



Application of *in Situ* Thermal Imaging to Estimate Crop Water Stress and Crop Water Requirements for Wheat in Koga Irrigation Scheme, Ethiopia

Tewodrose D. Meselaw^{1(✉)}, Fasikaw A. Zimale², Seifu A. Tilahun², and Petra Schmitter³

¹ Kombolcha Institute of Technology, Wollo University, Kombolcha, Ethiopia

² Faculty of Civil and Water Resources Engineering, Bahir Dar Institute of Technology, Bahir Dar University, Bahir Dar, Ethiopia

³ International Water Management Institute (IWMI), Colombo, Sri Lanka

Abstract. Enhancing performance of irrigation schemes requires an improvement in the timing and amount of irrigation application from head to tail of irrigation infrastructures. This can be achieved using non-invasive techniques using thermal imaging to assess soil moisture regimes and plant water status. An infrared thermometry with hand held thermal camera attached to a tablet was used to measure the temperature of wheat canopy under three irrigation treatments in Koga irrigation scheme: wetting front detector (WFD), chameleon and control reflecting farmers' practices. The experiment followed a randomized complete block design (RCBD) in two irrigation blocks (Adibera and Chihona) with three treatments and three replications. The temperature of the canopy was measured before and after irrigation. The calculated Crop Water Stress Index (CWSI) using canopy temperature was significantly different in the WFD treatment during the development stage given the larger irrigation intervals observed ($p > 0.05$). Overall, both irrigation technologies show potential in improving water management close to the overall estimated gross irrigation requirement with some further improvement in the mid development stage. The study showed the potential of using thermal imaging to not only identify CWSI and assess the effect of agronomic field trials using in-situ thermal camera's but also the potential of using canopy temperatures in estimating actual ET and therefore gross irrigation requirements. This would provide a new opportunity for agricultural extension agents to advice smallholder farmers in irrigation schemes and beyond on when and how much to apply without the need for WFD or chameleon sensors. Further research is needed to calibrate and validate the irrigation predictions based on different soil and crop types.

Keywords: Crop water stress index · Gross irrigation water requirements · Irrigation water productivity · Thermography

1 Introduction

In Ethiopia, the majority of agricultural land is under low input- low output rainfed agriculture and highly susceptible to rainfall variability both in magnitude as well as occurrence [1]. Ethiopia has great irrigation potential, which is estimated as 5.3 million hectares of land of which 3.7 million hectares can be developed using surface water sources and 1.6 million hectares using groundwater and rainwater management [2].

While the human population and demands for freshwater resources are increasing, drought and regular water scarcity can put global food security at risk by severely disrupting agricultural production. The challenge is to meet rising productivity demands by improving methods of crop management which requires a deeper understanding of plant response to abiotic stresses [3]. Water stress detection based on canopy temperature measurements is probably the most widely used plant-based approach for remote sensing that applies to irrigation scheduling of several crops. As plants absorb solar radiation, canopy temperature increases, but is cooled when that energy is used for evapotranspiration [4].

Canopy temperature measured with infrared thermometers or other remote infrared sensors is an important tool for detecting crop water stress [5]. The crop water stress index (CWSI) is the most often used index which is based on canopy temperature to detect crop water stress [6]. Detection of crop water stress and ET enhances decision making on irrigation timing and application amounts, which might increase crop water productivity, cut back percolation and nutrient losses below the root zone, and cut back irrigation associated labor.

In Northern Ethiopia highland, Bahir Dar Institute of Technology with International water management institute (IWMI) has worked with farmers to enhance water productivity by using water management tools such as the wetting front detector (WFD) and the chameleon sensor (<https://via.farm/>). Those instruments provide information on the soil moisture status, enhancing irrigation decision making [7]. Scholars have shown the positive effect of using WFD or chameleon sensors on crop yields and a reduction on irrigation water applied and nutrients leached [8]. However, little is known whether the plants are stressed at any given plant development stage and despite the positive effects on crop yields being recorded.

The crop water stress index (CWSI) has been used to characterize plant water stress and schedule irrigation. Romero et al. [9] showed that CWSI can successfully detect crop water stress of African eggplant under full and deficit irrigation treatment in the early development, vegetative and maturity stage. The study measured CWSI using individual eggplant leaves. However, wheat leaves are small and hence accurate CWSI might be challenging using mobile phone based thermal imaging. Therefore, this research evaluated the application of *in situ* thermal imaging of wheat canopy to detection of crop water stress and estimate actual ET requirement to further enhance irrigation performance and crop water productivity.

The main objective of this study was therefore to assess whether *in situ* thermal imaging can be used to estimate gross irrigation water requirements for wheat under different crop water stress levels. Firstly the study looked at whether crop water stress differed among different irrigation treatments of wheat. Secondly, the study assessed

whether there was a relationship between CWSI, soil moisture and stomata conductance and developed an equation to estimate gross irrigation requirements.

2 Methodology

2.1 Description of the Study Area

The data in this study were collected in Koga Irrigation scheme which is situated adjacent to the town of Merawi in the Mecha Woreda, West Gojam Zone in Amhara Regional State, Ethiopia (Fig. 1). In the Koga irrigation scheme, there are 11-night storages, which are used to irrigate 12 blocks. The catchment is situated between 11°10' to 11°32'N and 37°04' to 37°17'E. The catchment area contributing to the dam is 170.9 km² and extends to an altitude of 3,200 m.a.s.l. From 12 blocks the FAO water productivity projects introduced on-farm water management technologies in six blocks: Kudmi, Teleta, Tagel, Andinet, Adibera, and Chihona blocks. For this study fields using WFD and Chameleon sensors as well as control plots (i.e. farmers' practice) in Chihona and Adibera were selected. The storage capacity of the reservoir is 83.1 Mm³ with an altitude of 1998 masl. The command area has a total population of 57,155.

