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Water resource assessment, gaps, and constraints of vegetable production in Robit and Dangishta watersheds, Upper Blue Nile Basin, Ethiopia

Abeyou W. Worqlul[a,*], Yihun T. Dile[b], Petra Schmitter[c], Jaehak Jeong[a], Manyowa N. Meki[a], Thomas J. Gerik[a], Raghavan Srinivasan[b], Nicole Lefore[d], Neville Clarke[e]

[a] Texas A&M AgriLife Research, Temple, TX, USA
[b] Texas A&M University, College Station, TX, USA
[c] International Water Management Institute (IWMI), Nile Basin and East Africa Office, Addis Ababa, Ethiopia
[d] International Water Management Institute (IWMI), Southern Africa, Pretoria, South Africa
[e] The Norman Borlaug Institute for International Agriculture, Texas A&M AgriLife Research, College Station, TX, USA

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ABSTRACT

The vast majority of farmers in sub-Saharan Africa depend on rainfed agriculture for food production and livelihood. Various factors including but not limited to rainfall variability, land degradation, and low soil fertility constrain agricultural productivity in the region. The objectives of this study were to 1) estimate the water resources potential to sustain small-scale irrigation (SSI) in Ethiopia during the dry season so as to expand food supply by growing vegetables, and 2) understand the gaps and constraints of vegetable production. The case studies were conducted in the Robit and Dangishta watersheds of the Upper Blue Nile Basin, Ethiopia. To document farmers' cropping practices, field-level data were collected from 36 households who had been cultivating tomato (*Solanum lycopersicum* L.) and onion (*Allium cepa* L.) during the dry season (November – April). Two components of the Integrated Decision Support System (IDSS) - the Soil and Water Assessment Tool (SWAT) and Agricultural Policy Environmental eXtender (APEX) – were respectively used to assess impacts of SSI at the watershed and field-scale levels. Results suggest that there is a substantial amount of surface runoff and shallow groundwater recharge at the watershed scale. The field-scale analysis in the Robit watershed indicated that optimal tomato yield could be obtained with 500 mm of water and 200 to 250 kg/ha of urea applied with 50 kg/ha of diammonium phosphate (DAP). In Dangishta, optimum onion yield can be obtained with 400 mm of water and 120 to 180 kg/ha of urea applied with 50 kg/ha of DAP. The field-scale simulation indicated that the average shallow groundwater recharge (after accounting for other groundwater users such as household and livestock use) was not sufficient to meet tomato and onion water demand in the dry season (October to April). The field-scale analysis also indicated that soil evaporation attributed a significant proportion of evapotranspiration (60% for onion and 40% for tomato). Use of mulching or other soil and water conservation interventions could optimize irrigation water for vegetable production by reducing soil evaporation and thereby increasing water availability in the crop root zone.

1. Introduction

Agriculture is the core driver of the economy in many developing countries. Smallholder farms are often the base of these countries and are subjected to variability in weather as well as climate change, land degradation, poor soil fertility, weeds and pests, resulting in low crop yield (Awokuse and Xie, 2015; Taddese, 2001; Teklewold et al., 2013; Tibesigwa and Visser, 2015). In Ethiopia, agriculture employs about 80% of the labor force, claiming about 45–50% of the gross domestic product (GDP) and 85% of export earnings (Araya and Stroosnijder, 2011; Berry, 2003; Bewket and Conway, 2007; Worqlul et al., 2015). However, ninety-five percent of the country's croplands are rainfed and subsistence-based, with only 5–10% of the agricultural land is being irrigated (Awulachew et al., 2007).

The government of Ethiopia is pursuing an ambitious second growth and transformation plan (GTP-II) focusing on boosting agricultural production to improve the country's economy. The goals of GTP-II includes a substantial increase in irrigated crop production in the smallholder farming sector (MoFED, 2010; NPC, 2015). Key strategies involve expanding the area under irrigation through double cropping or

* Corresponding author.
E-mail addresses: aww64@cornell.edu, aworqlul@brc.tamus.edu (A.W. Worqlul).

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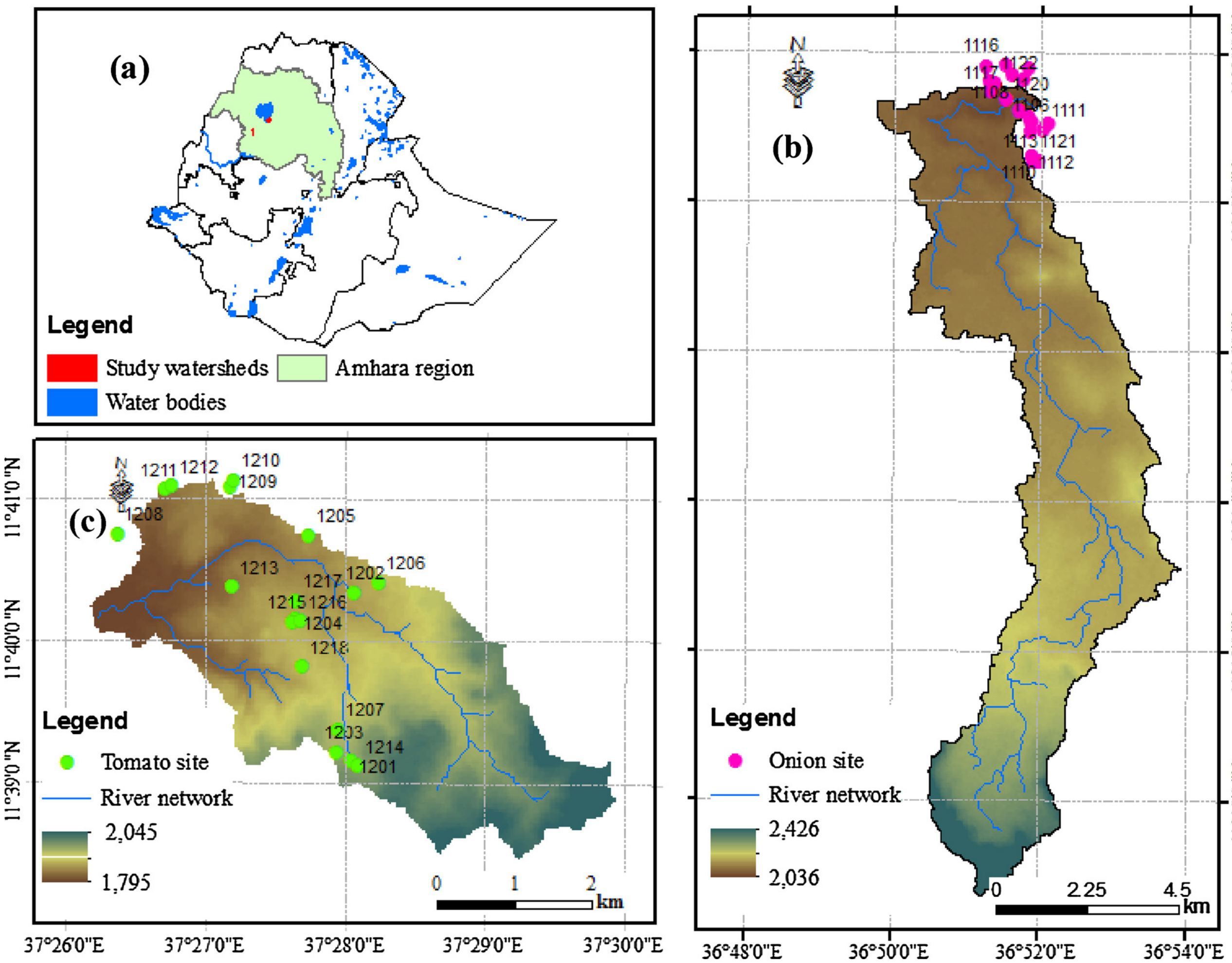

Fig. 1. Location of the study area. (a) Ethiopia regional map, (b) Dangishta, and (c) Robit watersheds showing the spatial distribution of tomato and onion field sites and river network (30 m resolution DEM background).

production of high-value industrial crops (MoFED, 2010), along with improving crop management practices through optimization of agricultural inputs. Higher productivity is necessary to improve food security, increased household income at the smallholder household level and enables irrigation adaptation environment.

