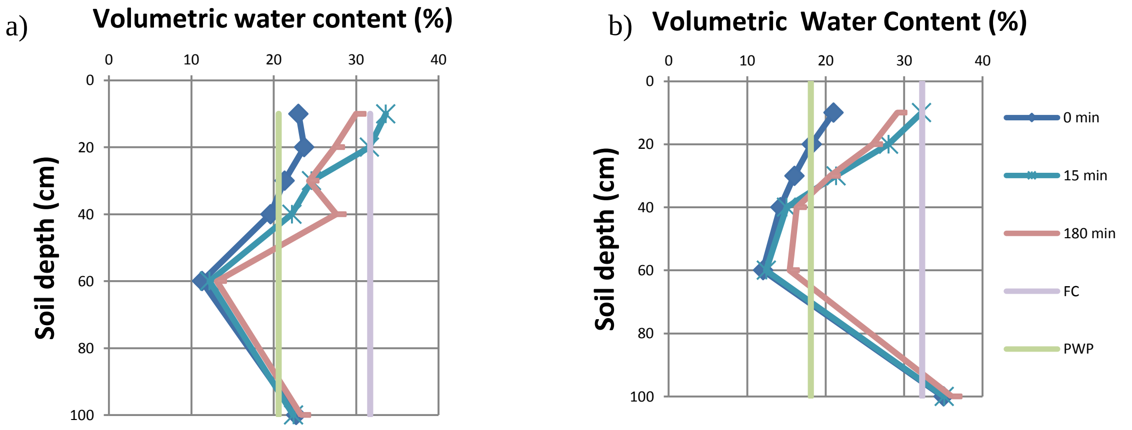

Figure 4: Soil moisture change throughout the soil profile for a) the WFD treatment (left) and b) the TDR group (right) before irrigation, response of the shallow detector at 15 min and 3 hours after irrigation. Field capacity (FC) and permanent wilting point (PWP) are given for both groups.

Similarly in the TDR plots the required soil moisture (32.7%) was achieved during 15 minutes of irrigation at the depth of 20 cm which is close to field capacity. However, in this case irrigation was ceased when the total volume calculated over the 40 cm root zone was applied. Hence, 3 hours after irrigation the soil moisture content at 60 cm the observed soil moisture after 3 h was higher in the TDR compared to the WFD plots.

Looking at the weekly soil moisture changes at 1 m no significant changes were observed in both the WFD and the TDR plots, confirming that deep percolation can be neglected.

3.3 Soil Water balance in the root zone

The precipitation measured on site during the cropping period was 240 mm between February and June 2015.

The irrigation water applied was on average 372 mm for the WFD and 462 mm in the TDR plots (Table 2). There is a non significant 24% reduction of irrigation water application in WFD plots. The average irrigation reduction obtained is a lower compared to those reported in Schmitter et al., (2015) for the furrow irrigation of potato (34 %) and wheat (39 %). In the latter study, experiments were conducted in Koga irrigation scheme where WFD plots were compared to farmers practice instead of soil moisture based irrigation scheduling.

The variation between the various farmers within the WFD group is half of the standard deviation obtained within the TDR group. The variation in the WFD treatment can be attributed to appropriate usage of the WFD. Water saving is partly related to the installation of the shallow detector at 20 cm compared to the full root zone calculations used to calculate the water requirement for the TDR group. In the WFD group the shallow detector is triggered when the soil moisture is around field capacity whereas the remaining portion of the root zone is slowly wetted with minimal water loss by percolation.

Table 2 Overview of the various soil water components during the cropping season for both irrigation treatments (WFD and soil moisture based (TDR)) and WFD.

	WFD				*Soil moisture based (TDR)*			
	I (mm)	R (mm)	ΔS (mm)	ET_c (mm)	I (mm)	R (mm)	ΔS (mm)	ET_c (mm)
*Minimum**	273	240	-16	529	268	240	9	499
*Maximum**	453	240	16	677	614	240	43	811
Mean	372^a	240	0.3	612^a	462^a	240	25.2	677^a
SD	66	0	20	70	128	0	15.2	123

*Minimum and maximum refers to the minim and maximum irrigation applied and the subsequent water balance, respectively. Means followed by the same letter for the same water balance component are not significantly different, WFD=Wetting Front Detector, TDR (Time domain reflectometer), significant difference are given at P>0.05.

The soil moisture change at the end of the season ranged from -16 mm to 16 mm in the WFD treatment and from 9 to 43 mm in the TDR treatment. On average the fields that were irrigated based on the measured soil moisture showed a slightly higher moisture content at the end of the season. If other flows are neglected positive changes in soil moisture content indicate that more water was added through irrigation then consumed through evapotranspiration given that rainfall was the same for all plots.

Based on Eq. 2-6, the ET_c for each field was calculated. On average 612 mm was used by the onion in the WFD plot which is 10 % less compared to the 677 mm in the TDR plot. Similarly to the total irrigation applied the standard deviation was larger in the TDR plot and no significant differences were found between both irrigation treatments.