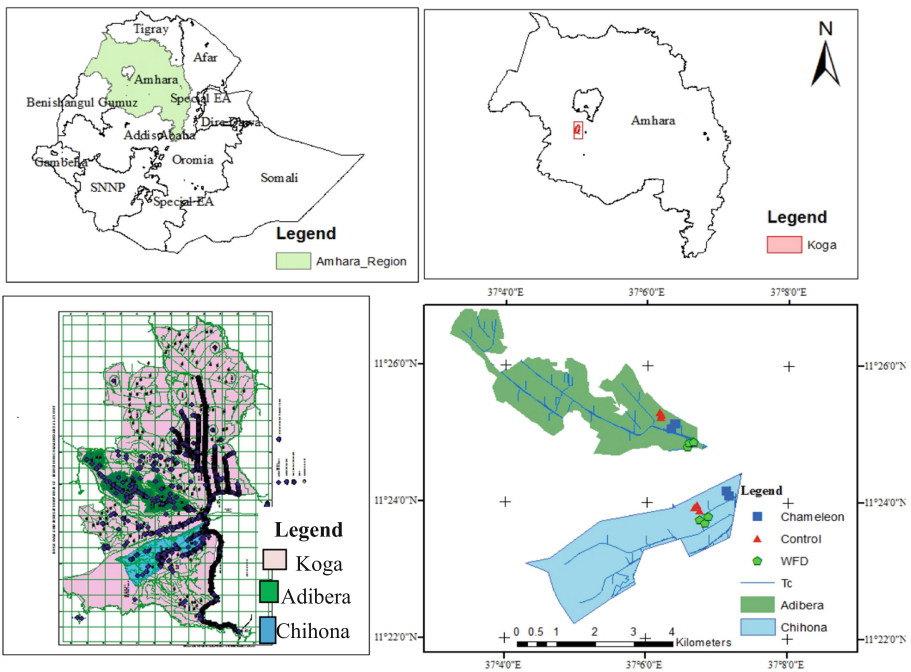


Fig. 1. Location map of the study area

The annual precipitation ranges from 800 to 2200 mm, with a mean of 1,420 mm [10] and an average day time temperature of 24 °C. The soil for all experimental plots are classified as clay loam with an average field capacity of 34.4% and permanent wilting point of 23.69%. The major crops irrigated are wheat, onion, potatoes, and tomatoes. As > 70% of the area irrigated is cultivated for wheat, wheat farmers were chosen.

2.2 Description of Irrigation Scheduling Tools

Bahir Dar Institute of Technology with International Water Management Institute introduced two low cost tools, the Chameleon soil moisture sensor and the Full Stop wetting front detector (https://via.farm/via_tools/) in Koga irrigation scheme. The chameleon reader measure soil water status at any given time and is connected to three gypsum blocks, each installed at different depths. Each depth is represented by a light, and each light can be blue (wet soil), green (moist soil) or red (dry soil). The lights give a picture of soil water conditions from the top to the bottom of the root zone. The wetting front detector records the depth of infiltration of the irrigation water and pops up an indicator when irrigation water has reached the WFD at the installed depth. These tools form the basis of an experimental learning system for small-scale irrigators. The study found that farmers quickly learned from the tools and changed their management within a short time. The cost of implementing a learning system would be a small fraction of that of building or revitalizing irrigation schemes.

2.3 Experimental Design and Treatment Setting

In Koga, two irrigation blocks, Adibera, and Chihona, were selected as the experimental site and the experimental design was a Randomized Complete Block Design (RCBD) with three replications for each irrigation treatment. In each block, nine farmers participated in the study: 3 farmers were using WFDs (WFD treatment), 3 were using chameleon sensors (chameleon treatment) and 3 were applying their own irrigation practice (control treatment). The proposed plot was selected based on the following criteria: a) all experiment plots have the same type of soil, b) all farmers use the same type and rate of fertilizer and c) all farmers follow the treatment recommendation. An overview of the experimental layout per block is given in Fig. 2. In each farmer field, 4 sub-plots (0.5 m * 0.5 m) were marked within one field (i.e. P1, P2, P3 and P4 in Fig. 2).

Farmers in the experimental field plowed each plot with traditional Marsha plow pulled by oxen for proper seed germination. Wheat (Kekeba genotype) was planted in December 2018 and irrigated using furrows with an average length of 30 m and a width of 25 cm. The furrow length for one farm was the same for all farmers to ensure that irrigation timing and quantity is as uniform as possible among farmers within one treatment group. A pair of wetting front detectors (shallow and deep WFD) was installed in the second or third and subsequent furrows from the border of the field. The WFD was installed at 75% of the furrow inlet where the shallow detector (yellow flag) was placed at 20 cm depth and the deep detector (red flag) at 40 cm depth details can be found in Stirzaker [11]. Chameleon was installed at 75% of the furrow inlet