In sub-Saharan Africa and specifically in Ethiopia, vegetable production significantly contributes to household food security and adds variety to the cereal-based staple diets (Uusiku et al., 2010). Tomato (*Solanum lycopersicum* L.) and onion (*Allium cepa* L.) are some of the most popular and widely grown vegetables in the world due to their wide adaptability and versatility (Asgedom et al., 2011; de Santa Olalla et al., 2004). Ethiopia has a high potential for tomato and onion production because of various factors favorable to growing these crops, including topography, climate, and soil (Hunde, 2017). However, the current production is very low due to agronomic, institutional and market constraints. Sustainable tomato and onion production would require overcoming these constraints by improving agricultural inputs such as water and fertilizer to maximize yield while minimizing negative environmental effects (Hebbar et al., 2004; Rinaldi et al., 2007).

In Ethiopia, tomato and onion are the basic constituents of cuisine contributing significantly to household food security and healthy improvement of the cereal-based staple diet (Tesfaye et al., 2008). These two vegetables are sources of vitamins and minerals. Tomato contains potassium, dietary fiber, vitamin C and A with low saturated fat, while onion contains biotin, vitamin C, vitamin B1, phosphorus, and potassium. The area dedicated to tomato and onion production in Ethiopia is larger than other irrigated crops due to their high profitability (Nikus and Mulugeta, 2010). However, yields are much lower in Ethiopia compared to other African countries like Senegal, Niger, Egypt, Morocco, Algeria, etc. (ESMIS, 2011).

This study aims at identifying the water resource potential, constraints and gaps in tomato and onion production in the Robit and Dahgishta watersheds in the Lake Tana sub-basin of the Upper Blue Nile Basin, Ethiopia. The gaps and constraints of tomato and onion production were evaluated by randomly selecting 36 farmers to grow tomato and onion in Robit and Dahgishta watersheds. Half of the farmers grew a tomato in Robit while the other half grew onion in Dangishta. Field-level data were collected from the 36 households to document farmers' cropping practices. Two components of the Integrated Decision Support System (IDSS, Clarke et al., 2016; Worqlul et al., 2018c) were used to evaluate the water resource potential and the impacts of fertilizer and irrigation water on tomato and onion production. The IDSS is a suite of spatially explicit models that include SWAT - Soil and Water Assessment Tool (Arnold et al., 1994), APEX - Agricultural Policy Environmental eXtender (Williams et al., 1998), and FARMSIM - Farm Income and Nutrition Simulator. Collectively, these models link production, economic, and environmental consequences of agricultural systems to provide an integrated assessment of new technology, and farm policy for decision-makers at multiple levels and across temporal and spatial scales. The models have been used extensively across the United States and various parts of the world (Abeysingha et al., 2015; Lu et al., 2015; Setegn et al., 2008; Wang et al., 2014). Within the IDSS framework, SWAT analyzes the water resource potential at a watershed scale, APEX examines the effects of agricultural practices on individual

Table 1
Cropping schedule of irrigated tomato and onion.

Operation	Tomato	Onion
Seeding date	Oct - 10	–
Planting/Transplanting date	Nov - 10	Oct -10
1st stage DAP application	–	(200 to 500 kg/ha) Oct - 14
1st stage urea application	(180 to 500 kg/ha) Dec - 30	–
Harvesting date	Apr - 16	Feb - 8

fields and; FARMSIM assesses the economic feasibility and nutritional impacts of a production system. However, in this study, only the findings of SWAT and APEX model simulations of the water resource potential, irrigation and fertilizer responses of onion and tomato in Robit and Dahgishta were presented.

2. Materials and methods

2.1. Study site

The study watersheds Robit and Dangishta are located in the Lake Tana sub-basin of the Blue Nile Basin, Ethiopia. Robit watershed is located east of Lake Tana between 11°37'00" N, 37°26'00" E and 11°42'00" N, 37°31'00" E, and the Dangishta watershed is located between 11°13'54.1" N, 36°50'24.9" E and 11°20'15.9" N, 36°53'54.48" E (Fig. 1). The areas at the watersheds' outlets are approximately 15 km^2 and 30 km^2 for Robit and Dangishta, respectively. The watersheds elevation extracted from a 30 m Digital Elevation Model (DEM) ranges between 1795 and 2045 m for Robit and 2036 and 2206 m for Dangishta. Robit watershed has an average slope of 8% while that of Dangishta is 5%. Both watersheds possess a relatively higher groundwater potential in the Lake Tana Basin, and farmers have experience with smallholder irrigation. Water lifting technologies to draw water from shallow wells in the study sites range from motor pumps to manual water-lifting devices.

2.2. Methods

In this study, to understand the water resource potential, gaps, and constraints of agricultural practices in the Upper Blue Nile Basin the study was undertaken in four stages: a) Field data on tomato and onion production that included information on soils, weather, cultural practices, inputs, and yield were collected from 36 randomly selected farmers in Robit and Dahgishta watersheds. Half of the farmers grew a tomato in Robit, while the other half grew onion in Dangishta. The collected data were analyzed to identify constraints and gaps in tomato and onion production. In addition, the collected data were used to parameterize the SWAT and APEX models, while rainfall data were used to characterize the rainfall pattern of the two watersheds. b) The SWAT model was used to investigate the water resource potentials of the Robit and Dangishta watersheds, including rainfall distribution patterns and totals, shallow groundwater recharge, and surface runoff. c) The APEX model was calibrated using predicted SWAT streamflow and field data to capture the measured tomato and onion yield. d) Finally, the calibrated APEX model was used to determine the optimum water and fertilizer amounts to maximize tomato and onion yield (see section 2.1.4).

2.2.1. Field experiments and data collection

Details of the collected field data are presented in (Nakawuka et al., 2017; Schmitter et al., 2016), and used to set up the APEX model. Data were collected at Robit and Dangishta field sites by faculty, scientists, and students of Bahir Dar University (BDU), and the International Water Management Institute (IWMI), Addis Ababa. The field dataset included 18 farmer households in each watershed growing vegetables in the dry season using irrigation water from shallow groundwater wells. In Robit watershed, farmers grew tomato, while in Dangishta, farmers grew onion. Water was withdrawn using a rope and washer (RWP) and rope with pulley and bucket (RP) pumps. The majority of the farmers in Robit used RWP (11 farmers), but in Dangishta they were divided equally. The method of irrigation scheduling varied among households. In Robit, ten of the households scheduled irrigation by measuring soil moisture with a Time Domain Reflectometer (TDR, *Delta-T Devices Ltd*, see Appendix 1), while others applied irrigation based on their traditional knowledge (farmer's traditional practice, FTP). In Dangishta, all farmers managed irrigation by measuring the soil moisture. Half of the households scheduled irrigation using TDR, while the other half used Wetting Front Detectors (WFD, *FullStop™*, see Appendix 1). The use of the WFD and TDR was meant to improve water use efficiency in the vegetable plots.

The field sizes varied from 100 to 230 m^2. The tomato variety grown was *Shanty PM,* and the onion variety was *Allium cepa*. Plant population, irrigation and fertilizer amounts and application dates, soil moisture, plant height, and yield were recorded following planting. Fertilizer amounts and application dates are shown in Table 1. For onion, diammonium phosphate (DAP) was applied immediately after planting. For tomato, urea was applied was applied about a month from planting (Table 1).

Soil samples collected from the top 30 cm were processed to determine the physical and chemical properties of the soil. Compiled soil properties include information on texture, field capacity, organic matter, pH, total nitrogen, available phosphorus, and electric conductivity.