3.4 Onion yield

The highest onion yield of 7087 kg ha^{-1} was obtained in the TDR treatment and lower than the highest yield of 5800 kg ha^{-}1 WFD treatment (Table 3). The difference in lowest yield (286 kg ha^{-1}) obtained in both treatments was much smaller compared to the highest yield. The variation of onion yield between the farmers differed strongly within each of the irrigation treatment resulting in rather similar average yields of 3430 kg ha^{-1} (TDR) and 3758 kg ha^{-1} (WFD). Although the average yield in the WFD plot was slightly (10 %) higher, yields did not differ significantly (p>0.05).

Table 3: Overview of onion yield (kg ha^{-1}) obtained for both irrigation treatments, i.e. WFD and soil moisture based (TDR).

	WFD	*TDR*
Minimum	1786	1500
Maximum	5800	7087
Mean	3758^a	3430^a
SD	1513	2018

Means followed by the same letter are not significantly different, WFD=Wetting Front Detector, TDR (Time domain reflectometer – soil moisture based scheduling), significant difference are given at P>0.05.

3.5 Water productivity and Water use efficiency

Water productivity obtained in the onion plots under the WFD treatment ranged between 0.32 kg m^{-3} and 0.84 kg m^{-3} while in the TDR plots values ranged between 0.23 kg m^{-3} and 0.98 kg m^{-3} (Figure 5, left). A slightly higher slope was found for the water productivity calculated in the WFD treatment indicating the slightly lower irrigation quantities applied to achieve similar yields. The average water productivity in the WFD treatment (0.60 kg m^{-3}) did not differ significantly from the 0.47 kg m^{-3} obtained in the TDR treatment (p>0.05). Similar values were found for water user efficiency given that soil moisture changes before and after the season were minimal (Figure 5, right). Overall the variation within and between plots were driven by both the crop management resulting in a relatively large yield variation within the treatment as well as the large variation of water applied. Hence, water use efficiency did not differ significantly between both treatment groups ($p>0.05$).

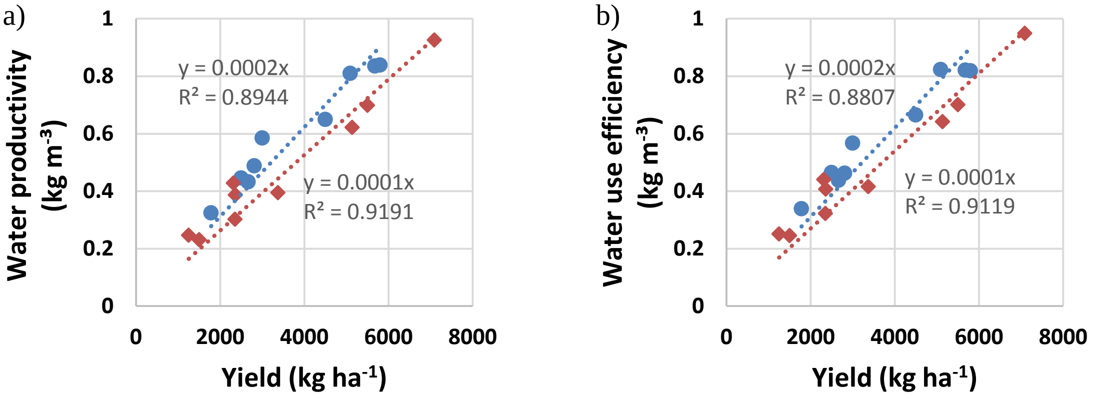

Figure 5: a) Yield in function of water productivity (kg m^{-3}) (left) and b) water use efficiency (right) for the WFD (blue circles) and TDR (red diamonds) treatments.

4 CONCLUSION AND RECOMMENDATION

Both irrigation treatments resulted in similar results with regards to the soil water balance, onion yield, water productivity and water use efficiency. Although the applied irrigation water decreased by 24% in the WFD treatment it was not found significant compared to the TDR treatment. Both water management methods led to negligible deep percolation losses beyond 60 cm. The use of the wetting front detector instead of the soil moisture based method did not negatively affect crop yield, water productivity or water use efficiency. Large variation between farmers within one treatment group as function of crop management, differences in irrigation experience and the small sample group results were not found to be significantly different. A larger sample group would help in validating the results found in this study.

Wetting front detectors seemed to be a good learning tool, given its simplicity, for smallholder farmers in guiding the amount of water to apply throughout the cropping season. However, as with all tools, it requires some experience and careful monitoring. It would be interesting to monitor the same farmers throughout multiple seasons in order to understand how the tool contributes to irrigation knowledge, if the variability in irrigation management between farmers is reduced and if it aids towards water usage optimization in the long term.

In this study, the response of the shallow detector during irrigation was close to field capacity. Further research on the appropriate land size or group of farmers that could benefit from one pair of WFD, given that they use the same crop type (i.e. root zone, similar crop coefficients and maximum allowable deficit), could improve on-farm water management at larger scale potentially reducing labor, fuel costs in relation to pumping and environmental effects associated with over-irrigation.

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