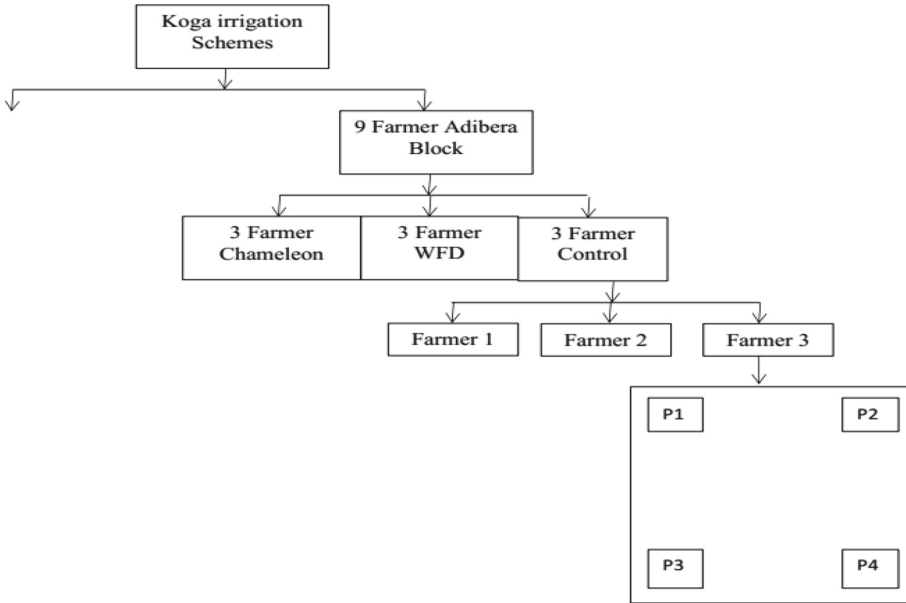


Fig. 2. General layout of the experimental plot for two blocks in Koga irrigation scheme

where the shallow detector was placed at 20 cm depth, amid detector was placed at 40 cm and the deep detector was placed at 60 cm.

2.4 Data Collection

Climatic Data. Daily meteorological data containing maximum and minimum temperature ($^{\circ}\text{C}$), wind speed (m/s), solar radiation ($\text{MJ}/\text{m}^2/\text{day}$), relative humidity (%) and the daily rainfall (mm/day) were collected from Ethiopia Meteorological Agency, Bahir Dar branch.

Thermal Image. In this study, a ground-based, handheld FLIR camera (model E30, FLIR Systems, Inc., Wilsonville, Oregon, USA) was used to take canopy thermal images. The thermal image was taken at four experimental sub-plots which have ($0.50\text{ m} \times 0.50\text{ m}$) size within one farmer's field (see Fig. 2). Two sub-plots were located $\frac{3}{4}$ of the furrow length from the inlet or $\frac{1}{4}$ of the length from the outlet and two plots were located at the top corner of the field in order to check the water distribution efficiency of the field. The vertical distance between wheat and the camera remained approximately equal for all measurements and the image was taken before and after irrigation. According to other studies, midday canopy temperature is the best indicator to detect crop water stress [4, 8, 13]. Therefore, measurements were taken between 12:00 am to 13:30 am during clear sky conditions throughout the season. At each measurement, three images were taken: (i) canopy temperature (T_{canopy}), (ii) some leaves were used as T_{wet} reference (i.e. no water stress) by spraying water on both sides

[14] and (iii) 1 or 2 leaves were used as T_{dry} reference by covering both sides with petroleum jelly (vaseline) to prevent transpiration (i.e. extreme water stress).

Soil Moisture Measurements. Soil moisture readings using a calibrated Time Domain Reflector meter (TDR) were taken within the sub-plots at 10 cm depth in each field before and after irrigation based on the irrigation interval. Measurements were taken in each treatment and used to explore a relationship between soil moisture status and CWSI.

Irrigation Depth Applied and Wheat Performance. The amount of irrigation water applied by the farmer was determined by measuring the flow rate using a 90° v-notch weir (triangular weir) at the field inlet and multiplying this by the irrigation duration for each field. The following equation was used to determine the discharge through a 90° v-notch weir:

$$Q = 1.38H^{5/2} \quad (1)$$

where Q = discharge (m^3/sec) and H = head (m) flowing over the vertex of the v-notch. Wheat yield was measured for all farmers by weighing the amount of the wheat bags and counting the number of wheat bags harvested per field. The collected yield converted to kg ha^{-1} using the harvested area.

2.5 Data Analysis

Thermal Image Processing and Canopy Temperature Calculation. ThermalCAM Researcher Pro 2.8 SR-1 (FLIR Systems, Inc., Boston, MA) software was used to convert the thermal JPEG format images to FLIR Public file (.fpf) format. The software calculates the average canopy temperature taking into account numerous canopy pixel points from the plant material in the image. As wheat has small leaf it needs, background pixels needed to be ignored. Hence, the spot meters' tool was used to only measures visible (RGB) or NIR from selected pixels to determine temperature of the leaves. The reference canopy temperature (T_{canopy}) was calculated by averaging the sample leaf temperature. Then finally the canopy temperature of the farm was taken by averaging the plot temperature from the 4 sub-plots in each field. The dry leaf temperatures (T_{dry}) were taken from the spot measurements for the leaves under Vaseline treatment. The wet leaf temperature (T_{wet}) was taken from the spot measurements for the leaves which were sprayed with water.

Crop Water Stress Index (CWSI). Crop water stress index measures the plant water status. The value of CWSI varies between 0 and 1, where 1 represents full stress (i.e. actual evapotranspiration is zero), and 0 represents the absence of stress (i.e. potential evapotranspiration) as plants transpire at a maximum rate. CWSI was calculated for each sub-plot according to Jones developed by Idso [13] as follows:

$$CWSI = (T_{\text{canopy}} - T_{\text{wet}}) / (T_{\text{dry}} - T_{\text{wet}}) \quad (2)$$

where, T_{canopy} is the mean canopy temperature of the plot (the average of 10 spot measurements from the thermal image), T_{wet} and T_{dry} are the temperatures of the leaves when stomata are opened and stomata are closed, respectively.