2.2.2. Rainfall data analysis of Robit and Dangishta watersheds

The watersheds are equipped with an automatic rain gauge station since 2014. Two nearby weather stations, Bahir Dar (Robit watershed) and Dangila (Dangishta watershed), operated by Metrological Agency of Ethiopia (MAE) have collected daily weather data since 1960s. The annual rainfall from 1994 to 2016 varies between 1100 to 1900 mm in Robit with a standard deviation of 190 mm. In Dangishta, rainfall varies between 1200 to 2000 mm with a standard deviation of 240 mm. Daily rainfall data of the two nearby towns, along with the rainfall data collected at the field sites were used to analyze the rainfall pattern of the two watersheds from 1994 to 2016. The average monthly rainfall and number of raining days were calculated to estimate rainfall contribution during the vegetable growing period. We also used the Standardized Precipitation Index **(**SPI) (McKee et al., 1993; Svoboda et al., 2012) to characterize meteorological drought during the irrigation period. Detailed information on the mathematical computations of the SPI can be obtained from the World Meteorological Organization (Bonaccorso et al., 2015). In summary, the growing season precipitation data were fitted to a probability distribution, which was then transformed into a normal distribution. Because the SPI is normalized, the index can capture both dry and wet events in the same computation (Svoboda et al., 2012). SPI value refers to the number of standard deviation that the growing season rainfall would deviate from the long-term average precipitation. SPI value ranges between -1 and 1 represent a near-normal season, while SPI values between 1 and 2 represent moderately wet conditions, and SPI greater than 2 represents an extremely wet season. SPI values between -1 and -2 represent moderately dry conditions, while SPI less than -2 represents extremely dry conditions.

2.2.3. Watershed and field-scale simulation

Simulation models can be used as a research tool to help improve the current understanding of the hydrology, basic physiology of crop growth, development, and yield (Hunt et al., 1998). For optimum results, the model should ideally be calibrated and validated with observed data. For this study, streamflow, agronomic and yield data

Table 2
SWAT and APEX model parameters description and their respective parameter space.

	Parameter	Name	Parameter space
SWAT	SCS runoff curve number	r_CN2.mgt	−0.25 – 0.25
	Soil evaporation compensation factor	v_ESCO.hru	0.01 – 1.0
	Baseflow alpha factor (days)	v_ALPHA_BF.gw	0.00 – 1.0
	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	v_GWQMN.gw	0.0 – 5000
	Groundwater "revap" coefficient	v_GW_REVAP.gw	0.02 – 0.2
	Threshold depth of water in the shallow aquifer for "revap" to occur (mm)	v_REVAPMN.gw	−0.50 – 0.5
	Effective hydraulic conductivity in main channel	v_CH_K2.sub	0.01 – 0.3
APEX	Runoff curve number initial abstraction	v_PARM_20	0.05 – 0.4
	SCS curve number retention parameter	v_PARM_42	0.30 – 2.5
	Soil evaporation coefficient	v_PARM_12	1.50 – 2.5
	Return Flow / (Return Flow + Deep Percolation)	v_RFPO	– 0.98
	Ground water residence time in days	v_RFTO	0.00 – 50.0

collected at the Robit and Dangishta field sites were used for SWAT and APEX model calibration and validation.

2.2.3.1. SWAT and APEX models. Although SWAT and APEX models differ substantially, they share many common attributes including the ability to simulate the effect of crop management practices on agricultural production and the environment (Arnold et al., 1994; Gassman et al., 1998; Williams et al., 1998). The SWAT model is a basin-scale distributed hydrological model. In SWAT, a watershed can be divided into multiple sub-watersheds and further into multiple hydrologic response units (HRUs). The HRUs are assumed to have homogeneous land use, soil, and slope combinations. Soil water content, nutrient cycles, surface runoff, and sediment yield are simulated at HRU level and then aggregated to each sub-basin before being routed through the stream network further to the outlet (Neitsch et al., 2005).

APEX is a field or small watershed-scale model. In APEX, a sub-watershed is assumed to have a single HRU and is called a subarea. Unlike HRUs in SWAT, APEX subareas have a spatial relationship and can be routed in a specified order (Saleh et al., 2008). APEX is capable of simulating detailed field conditions including crop management and growth, nutrient and pesticide fate, hydrology, soil temperature, erosion-sedimentation as well as costs and returns of the various management practices (Saleh and Gallego, 2007; Wang et al., 2011; Worqlul et al., 2018a). Both SWAT and APEX operate on a daily time step.

SWAT and APEX share similar spatial input data including digital elevation model (DEM), soil and land use. The DEM used to characterize the watersheds in this study has a spatial resolution of 30 m; the soil data contains physical and chemical properties. For SWAT, the land use and soil spatial data were obtained from the Ethiopia Ministry of Water, Irrigation, and Electricity (EMWIE), while for APEX, soil and land use information was collected at the field sites. The main streamflow calibration parameters for both SWAT and APEX were identified based on the literature review (Bitew and Gebremichael, 2010; Mengistu and Sorteberg, 2012).

2.2.3.2. SWAT and APEX model setup, calibration, and validation. Streamflow at the outlets of the Robit and Dangishta watersheds has been monitored from June 2015 to September 2016. To better capture, the water balance components of the watersheds observed long-term streamflow data of the nearby watersheds of Gumara (for Robit) and Gilgel Abay (for Dangishta) were used to calibrate the SWAT model. Observed streamflow of Gumara and Gilgel Abay were obtained from the EMWIE for the period 1994 to 2016. SWAT model was calibrated using the Sequential Uncertainty Fitting (SUFI-2) algorithm under the SWAT Calibration Uncertainty Procedures (SWAT-CUP, Abbaspour et al., 2007). The streamflow simulation periods of SWAT for Gumara and Gilgel Abay watersheds were divided into warm-up (1994), calibration (1995 to 2010) and validation (2011 to 2016) periods. The calibrated SWAT model parameters were transferred to the respective Robit and Dangishta watersheds based on the assumption that catchments proxy to each other will likely have similar runoff regime leading to similar model parameters, which are used to initialize Robit and Dangishata SWAT model set ups (Wale et al., 2009; Worqlul et al., 2018a). The transferred parameters were further fine-tuned to adequately capture the observed streamflow of the Robit and Dangishta watersheds. The purpose of the SWAT simulation at the watershed scale was to access the spatial and temporal distribution of available surface runoff and shallow groundwater potential at the smallest hydrological response units (HRUs).

The APEX model set up, calibration and validation were achieved using the information on soils, weather, cultural practices, and management data gathered in the farmers' fields. Adjustments with respect to default crop parameters for tomato and onion were minor. Model calibration was achieved using auto-Calibration and UncerTainty Estimator (APEX-CUTE, Wang et al., 2014). The APEX crop yield calibration was based on 2015/2016 field data.

The calibrated APEX model was used to develop tomato and onion input production functions on water and fertilizer to understand constraints and gaps of vegetable production in the Robit and Dangishta watersheds. A detailed discussion of the water and fertilizer production functions is given under section 2.1.4. Table 2 shows the list of selected parameters and their respective model parameter space used to calibrate the SWAT and APEX models.

2.2.3.3. SWAT and APEX model performance evaluation. The simulated daily streamflow and vegetable yield were compared with the observed data, and the simulation performance was evaluated with multiple statistics that include: coefficient of determination (R-Squared), root mean square error (RMSE), percent bias (PBIAS), and Nash-Sutcliffe Efficiency (NSE). R-Square evaluates the degree of linear association between simulated and observed variable, while PBIAS measures the relative volume difference between simulated and observed variables. NSE is the normalized statistic that describes the relative magnitude of residual variance compared to the observed streamflow variance.

2.2.4. Water and fertilizer production function

Appropriate irrigation water management is important to preserve water resources and to minimize a farmer's workload while optimizing crop productivity. The water use efficiency of onion and tomato were developed by running the calibrated APEX model multiple times over a 22-year period (1995 to 2016) while varying the irrigation amounts at two-day intervals. The two-day irrigation interval used in the model was to match the practices by the farmers in the field studies. For farmers, the two-day irrigation interval allowed them to have sufficient water to recharge the shallow groundwater wells. The irrigation scenario was developed for a total amounts of water ranging from 100 to 700 mm at 100 mm intervals (i.e. 100, 200, 300, 400, 500, 600 and 700 mm irrigation amounts) that were applied throughout the growing period. For example, for tomato, which has a 170-day growing period, 8.33 mm of water was applied every two days for a total irrigation of 700 mm. The optimal amount of water was associated with the volume of water producing the maximum yield.

Similarly, the fertilizer production function, i.e., the response of onion and tomato yield to the amount of fertilizer applied was developed by running the calibrated APEX model at the optimal applied water level estimated with the water production function and applying different amounts of urea and diammonium phosphate (DAP). Again, the timing of fertilizer application was the same as in the farmer-managed field studies; with DAP applied at seeding and urea applied one month from planting for onion and multiple times for tomato. Urea used in the field studies contains 46 percent nitrogen. DAP is used commonly in Ethiopia and it is the source of phosphorus and nitrogen containing 46 percent and 18 percent, respectively.

3. Results and discussion

3.1. Field data analysis

Out of the 36 plots, irrigation amounts and yield were successfully recorded on 27 plots: 16 onion and 11 tomato plots. The remaining plots were damaged by pest or grazed by animals or irrigation was stopped due to water shortage. In Robit, farmers using TDR to manage irrigation, applied water more frequently (approximately every 1.8 days) compared to farmers that used FTP (on average water was applied every 2.1 days). Higher variability was found for the applied irrigation water in FTP compared to TDR practice with a coefficient of variation of 27.1% and 15.5%, respectively. Tomato yield between the two management practices was significantly different ($p < 0.05$). On average, yields of the FTP managed plots were half of the TDR managed plots. In Dangishta, the total number of irrigation days between WFD and TDR managed field plots were not significantly different. The field data also indicated that WFD managed plots were irrigated with a lower coefficient of variability (23.0%) compared to TDR practice (36.0%). Onion yields between the two irrigation management treatments were not significantly different.

Overall, the field data did not show a significant linear relationship between total water applied and yield for both vegetables and water management practices except in Robit, where the traditional farmers' practice indicated a significant inverse linear relationship between the amount of water applied and yield with a correlation coefficient of 0.62.

Tomato is a deep-rooted crop, with roots reaching up to 60 to 90 cm. Therefore irrigation management with the TDR, which only measures soil moisture in the top 20 cm of soil could not be effective at later growth stages of the crop when the crop had developed much deeper roots. However, for onion, which has a root depth varying between 30 and 45 cm, the TDR irrigation management practice can be effective. While monitoring of soil moisture dynamics of agricultural land is vital to improve water productivity, it is important to measure additionally the deeper soil moisture layers aside from the topsoil horizon.

Furthermore, the field data indicated that pests and diseases were the main constraints on tomato production, as 38% of the 18 plots failed at different times during the growing period. In addition, in Robit, water use competition between the commonly grown cash crop *Catha eduli* (khat) and tomato was reported. Khat, a perennial tree crop which has a high return on investment, has become an irresistible investment for farmers.

3.2. Water resource assessment

3.2.1. Rainfall data analysis

The long-term average monthly rainfall and the average number of raining days for Robit and Dangishta watersheds are shown in Fig. 2 (1994 to 2016). Both watersheds show a similar unimodal rainfall pattern receiving 60 to 94% of the annual rainfall in the major rainfall season June through September. On average, the number of raining days exceeds 18 days per month during the major rainfall season (June to September), with a higher percentage of rain every two days (Fig. 2). Months before and after the major rainfall season, May and October indicated an average of more than 8 raining days. The dry season extends from November through April. During this period, the number of raining days and the rainfall amount are insufficient to support vegetable production. The average rainfall during tomato and onion growing periods is approximately 122 and 60 mm, respectively, with standard deviations of 60 and 38 mm, respectively (1994 to 2016). Most of the rainfall during this period comes at the end of the growing period.

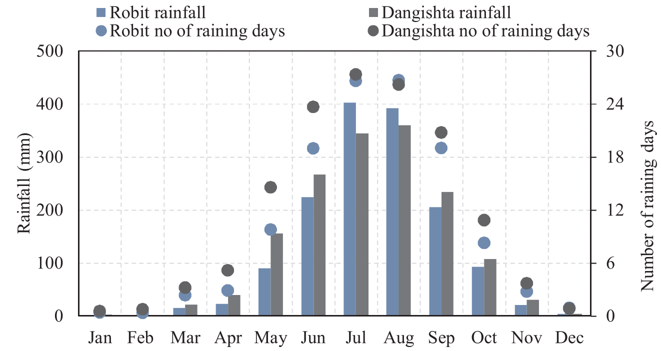

Fig. 2. Long-term monthly average rainfall and average number of raining days in Robit and Dangishta watersheds.(1994–2016).

The rainfall pattern for the vegetable growing season for the period 1994–2016 was further analyzed to evaluate the severity of meteorological drought using the Standardized Precipitation Index (Fig. 3). The SPI shows that 86% and 77% of the study period in Robit and Dangishta watersheds, respectively, received above normal rainfall whereas the other years were identified as moderately dry. The analysis does not indicate a strong rainfall contribution in the dry season. Furthermore, higher rainfall variability is observed in Robit with a coefficient of variation of 57% compared to 49% for Dangishta watershed.

3.2.2. Watershed-scale analysis

The performance of SWAT model in simulating streamflow for Gumara and Gilgel Abay watershed was reasonably good with a Nash-Sutcliff efficiencies (NSE) of 0.80 and 0.83, respectively, and Percent Bias (PBIAS) of 5.4% and 6.4%, respectively, for the calibration period (1995 to 2010). Similar model performance was also reported in Worqlul et al. (2018b); Adem et al. (2014) and Setegn et al. (2010). The model was validated from 2011 to 2016 and the performance was acceptable with NSE of 0.78 and 0.80 and PBIAS of 6.4% and 5.6% for Gumara and Gilgel Abay watersheds, respectively. The calibrated and validated model parameters were transferred to the Robit and Dangishta watersheds. The parameters were further fine-tuned to

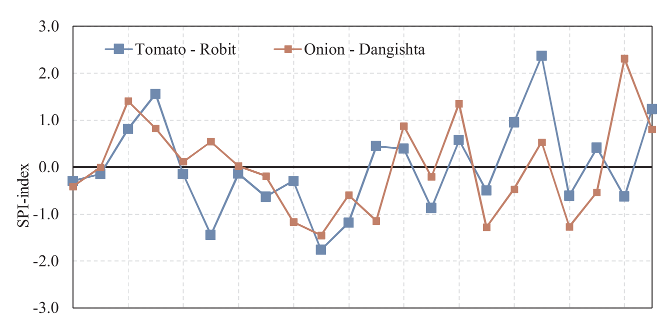

Fig. 3. Standardized precipitation index (SPI) for Robit and Dangishta watersheds for tomato and onion growing periods (1994–2015).

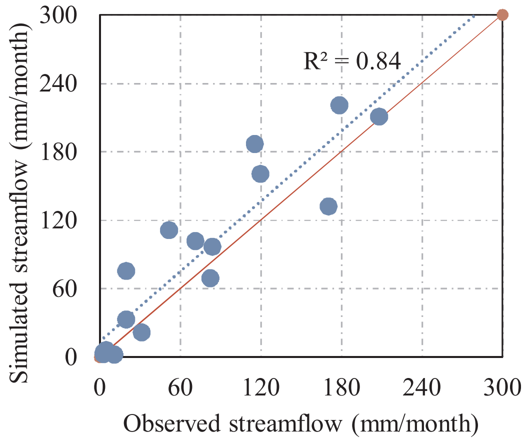

Fig. 4. Monthly scatter plot of simulated vs. observed streamflow of Dangishta watersheds (June 2015 to September 2016).

adequately capture the observed streamflow of Robit and Dangishta watersheds (June 2015 to Sep 2016). Fig. 4 shows the performance of the SWAT model in simulating monthly streamflow of Dangishta watershed. The simulation also indicated the spatial distribution of groundwater recharge and surface runoff of Robit and Dangishta watersheds (Fig. 5a–d).

In Robit, the average annual surface runoff varies between 440 and 535 mm (Fig. 5a), and the annual average groundwater recharge varies between 250 and 320 mm. In Dangishta, surface runoff and groundwater recharge vary between 195–300 and 285–456 mm, respectively (Fig. 5c and d). The availability of water resource both as surface and shallow groundwater recharge suggests that small-scale irrigation (SSI) technologies could be utilized to grow crops in the dry season.