According to Jones developed by Idso [13], stomatal conductance (gl) can be calculated as follows:

$$gl = (T_{\text{dry}} - T_{\text{canopy}}) / (T_{\text{canopy}} - T_{\text{wet}}) \quad (3)$$

Estimating Actual Crop Evapotranspiration. The actual canopy evapotranspiration can be directly calculated using the energy balance model from the measured canopy temperature. In this approach, canopy temperature measurements provide the real-time feedback aspect. The ET_c at a given time can be estimated using the following equation developed by Jackson [4]:

$$ET_c = ET_o(1 - CWSI)k_c \quad (4)$$

where CWSI is the crop water stress index, k_c is the crop coefficient and ET_o the potential evapotranspiration. CWSI was calculated for each irrigation event by considering the stress index before and after irrigation and the crop coefficient value was taken from FAO following the respective growth stages.

The ET_c per irrigation event was estimated as the average of the ET_c after and before irrigation. The average ET_c was multiplied with the number of days between these two irrigation events and summed to obtain the total ET_c throughout the season.

Net and Gross Irrigation Requirements Under Different Irrigation Treatments:

The net irrigation requirement (I_{net}) was calculated by subtracting the effective rainfall (P_e) from the estimated ET_c :

$$I_{\text{net}} = ET_c - P_e \quad (5)$$

Gross irrigation requirement (I_{gross}) are equal to net irrigation requirement divided by application efficiency (E_a).

$$I_{\text{gross}} = I_{\text{net}} / E_a \quad (6)$$

An application efficiency of 0.65 was used for furrow [15].

2.6 Statistical Analysis

The collected data were analyzed using R software. For each block, the significance of a treatment was assessed using a two-way analysis of variance (ANOVA) at a 5% significance level. Before analysis, the quality of the data was checked by the Q-Q normality test and by frequency distribution graph.

3 Results and Discussion

3.1 Irrigation Depth Applied Under Different Irrigation Treatments

The average seasonal total irrigation depth for each treatment is presented in Fig. 3. As expected, farmers applied the most water in the control treatment (675 mm from Adibera block and 689 mm from Chihona block) followed by the chameleon and the WFD. The depth of irrigation applied per season in the chameleon and WFD treatments were significantly lower ($p < 0.05$) and on average 71% and 58% of those applied in the control treatment, respectively.

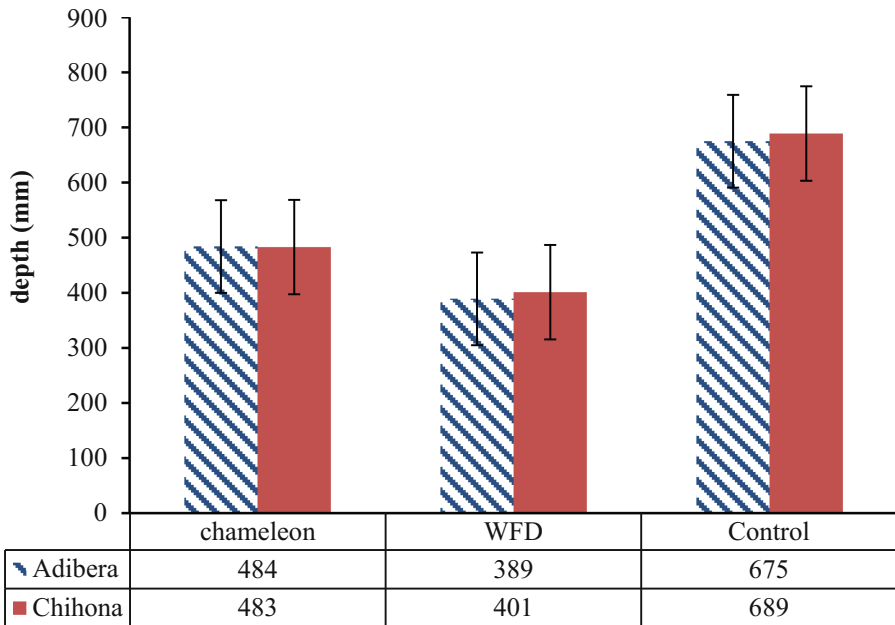


Fig. 3. Seasonal total irrigation depth for each irrigation treatment

3.2 Variation in CWSI Between Irrigation Treatments

Before irrigation, the maximum CWSI were observed in the WFD treatment (0.45 to 0.6), followed by the chameleon treatment (0.40 to 0.56) and the control (0.42 to 0.52) (Fig. 4). Comparison of the CWSI values before irrigation showed a significant difference between the WFD and other two treatments (i.e. control and chameleon) during the development stage, indicating that the larger irrigation interval for WFD has resulted in a significantly higher CWSI ($p < 0.05$). There were no significant differences observed in CWSI between the different phenological changes for the same treatment or between treatments for the other crop growth stages.

Across the two irrigation blocks, the CWSI after irrigation varied between 0.10 and 0.22, 0.11 and 0.23, 0.11 and 0.22 for chameleon sensor, WFD, and control treatment

respectively. According to the Attahi [16] adopted threshold, little or no water stress regimes were found in the 3 treatments ($p > 0.05$) (Fig. 4). This means that for all irrigation treatments the crop water demand was satisfied.

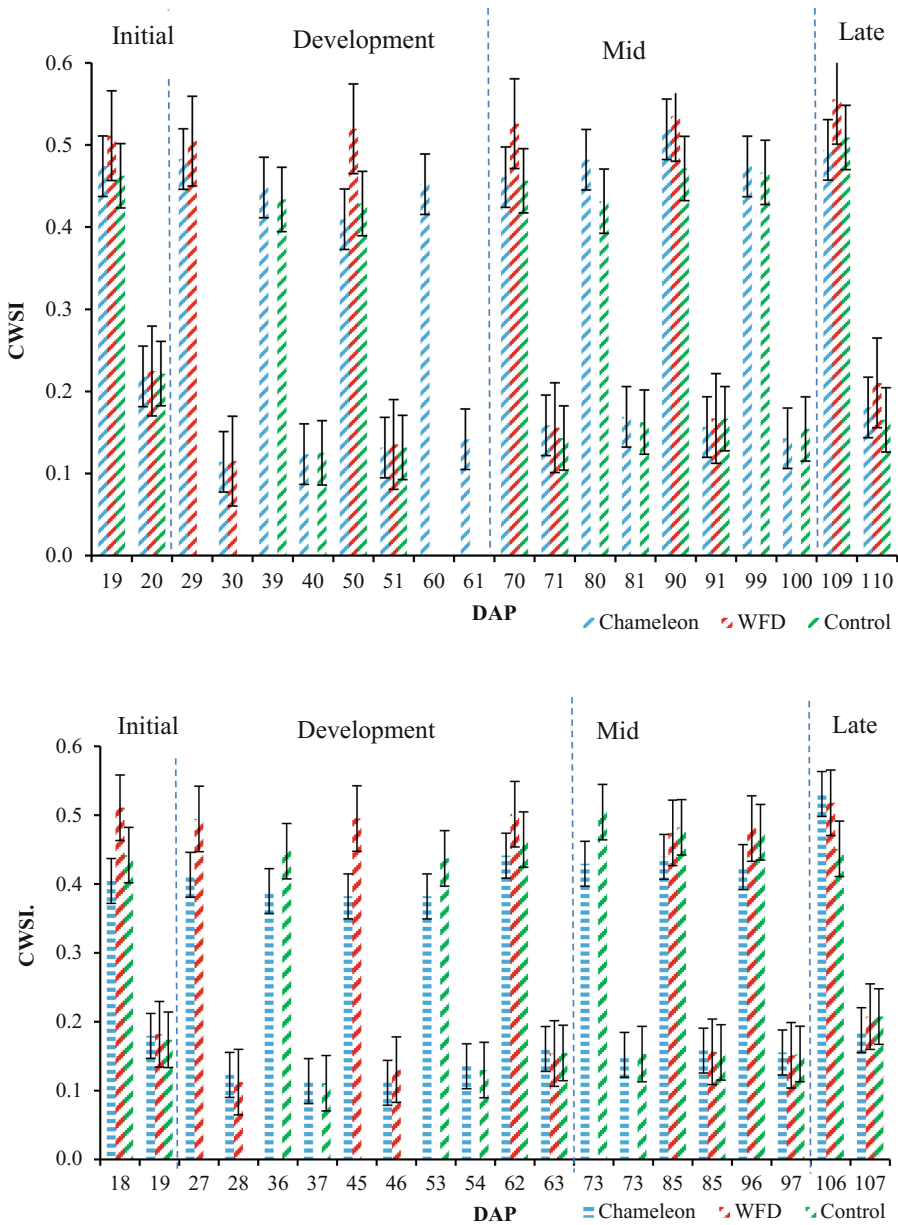


Fig. 4. The variation of the average CWSI both after and before irrigation conditions at different stage in Adibera (top) and Chihona block (bottom).

3.3 Relationship Between CWSI, Soil Water Status and Stomatal Conductance

A linear relationship was found between CWSI and the soil water content measured at 10 cm depth for all treatments (Fig. 5). A unit decrease in soil moisture resulted in a larger increase in CWSI in the control group (-0.53) compared to the WFD (-0.41) and chameleon (-0.41).

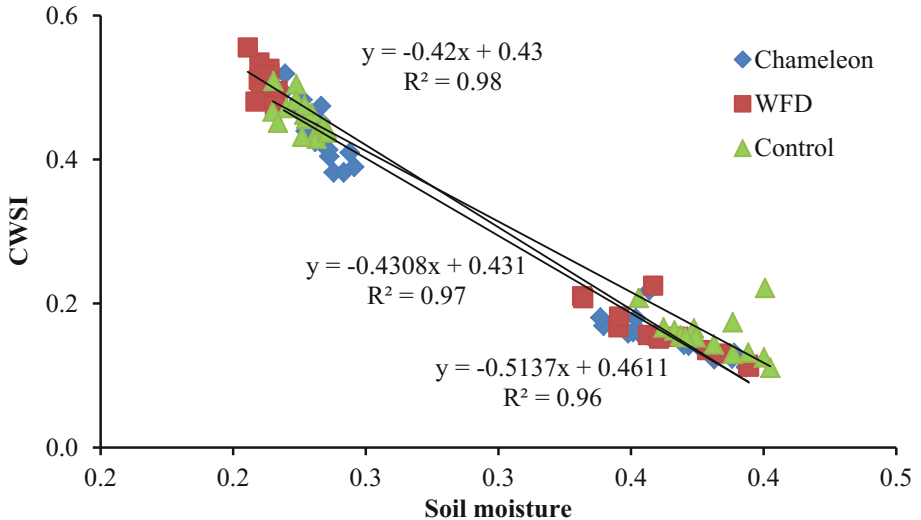


Fig. 5. The relationship of CWSI and soil moisture in all treatment

The relationship between CWSI and stomatal conductance is well established. The study investigated the relationship between the soil moisture and the estimated stomatal conductance. A linear relationship confirmed that the higher soil moisture values corresponded to a higher stomatal conductance and therefore a lower CWSI. of stomata conductance with soil water content in all treatment. A unit decline in soil moisture resulted in a stronger decline in the stomatal conductance of wheat in the WFD fields (Fig. 6). in chameleon treatment for average soil moisture at 10cm depth with stomata conductance.