3.3. Field-scale simulation

3.3.1. APEX crop yield simulation

The APEX model was set up for the seven onion and nine tomato undisturbed field plots in Dangishta and Robit watersheds, respectively. The selected field plots had adequate datasets for the APEX model setup. The remaining field plots did not have soil physical and chemical properties to set up the APEX model. The performance of the APEX model in simulating crop yield in the two watersheds is shown in Fig. 6a and b. The model adequately captured the observed tomato and onion yields. For tomato, 89% of the yield variability was captured by the model with a RMSE of 5.3 t/ha. For the onion, the APEX model captured 93% of the yield variability with a RMSE of 0.89 t/ha. However, the APEX model was unable to adequately predict observed high yields.

3.3.2. Water use efficiency of tomato and onion

Irrigation scheduling with the right amount and timing is critical for sustainable and optimal use of scarce water resources. Results of the 22-year APEX simulation of tomato yield and number of water stress days for irrigation input amounts ranging from 100 to 700 mm are shown in Fig. 7a and b. The number of water stress days were estimated by comparing the available amount of soil water in the root zone and daily demand required for optimal growth. For example, the number of water stress days is estimated at 0.1 days if the root zone readily available soil moisture meets only 90% of the optimal crop water requirement. In Robit, when tomato was grown with 100 mm of water, the yield was limited by water stress with an average of 25 stress days. When the irrigation amount increased to 200 mm, the number of water-stress days declined by 24%, and consequently yield increased by 20%. As irrigation approached 500 mm and beyond, yields did not significantly increase (p-value > 0.05). The irrigation production function indicated that tomato yield was maximized when an average amount of 500 mm of water was applied indicating an average of 3 water stress days throughout the growing period (Fig. 7a). For Dangishta, 400 mm was the optimal amount of water for onion production (Fig. 7b).

The optimal irrigation water required to grow tomato and onion estimated with the field scale APEX model was close to the shallow groundwater recharge. However, all of the recharge is not available for cropping as groundwater must also provide for the smallholder farmer's domestic and livestock needs. While needs vary amongst smallholders, Altchenko and Villholth (2014) and Pavelic et al. (2013) estimate that smallholder farmers use 20–30% of the groundwater to support their domestic and livestock needs, which potentially limits the amount of water available for irrigating crops. While groundwater recharge and surface runoff during the wet season can supplement rainfall, capturing and retaining runoff for use during the dry season remains a challenge.

The water balance components including actual evapotranspiration (AET), plant transpiration (TRS) runoff (Q), percolation below the root zone (PRK), potential evapotranspiration (PET), and rainfall (Prcp) for the growing season were estimated using the APEX model for tomato and onion. Fig. 8 shows the different water balance components of the 200, 400 and 600 mm of irrigation amounts. In all cases, the evapotranspiration demand could not be met when 200 mm of water was applied. As a result, very little runoff was generated. Actual evaporation (ETA) was satisfied when an irrigation of 400 mm was applied in Robit. However, runoff generated for 400 mm of irrigation did not differ significantly compared to 200 mm of irrigation. When the irrigation increased from 400 to 600 mm and above more water was lost through percolation below the root zone in Dangishta and as surface runoff in Robit. The results also illustrate that for onion production, a significant amount of water was lost through soil evaporation (actual evapotranspiration minus transpiration). Approximately 60 to 65% of the actual evapotranspiration was lost as soil evaporation resulting from low leaf area coverage (Fig. 8b). The soil evaporation component for tomato was approximately 30 to 40% of the total evapotranspiration. Hence, adding a protective layer to cover the soil, such as organic mulch and net shading to protect the soil from incoming solar radiation or using efficient water application techniques such as drip irrigation to minimize soil evaporation could extend the limited amounts of shallow groundwater for vegetable production in the dry season.

3.3.3. Fertilizer use efficiency of tomato and onion

Optimal fertilizer application is necessary to maximize crop yield. Surveys conducted by the Central Statistical Authority (CSA) and the Livestock and Irrigation Value chains for Ethiopian Smallholders (LIVES) indicated that fertilizer applied for most crops in Ethiopia is far below the recommended rate (Awulachew et al., 2005; Zerfu and Larson, 2010). It is estimated that only 30–40% of smallholders use fertilizer (Rashid et al., 2013). Insufficient fertilizer application stifles productivity and depletes soil nutrients and organic matter.

Using the APEX model, a fertilizer production function for tomato and onion was developed to determine the fertilizer amount required for optimal production in the study sites. The fertilizer production function was developed by applying the optimal amount of water estimated under section 3.3.2., and different combinations of urea and DAP. APEX simulated results of the fertilizer production function are shown in Fig. 9a and b. When the tomato was grown with no fertilizer, a low fresh yield of approximately 2.5 t/ha was obtained. Similarly, when onion was grown with no fertilizer, a very low fresh yield of approximately 0.12 t/ha was obtained. For both crops, yield response to increased N (urea) was low when DAP was not applied. The fertilizer production function indicates that for both crops, yield increases when urea and DAP application rates increase; however, the yield response to increased fertilizer application above the optimal amount was insignificant (Fig. 9a and b). In Robit, optimal tomato yield could be obtained when 200 to 250 kg/ha of urea with 50 kg/ha of DAP is applied, while in Dangishta, optimum onion yield can be obtained when 120 to 180 kg/ha of urea with 50 kg/ha of DAP is applied. However, in both