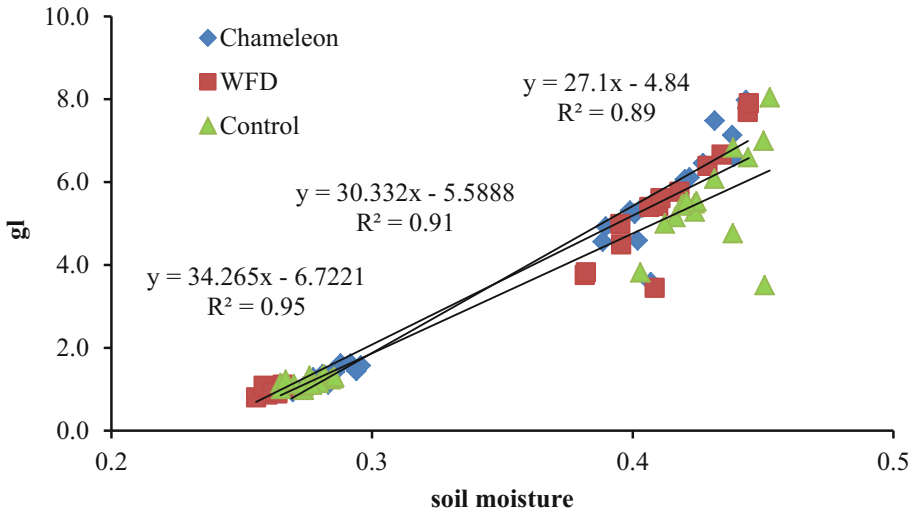


Fig. 6. The relationship of stomatal conductance and soil moisture

3.4 Estimated Crop Evapotranspiration (ET_c)

The total estimated crop evapotranspiration with the potential evapotranspiration for the growing season are shown in Fig. 7. In all irrigation treatments the estimated ET_c was significantly lower than the ET₀. In Adibera the estimated ET_c was significantly lower for the WFD treatment compared to the other two treatments whereas in Chihona no difference.

3.5 Irrigation Water Productivity

The average yield for the WFD treatment was 2.7 t/ha, 2.4 t/ha for the chameleon and 2.2 t/ha for the control. This resulted in a 20.7% (WFD) and 11.2% (chameleon) yield increase compared to the control. A positive reduction in irrigation depth and increase in yield resulted in an increase in irrigation water productivity. Average irrigation productivity for WFD treatment was 0.72 kg/m³ and 0.64 kg/m³ in Adibera and Chihona block respectively and significantly higher than those obtained in the control field (0.34 kg/m³ and 0.32 kg/m³). The difference was significant at a 5% significance level at both blocks between the technology user (both chameleon and WFD) and control farmer. However, there was no significant difference between WFD and Chameleon treatment in both blocks (Table 1).

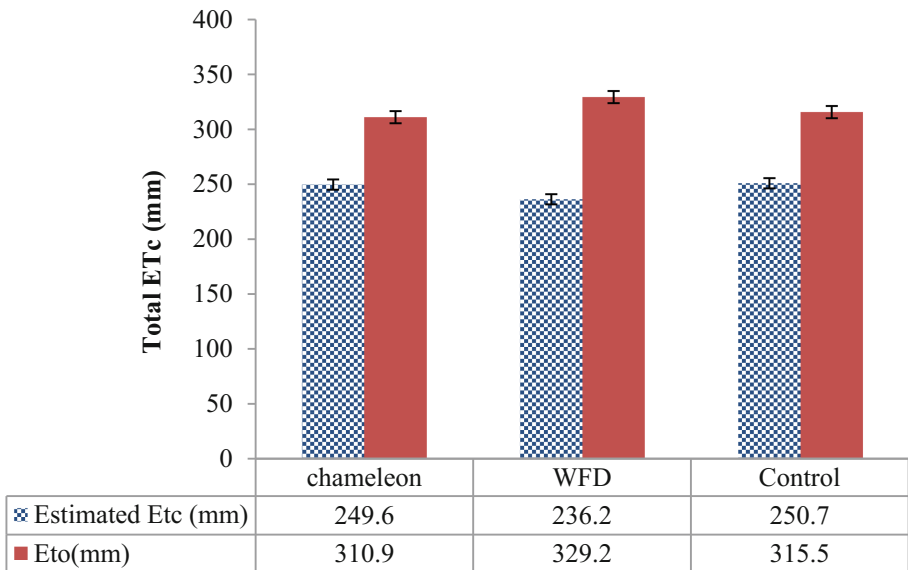
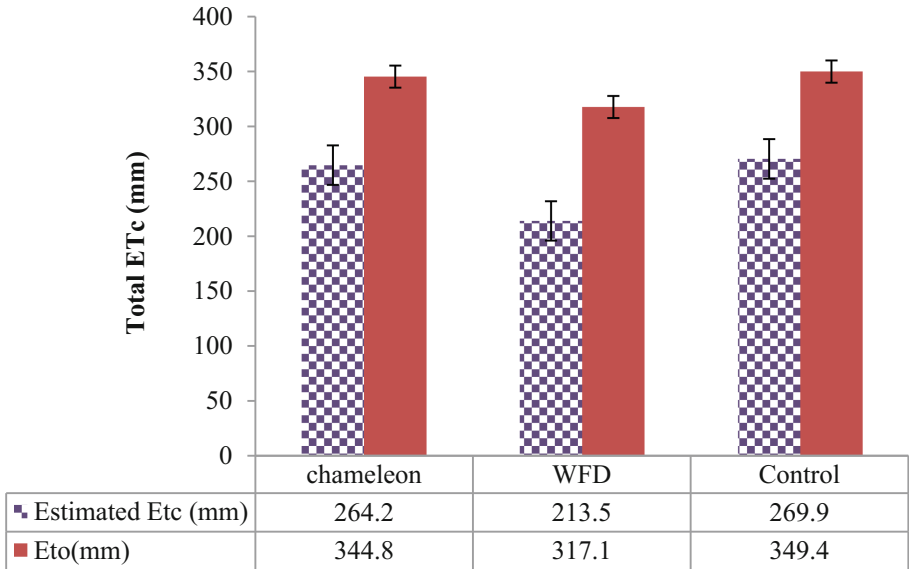


Fig. 7. The total estimated crop evapotranspiration (ETc) and potential evapotranspiration (ETo) of each irrigation treatment in Adibera (top) and Chihona block (bottom)

Table 1. Irrigation water productivity (kg/m^3) measured in both blocks across the three irrigation treatments.

IWP (kg/m^3)			
Chameleon		Adibera	Chihona
	Average	0.53 ^a	0.44 ^a
	Max.	0.66	0.49
	Min.	0.37	0.36
	Stdev	0.15	0.07
WFD	Average	0.72 ^a	0.64 ^a
	Max.	0.75	0.69
	Min.	0.71	0.57
	Stdev	0.02	0.06
Control	Average	0.34 ^b	0.32 ^b
	Max.	0.41	0.35
	Min.	0.28	0.29
	Stdev	0.08	0.03

3.6 Estimated Gross Irrigation Requirement

The estimated total average gross irrigation requirement in the system varied from 308 to 395 mm and from 344 to 364 mm for Adibera and Chihona block, respectively. The highest average gross irrigation requirement was estimated in the control treatment (395 mm) and the lowest was estimated in WFD (308 mm) irrigated fields in the Adibera block. This is could be potentially related to the number of irrigation events. In this study the ET_c was calculated for each irrigation event by considering its stress index so control treatment had more irrigation event than others a result of the different irrigation treatments.

As shown in Fig. 8, the cumulative estimated gross irrigation was lower than the cumulative applied depth of irrigation for all treatment indicating a potential room for further improvement. All three treatments, the mid development stage showed the largest room for improvement (i.e. 50–70 days after planting). The difference between the irrigation application recorded and the gross irrigation depth calculated was smallest for the chameleon followed by the WFD. This is related to the functioning of both technologies where the chameleon sensors provide more gradual information on soil moisture along the soil profile whereas the WFD provides the wetting front at one particular depth.

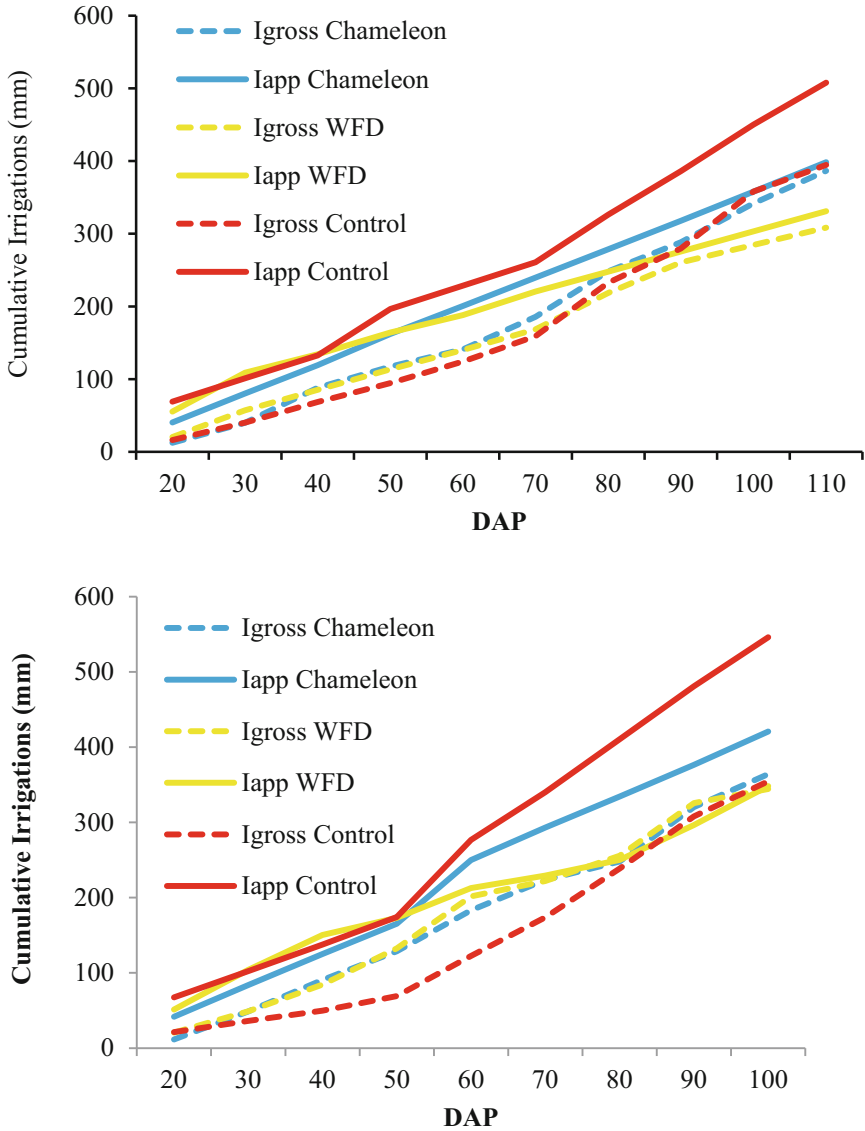


Fig. 8. Cumulative depth of irrigation application (I_{app}) and Cumulative estimated gross irrigation application (I_{gross}) in Adibera (top) and Chihona block (bottom)