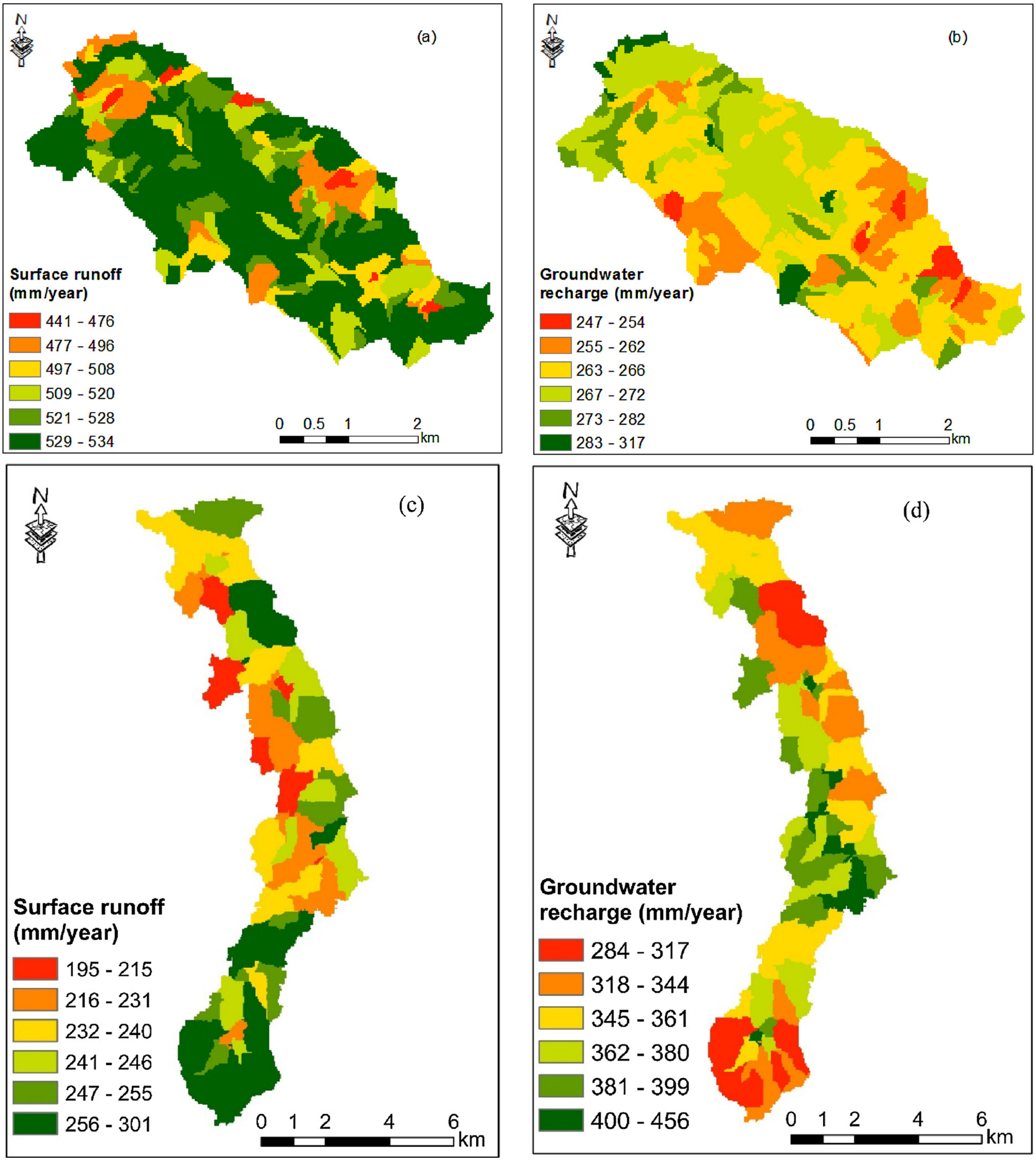

Fig. 5. Water resource potential of Robit and Dangishta watersheds: (a) annual average surface runoff, and (b) annual average groundwater recharge of Robit watershed (mm/year); (c) annual average surface runoff, and (d) annual average groundwater recharge of Dangishta watershed (mm/year).

study sites, farmers applied higher amounts of fertilizer, a practice detrimental to the environment. The excess nutrients from fertilizer can be washed away into the river system or contaminate groundwater through leaching.

4. Conclusion

The field data collected in the 36 farmers managed plots in Robit and Dangishta watersheds coupled with the SWAT and APEX simulation model results revealed the water resource potential, gaps, constraints, and opportunities of vegetable production in Ethiopia.

The hydro-meteorological data analysis indicated a potentially large availability of groundwater to support irrigation in the dry season despite the limited rainfall of 60 mm over the growing period. The rainfall distribution pattern also indicated a great deal of variability with a coefficient of variation of 49% and 63% in Robit and Dangishta, respectively. The temporal variability manifested in terms of variable mean seasonal distribution patterns would cause a severe crop failure to support vegetable production in the dry season. The APEX predicted optimal water required to grow tomato and onion were close to the shallow groundwater recharge. However, all of the recharge is not available for cropping, as groundwater must also provide for the

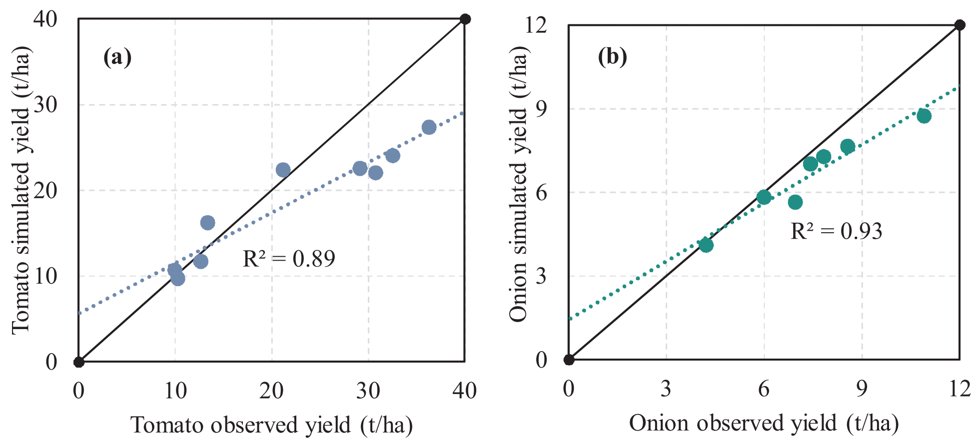

Fig. 6. Observed vs. APEX simulated yield of (a) tomato and (b) onion.

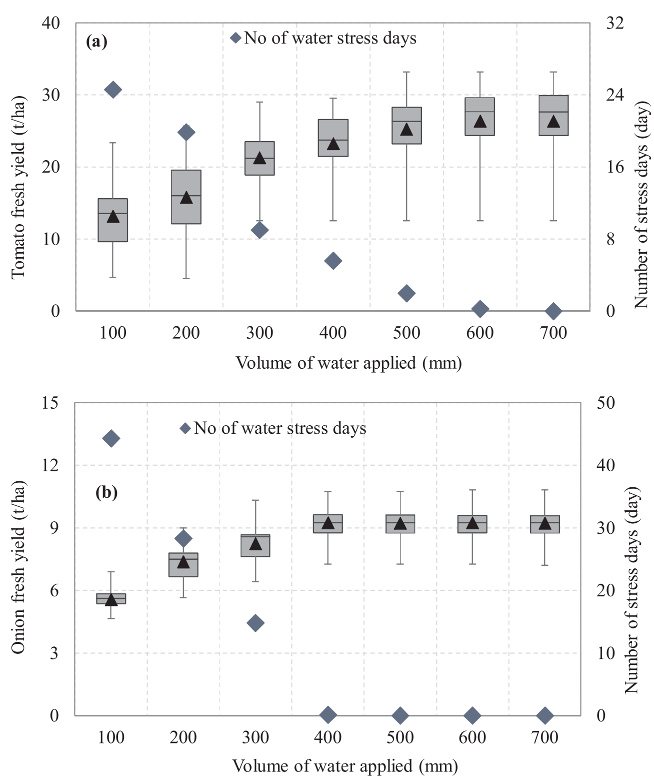

Fig. 7. Twenty two-year (1995–2016) APEX simulated tomato (a) and onion (b) irrigation production function for Robit and Dangishta watersheds. The rectangular boxes represent the first and the third quartile of tomato yield; the median yield is represented by a segment inside the rectangle; average yield is represented by the triangle, and whiskers above and below represent the minimum and maximum tomato yield.

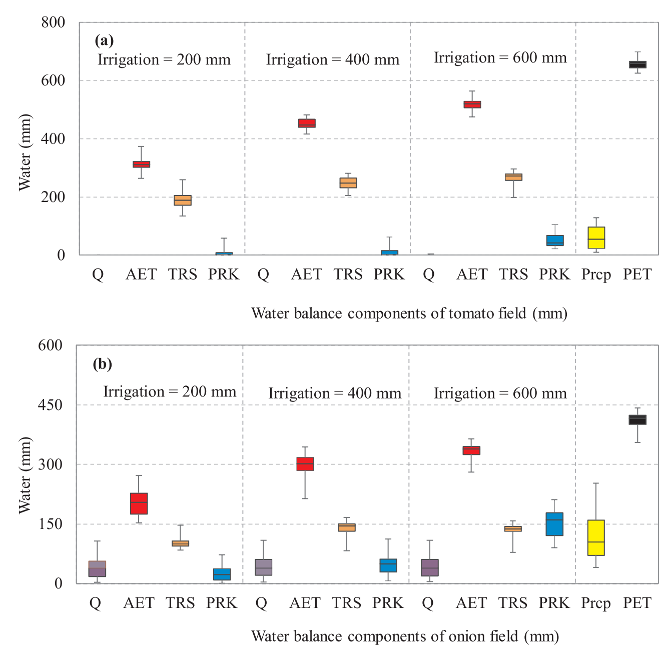

Fig. 8. APEX simulated average surface runoff (Q, mm), actual evapotranspiration (ETA, mm), transpiration(Trns, mm) and percolation (PRK, mm) over the growing period of (a) tomato and (b) onion at three irrigation volumes: 200, 400 and 600 mm in Robit and Dangishta watersheds, respectively (1995–2016).

smallholder's domestic and livestock needs. Indicating that water could be a constraint for intensification of dry season irrigation on both sites. On top of this, the other constraint for vegetable production in Robit was water use competition of khat with other vegetable crops that grew in the dry season; and the need to control pests and diseases that claimed a large proportion of tomato plots resulting in productivity failures.