4 Conclusions

The study showed that the use of wetting front detector (WFD) and chameleon sensors could reduce irrigation amounts without significantly introducing crop water stress. At farm level there was no significant difference ($p > 0.05$) in CWSI between the different crop phenological stages within the same treatment. However, the CWSI was highest in the WFD and was related to the larger irrigation interval and a reduction in 42% of water being applied compared to the control treatment. Overall, both technologies show potential in improving water management close to the overall estimated gross irrigation requirement with some further improvement in the mid development stage.

The study showed the potential of using thermal imaging to not only identify CWSI and assess the effect of agronomic field trials using in-situ thermal camera's but also the potential of using canopy temperatures in estimating actual ET and therefore gross irrigation requirements. This would provide a new opportunity for agricultural extension agents to advice smallholder farmers in irrigation schemes and beyond on when and how much to apply without the need for WFD or chameleon sensors. Further research is needed to calibrate and validate the irrigation predictions based on different soil and crop types.

Acknowledgments. The research was implemented under a collaborative partnership between the International Water Management Institute (IWMI) and Food and Agricultural Organization so the authors would like to thank to those organizations for the financial and other support during this work. We also acknowledge the anonymous reviewers, whose comments greatly improved the paper.

Author Contributions: T.D. conceived and developed the research framework. T.D. and F.A undertook the data processing and analysis. T.D. and S.T. wrote and revised the manuscript. P.S. supervision and revised the manuscript. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Haile, G.G., Kassa, A.K.: Irrigation in Ethiopia : a review. *J. Dry lands* (2015)
2. Tesgera, W.D., Guluma, W.: The role and significance of small scale irrigation in improving household income in Ethiopia. *Int. J. Res. Bus. Stud. Manage.* **7**(3), 20–35 (2020)
3. Padhi, J., Misra, R.K., Payero, J.O.: Estimation of soil water deficit in an irrigated cotton field with infrared thermography. *F. Crop. Res.* **126**, 45–55 (2012)
4. Jackson, R.D., Reginato, R.J., Idso, S.B.: Wheat canopy temperature: a practical tool for evaluating water requirements. *Water Resour. Res.* **13**(3), 651–656 (1977)
5. Möller, M., et al.: Use of thermal and visible imagery for estimating crop water status of irrigated grapevine. *J. Exp. Bot.* **58**(4), 827–838 (2006)
6. Jones, H.G., Serraj, R., Loveys, B.R., Xiong, L., Wheaton, A., Price, A.H.: Thermal infrared imaging of crop canopies for the remote diagnosis and quantification of plant responses to water stress in the field. *Funct. Plant Biol.* **36**(11), 978–989 (2009)

7. Stirzaker, R., Mbakwe, I., Mziray, N.R.: A soil water and solute learning system for small-scale irrigators in Africa. *Int. J. Water Resour. Dev.* **33**(5), 788–803 (2017)
8. Mdemu, M., et al.: The role of soil water monitoring tools and agricultural innovation platforms in improving food security and income of farmers in smallholder irrigation schemes in Tanzania. *Int. J. Water Resour. Dev.* **36**(1), 1–23 (2020)
9. Romero-Trigueros, C., Bayona Gambín, J.M., Nortes Tortosa, P.A., Alarcón Cabañero, J.J., Nicolás, E.N.: Determination of crop water stress index by infrared thermometry in grapefruit trees irrigated with saline reclaimed water combined with deficit irrigation. *Remote Sens.* **11**(7), 1–23 (2019)
10. Ministry of Water Resources and the National Meteorological Services Agency: Initial national communication of Ethiopia to the united nations framework convention on climate change, pp. 1–113, June 2001
11. Stirzaker, R., Car, N., Christen, E.: A traffic light soil water sensor for resource poor farmers: proof of concept. Final Project report. Australian Centre for International Agricultural Research (ACIAR), Canberra. http://aciarc.gov.au/files/aciarc_traffic_light_final_report_sept_14_2_2.pdf (2014). Accessed 9 May 2017
12. Anteneh: Application of thermal imaging for the assessment of irrigation water stress in tomato plant. MSc thesis (2018)
13. Jackson, R.D., Idso, S.B., Reginato, R.J., Pinter, P.J.: Canopy temperature as a crop water stress indicator. *Water Resour. Res.* **17**, 1133–1138 (1981)
14. Zia, S., Wenyong, D., Spreer, W., Spohrer, K., Xiongkui, H., Müller, J.: Assessing crop water stress of winter wheat by thermography under different irrigation regimes in North China plain. *J. Exp. Bot.* **5**(3), 24–34 (2014)
15. Holzapfel, E.A., Leiva, C., Mariño, M.A., Paredes, J., Arumí, J.L., Billib, M.: Furrow irrigation management and design criteria using efficiency parameters and simulation models. *Chil. J. Agric. Res.* **70**, 287–296 (2010)
16. Attahi, F., Abazadeh, K.B., Ajafi, N., Edghi, P.S.: Scheduling maize irrigation based on crop water stress index (CWSI). *Appl. Ecol. Environ. Res.* **16**(6), 7535–7549 (2018)