The field data and observations revealed significant differences and gaps in knowledge of farmers and their understanding of managing irrigation, fertilization, and pest control. Traditional or common irrigation practices used by farmers were highly variable in the timing and amounts of water applied. However, when farmers used soil moisture monitoring instruments to schedule irrigation water applications became more consistent and yield improved. The study also revealed that even though monitoring the soil moisture dynamics of agricultural land is vital to improve the water productivity, it is important to select appropriate soil moisture measuring devices to monitor soil moisture dynamics across the crop root depth. Deep-rooted crop such as tomatoes soil moisture was successfully monitored with WFD, while TDR supported soil moisture-based irrigation of shallow-rooted vegetable.

The APEX simulation revealed the adverse environmental impact of over-irrigation. Applying irrigation exceeding the optimal crop water requirement increased surface runoff and leaching resulting in nutrient losses. The fertilizer production function indicated that tomato and onion are optimized when urea was applied in combination with DAP.

Given the country rising income level and rapidly growing population and considering tomato and onion are the basic constituents of cuisine obviously magnifies the opportunity of vegetable production in Ethiopia.

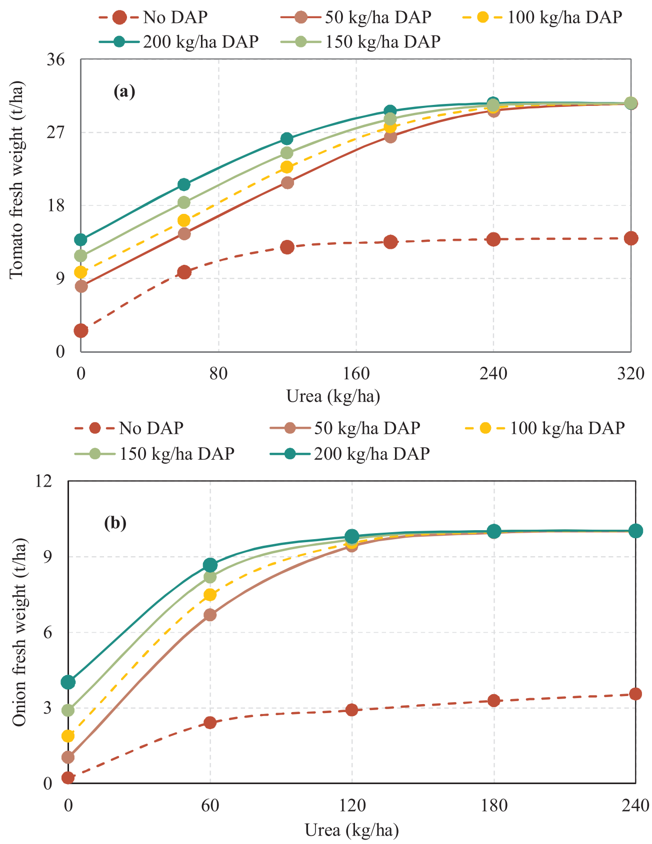

Fig. 9. The average simulated yield for different amounts of fertilizer, varying the amounts of urea and DAP (1995–2016). APEX simulated fertilizer response functions for (a) Tomato - Robit watershed, and (b) Onion – Dangishta watershed (1995–2016).

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Appendix A. Soil moisture measuring devices used for irrigation management

The Wetting Front Detectors (WFD) is a funnel-shaped device that is buried in the soil containing a calibrated floating device. When the soil water content reaches a certain level and reaches the funnel, the water will activate an electrical float switch. The float switch connected to the signal indicates when the desired level of wetness has been reached (Stirzaker, 2003; Stirzaker and Hutchinson, 2006). The WFD was installed at two alternative depths of 20 cm and 40 cm.

Time Domain Reflectometer (TDR) determines the dielectric constant of an object using simple electrodes inserted in a medium (Noborio, 2001). TDR soil moisture measurement is based on the electromagnetic properties of the soil-air-water mixture by measuring the electromagnetic wave traveling time between metal rods embedded in the ground (Herkelrath et al., 1991). TDR has a superior accuracy and it is portable, however, it only measures soil moisture of the top 20 cm. Irrigation was applied to bring the soil moisture up to field capacity for both management groups.

References

Abbaspour, K., Vejdani, M., Haghighat, S., 2007. SWAT-CUP Calibration and Uncertainty Programs for SWAT, MODSIM 2007 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand.
Abeysingha, N., Singh, M., Sehgal, V., Khanna, M., Pathak, H., Jayakody, P., Srinivasan, R., 2015. Assessment of water yield and evapotranspiration over 1985 to 2010 in the Gomti River basin in India using the SWAT model. Curr. Sci. 108, 2202.
Adem, A.A., Melesse, A.M., Tilahun, S.A., Setegn, S.G., Ayana, E.K., Wale, A., Assefa, T.T., 2014. Climate Change Projections in the Upper Gilgel Abay River Catchment. Blue Nile Basin Ethiopia, Nile River Basin. Springer, pp. 363–388.
Altchenko, Y., Villholth, K.G., 2014. Mapping irrigation potential from renewable groundwater in Africa—a quantitative hydrological approach. Hydrol. Earth Syst. Sci. Discuss. 11.
Araya, A., Stroosnijder, L., 2011. Assessing drought risk and irrigation need in northern Ethiopia. Agric. For. Meteorol. 151, 425–436.
Arnold, J., Williams, J.R., Srinivasan, R., King, K.W., Griggs, R.H., 1994. SWAT (Soil and Water Assessment Tool). Grassland, Soil and Water Research Laboratory. USDA, Agricultural Research Service.
Asgedom, S., Struik, P.C., Heuvelink, E., Araia, W., 2011. Opportunities and constraints of tomato production in Eritrea. Afr. J. Agric. Res. 6, 956–967.
Awokuse, T.O., Xie, R., 2015. Does agriculture really matter for economic growth in developing countries? Can. J. Agric. Econ./Revue Canadienne d'Agroeconomie 63, 77–99.
Awulachew, S.B., Merrey, D., Kamara, A., Van Koppen, B., Penning de Vries, F., Boelee, E., 2005. Experiences and Opportunities for Promoting small-scale/micro Irrigation and Rainwater Harvesting for Food Security in Ethiopia. IWMI.
Awulachew, S.B., Yilma, A.D., Loulseged, M., Loiskandl, W., Ayana, M., Alamirew, T., 2007. Water Resources and Irrigation Development in Ethiopia. Iwmi.
Berry, L., 2003. Land Degradation in Ethiopia: Its Extent and Impact. Commissioned by the GM With WB Support.
Bewket, W., Conway, D., 2007. A note on the temporal and spatial variability of rainfall in the drought-prone Amhara region of Ethiopia. Int. J. Climatol. 27, 1467–1477.
Bitew, M.M., Gebremichael, M., 2010. Evaluation through independent measurements: complex terrain and humid tropical region in Ethiopia. Satellite Rainfall Applications for Surface Hydrology. Springer, pp. 205–214.
Bonaccorso, B., Cancelliere, A., Rossi, G., 2015. Probabilistic forecasting of drought class transitions in Sicily (Italy) using Standardized Precipitation Index and North Atlantic Oscillation Index. J. Hydrol. 526, 136–150.
Clarke, N., Bizimana, J.-C., Dile, Y., Worqlul, A., Osorio, J., Herbst, B., Richardson, J.W., Srinivasan, R., Gerik, T.J., Williams, J., 2016. Evaluation of New Farming Technologies in Ethiopia Using the Integrated Decision Support System (IDSS). Agricultural Water Management.
de Santa Olalla, F.M.N., Domınguez-Padilla, A., Lopez, R., 2004. Production and quality of the onion crop (Allium cepa L.) cultivated under controlled deficit irrigation conditions in a semi-arid climate. Agric. Water Manage. 68, 77–89.
ESMIS, 2011. U.S. Onion Statistics. United States Department of Agriculture Economics. United States Department of Agriculture Economics, Statistics and Market Information System. http://usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?documentID=1396.
Gassman, P.W., Abraham, J., Hauck, L., Saleh, A., Keplinger, K., 1998. Simulation of nutrient losses from chicken litter applications in east central Texas with APEX and SWAT, 2001 ASAE Annual meeting. Am. Soc. Agric. Biol. Eng. 1.
Hebbar, S., Ramachandrappa, B., Nanjappa, H., Prabhakar, M., 2004. Studies on NPK drip fertigation in field grown tomato (Lycopersicon esculentum Mill.). Eur. J. Agron. 21, 117–127.
Hunde, N.F., 2017. Opportunity, Problems and Production Status of Vegetables in Ethiopia: A Review.
Hunt, L., Kuchar, L., Swanton, C., 1998. Estimation of solar radiation for use in crop modelling. Agric. For. Meteorol. 91, 293–300.
Lu, Z., Zou, S., Xiao, H., Zheng, C., Yin, Z., Wang, W., 2015. Comprehensive hydrologic calibration of SWAT and water balance analysis in mountainous watersheds in northwest China. Phys. Chem. Earth Parts A/B/C.
McKee, T.B., Doesken, N.J., Kleist, J., 1993. The relationship of drought frequency and duration to time scales. In: Proceedings of the 8th Conference on Applied Climatology. American Meteorological Society Boston, MA. pp. 179–183.
Mengistu, D., Sorteberg, A., 2012. Sensitivity of SWAT simulated streamflow to climatic changes within the Eastern Nile River basin. Hydrol. Earth Syst. Sci. 16, 391–407.
MoFED, 2010. Growth and transformation plan (GTP) 2010/11-2014/15. Ministry of Finance and Economic Development (MoFED). T.F.D.R.o.E. Growth and Transformation Plan (GTP), Addis Ababa.
Nakawuka, P., Schmitter, P., Tesema, M., Mulugeta, H., Ewnetie, T., Tegegne, D., Tilahun, S., Adie, A., Ayana, M., Barron, J., Langan, S., 2017. Testing Appropriate Smallholder Irrigation Technologies for Increased and Sustainable Agricultural Production in Ethiopia (DRAFT). International Water Management Institute, East Africa and Nile Basin Office, Addis Ababa p. 40.
Neitsch, S., Arnold, J., Kiniry, J., Srinivasan, R., Williams, J., 2005. Soil and Water Assessment Tool input/output File Documentation, Version 2005. USDA. ARS Grassland. Soil and Water Research Laboratory, Temple, TX Available at:

www.brc.tamus.edu/swat/doc. Html (accessed 01.11. 2006.).
Nikus, O., Mulugeta, F., 2010. Onion seed production techniques. A Manual for Extension Agents and Seed Producers. FAOCDMDP, Asella, Ethiopia.
NPC, 2015. The second growth and transformation plan (GTP II) (2015/16-2019/20). In: Commission, N.P (Ed.), The Federal Democratic Republic of Ethiopia. National Planning Commission, Addis Ababa, Ethiopia.
Pavelic, P., Villholth, K.G., Shu, Y., Rebelo, L.-M., Smakhtin, V., 2013. Smallholder groundwater irrigation in Sub-Saharan Africa: country-level estimates of development potential. Water Int. 38, 392–407.
Rashid, S., Tefera, N., Minot, N., Ayele, G., 2013. Fertilizer in Ethiopia: An Assessment of Policies, Value Chain, and Profitability.
Rinaldi, M., Ventrella, D., Gagliano, C., 2007. Comparison of nitrogen and irrigation strategies in tomato using CROPGRO model. A case study from Southern Italy. Agric. Water Manage. 87, 91–105.
Saleh, A., Gallego, O., 2007. Application of SWAT and APEX using the SWAPP (SWAT-APEX) program for the upper north Bosque River watershed in Texas. Trans. ASABE 50, 1177–1187.
Saleh, A., Osei, E., Gallego, O., 2008. Use of CEEOT-SWAPP modeling system for targeting and evaluating environmental pollutants. In: 21st Century Watershed Technology: Improving Water Quality and Environment Conference Proceedings. 29 March-3 April 2008, Concepcion, Chile. pp. 36 American Society of Agricultural and Biological Engineers.
Schmitter, P., Tegegne, D., Abera, A., Tamirat, T., Boudron, F., Blummel, M., Lefore, N., Barron, J., 2016. Evaluation of Suitable Water Lifting and On-farm Water Management Technologies for the Irrigation of Vegetables and Fodder in Lemo. International Water Management Institute (IWMI), Addis Ababa, Ethiopia.
Setegn, S.G., Srinivasan, R., Dargahi, B., 2008. Hydrological modelling in the Lake Tana basin, Ethiopia using SWAT model. Open Hydrol. J. 2, 49–62.
Setegn, S.G., Srinivasan, R., Melesse, A.M., Dargahi, B., 2010. SWAT model application and prediction uncertainty analysis in the Lake Tana Basin, Ethiopia. Hydrol. Process. 24, 357–367.
Svoboda, M., Hayes, M., Wood, D., 2012. Standardized Precipitation Index User Guide. World Meteorological Organization, Geneva, Switzerland.
Taddese, G., 2001. Land degradation: a challenge to Ethiopia. Environ. Manage. 27, 815–824.
Teklewold, H., Kassie, M., Shiferaw, B., Köhlin, G., 2013. Cropping system diversification, conservation tillage and modern seed adoption in Ethiopia: impacts on household income, agrochemical use and demand for labor. Ecol. Econ. 93, 85–93.
Tesfaye, A., Bogale, A., Namara, R.E., Bacha, D., 2008. The impact of small-scale irrigation on household food security: the case of Filtino and Godino irrigation schemes in Ethiopia. Irrig. Drain. Syst. 22, 145–158.
Tibesigwa, B., Visser, M., 2015. Small-scale Subsistence Farming, Food Security, Climate Change and Adaptation in South Africa. Male-Female Headed Households and Urban-Rural Nexus.
Uusiku, N.P., Oelofse, A., Duodu, K.G., Bester, M.J., Faber, M., 2010. Nutritional value of leafy vegetables of sub-Saharan Africa and their potential contribution to human health: a review. J. Food Compos. Anal. 23, 499–509.
Wale, A., Rientjes, T., Gieske, A., Getachew, H., 2009. Ungauged catchment contributions to Lake Tana's water balance. Hydrol. Process. 23, 3682–3693.
Wang, X., Kannan, N., Santhi, C., Potter, S., Williams, J., Arnold, J., 2011. Integrating APEX output for cultivated cropland with SWAT simulation for regional modeling. Trans. ASABE 54, 1281–1298.
Wang, X., Yen, H., Liu, Q., Liu, J., 2014. An auto-calibration tool for the Agricultural Policy Environmental eXtender (APEX) model. Trans. ASABE 57, 1087–1098.
Williams, J.R., Arnold, J.G., Srinivasan, R., Ramanarayanan, T.S., 1998. APEX: a new tool for predicting the effects of climate and CO2 changes on erosion and water quality. Modelling Soil Erosion by Water. Springer, pp. 441–449.
Worqlul, A., Dile, Y., Bizimana, J.-C., Jeong, J., Gerik, T., Srinivasan, R., Richardson, J., Clarke, N., 2018a. Multi-dimensional evaluation of simulated small-scale irrigation intervention: a case study in Dimbasinia Watershed, Ghana. Sustainability 10, 1531.
Worqlul, A.W., Ayana, E.K., Yen, H., Jeong, J., MacAlister, C., Taylor, R., Gerik, T.J., Steenhuis, T.S., 2018b. Evaluating hydrologic responses to soil characteristics using SWAT model in a paired-watersheds in the Upper Blue Nile Basin. Catena 163, 332–341.
Worqlul, A.W., Collick, A.S., Rossiter, D.G., Langan, S., Steenhuis, T.S., 2015. Assessment of surface water irrigation potential in the Ethiopian highlands: the Lake Tana basin. Catena 129, 76–85.
Worqlul, A.W., Dile, Y.T., Bizimana, J.-C., Jeong, J., Gerik, T.J., Srinivasan, R., Richardson, J.W., Clarke, N., 2018c. Multi-dimensional evaluation of simulated small-scale irrigation intervention: a case study in Dimbasinia Watershed, Ghana. Sustainability 10, 1–23.
Zerfu, D., Larson, D.F., 2010. Incomplete Markets and Fertilizer Use: Evidence From Ethiopia. World Bank Policy Research Working Paper Series Vol.